Complexity Science and Knowledge Technology for Defence Industry and Military Forces in the 21st Century

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Abstract - Complexity of the Internet-based global economy and geo-political/military constellations is growing relentlessly increasing their dynamics and uncertainty. We are engaged in building a global digital network, which connects around 40% of the world population today, whilst 20 years ago, in 1995, it connected less than 1%. The ***first billion*** *was reached in 2005, the* ***second billion*** *in 2010 and the* ***third billion*** *in 2014. The same network contains vast amount of printed documents, books, magazines, newspapers, films, videos, images, voice recordings and music. And now we are connecting to the network all objects that are useful to us by attaching to them electronic tags that enable these objects to communicate with each other bypassing their users - the Internet of Things. As a result the world has become a highly interconnected Global Village in which no nation, no military force, no industry and no individual can prosper in isolation. We all have to learn how to become a competent participant in social, economic, political and military environments that are perpetually evolving and subject to unpredictable changes. A new science of complexity has recently emerged from the efforts to comprehend and resolve complex issues, which cannot be explained or resolved by laws of conventional, Newtonian science. Digital technology is a powerful tool for discovery, processing, storage, distribution and application of knowledge, and in the Global Village, knowledge is the most important resource for all key activities. The power of Complexity Science and Knowledge Technology is illustrated with practical applications, such as:*

Families of robots – new discoveries in multi-agent software technology combined with comprehensive sensor and knowledge technology enable design of mobile robots capable of working in space or reaching and destroying targets in complex urban or mountain environments.

Co-ordination of power, communication and weapon systems on destroyers – Rapid resolution of conflicting requirements for these three systems can be achieved by collaboration of intelligent software agents each representing a negotiating party and a knowledge base containing information on instantaneous priorities.

Defence against cyberattacks – agent-based early warning and rapidly reacting systems are designed to emulate human immune systems. The same technology can be used for protection from hackers.

The following are integrated in this presentation to show how inculcating professionalism in radiography profession (one of allied health professions) leads to a healthier nation.

- *Professionalism*
- *Biological effects of radiation*
- *Radiation protection*
- *Evidence based practice*

I. PROFESSIONALISM

Complexity is an inherent property of many systems that constitute the environment in which we live and work, namely, ecological, biological, thermodynamic and social systems (including political, administrative, economic, business and socio-technical systems). Until recently levels of complexity of social systems were low and consequently complexity was largely ignored. However, with the rapid development of digital technology the situation has changed, particularly when the Internet transformed the world into a "global village" and linked regional and national markets into a single "global market".

Many researchers have contributed to the understanding of complexity, notably Prigogine [1, 2], Kaufman [3], Holland [4] and many others. This paper is based on pioneering work devoted to developing experimental science and art of Managing Complexity by Rzevski and Skobelev [5].

II. WHAT IS COMPLEXITY

Complexity is a property of open systems that consist of a large number of diverse, interacting components, often called agents. Complex systems can be distinguished from other systems by the seven features: connectivity, autonomy, emergence, nonequilibrium, nonlinearity, self-organisation and co-evolution.

1. Connectivity - Agents are interconnected. Complexity of the system increases with the number of links that connect agents to each other. Complexity also depends on the strengths of links. The weaker the links between agents, the easier is to break them and form new ones, which increases system complexity.

2. Autonomy - Agents have certain freedom of behaviour (autonomy), which is always limited by norms, rules, regulations, and/or laws. The increase in autonomy of agents increases complexity and if all constraints on agent behaviour are removed the system switches from complex to random behaviour. Inversely, if autonomy of agents is reduced (by tightening of laws and regulations), the system complexity will decrease, and in the extreme, the system will become deterministic. Complex systems have no central control.

3. Emergence - Behaviour of complex systems emerges from the interactions of agents and is not predictable and yet it is not random. Uncertainty about the outcome of agent interactions is always between 0 and 1. Emergence, in general, denotes a property of a system that is evident in the system as a whole but it is not present in any of its components.

4. Nonequilibrium - Complex systems are subjected to perpetual change experienced either as a succession of discrete disruptive events or as a slow, imperceptible drift into failure. Frequency of disruptive events varies with complexity. In systems of high complexity disruptive events occur so frequently that the system has no time to return to stable equilibrium before the next disruption occurs. When complexity levels are very high the system is said to be at the edge of chaos because the uncertainty of behaviour is close to 1.

5. Nonlinearity - Relations between agents are nonlinear. Nonlinearity may amplify a small, insignificant disruptive event and cause a catastrophic outcome (an extreme event), the property called butterfly effect. Butterfly effect increases with complexity. In complex systems outcomes are, as a rule, consequences of numerous interacting causes, and therefore the cause-effect analysis is inappropriate.

6. Self-organisation - Complex systems have a propensity to react to disruptive events by autonomously self-organising with the aim of eliminating or, at least, reducing consequences of the disruption, the property called adaptation. Self-organisation may be also caused autonomously by a propensity to improve own performance, the property called creativity or innovation. To initiate and perform adaptive and creative activities the system must be intelligent. Intelligence, adaptation and creativity are emergent properties exclusive to complex systems and their levels increase with complexity.

7. Co-evolution – With time, complex systems change as their environments change and, in turn, they change their environments. Co-evolution is irreversible.

III. COMPLEX VERSUS DETERMINISTIC AND RANDOM SYSTEMS

Let us use uncertainty of behaviour as the demarcation parameter to distinguish complex systems from deterministic and random, as shown in Table 1.

The term deterministic implies that uncertainty is equal to zero, whilst the term random means that uncertainty is equal to one. Complex Systems have uncertainty value between zero and one.

Table 1. Complex Systems versus Deterministic and Random

RANDOM SYSTEMS	**COMPLEX SYSTEMS**	**DETERMINISTIC SYSTEMS**
Uncertainty of outcome = 1	1 > Uncertainty of outcome > 0	Uncertainty of outcome = 0
Components have full autonomy	Components (called agents) have partial autonomy	Components have no autonomy
Disorganised	Self-organising and Evolving	Organised
Unpredictable behaviour	Emergent behaviour	Predictable behaviour

Table 1 highlights the link between complexity and uncertainty of system behaviour: uncertainty is a consequence of complexity and it increases with complexity. Low complexity systems have uncertainty close to 0 and their behaviour differs little from the behaviour of deterministic systems. The behaviour of highly complex systems with uncertainty close to 1 is “far from equilibrium”. This systems have increased propensity for self-organisation, generation of unpredictable extreme events and co-evolution.

The distinction between complex and deterministic systems is very important and has philosophical repercussions. For centuries eminent philosophers and scientists have believed that the world is deterministic – that it behaves in accordance with natural laws in a predictable manner and that any uncertainty of outcomes is a result of our lack of knowledge how the world works. In other words, for supporters of determinism the world is complex only for those who do not understand it.

A more plausible alternative view has been put forward recently by Prigogine [1, 2]. The world is inherently complex and it evolves with time. Future is not given; it emerges from the interaction of billions of activities performed by constituent agents, including people, animals, plants as well as natural forces such as climate, erosion, volcanic eruptions, and solar spots. Only certain limited parts of the world can be represented by deterministic models, such as Newton’s laws.

IV. CO-EVOLUTION OF SOCIETY AND TECHNOLOGY

Historically, complexity of social systems increased in steps, driven by the advances in technology, as depicted in Table 2, and at each step the impact on the way we live and work was dramatic.

During the transition between the agricultural and the industrial societies the rapid migration of the population from the countryside to the cities, to take advantage of new employment opportunities, increased the social connectivity in the increasingly dense cities and, as a result, raised the level of social complexity. The massive movement of population caused well-documented disturbances as a rigid, traditional social order based on land ownership was replaced by a chaotic transition, which then settled into a new social order based on ownership of capital.

The current transition from the industrial to the information society, which began after the end of the World War 2 with the invention of computers, is particularly notorious by the very steep increase in social complexity caused by the rapid spread of digital technology, which offers unparalleled social connectivity (social density) but this time without any need for the population to move. Now we can form communities of interests across the globe. Distances do not matter anymore.

Table 2. Co-Evolution of technology and society

SOCIAL STAGES	**KEY RESOURCES**	**DISTRIBUTION**	**SCOPE**	**SUCCESS FACTORS**
Information Society supported by digital technology	Knowledge	Digital Networks	Global	Adaptability
Industrial Society supported by mass-production technology	Capital	Railways Motorways	National	Economy of Scale
Agricultural Society supported by manual labour	Land	Local Roads	Local	Hard Work

Thanks to digital technology, participants in the information society interact faster, more frequently and with greater number of correspondents than ever before. In the year 2013 approx. 3 billion people have used the Internet, which is more than 40% of the total number of people on the planet and, according to the Time News Feed, up to 6 billion people had access to a mobile phone. This is an astonishing increase in connectivity causing an accelerated growth of complexity.

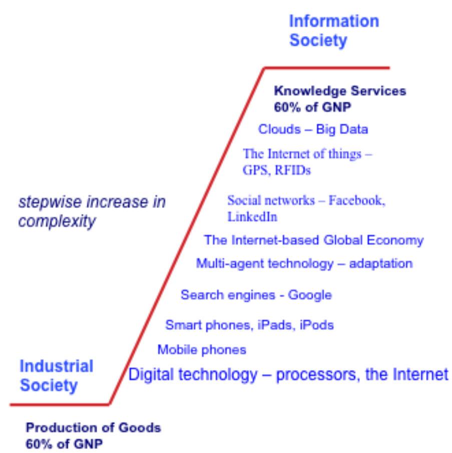

Fig. 1. Stepwise increase in social complexity

As connectivity increased we have experienced a very important shift from nation-centred industrial markets to the global economy dominated by knowledge-based services. In the industrial economy money could buy any knowledge needed for business. In the knowledge economy the knowledge how to solve complex problems can attract investments that are required to start and sustain an economic activity. Pioneers of the knowledge economy, founders of knowledge-based companies such as Apple, Google, Amazon, Microsoft and Facebook, are the new economic elite. The shift of mass manufacturing from the developed to the developing countries is a part and parcel of globalisation. However, the replacement of mass manufacturing by knowledge-based services as the main wealth creation activity occurred only in the countries where there exists expertise in advanced IT and a large number of high-class knowledge workers: researchers, designers and decision makers in financial services, IT, engineering, consulting, construction, architecture, entertainment, media, etc.

Big monolithic corporations are the product of the Industrial economy, which was characterised by stable markets generating steady demands for identical, mass produced goods. Big corporations were designed to be rigid and permanent and they thrived in the era when the Economy of Scale was the key success factor. The new complex global market is the enemy of anything big and rigid. The new critical success factor is Adaptability and therefore we can safely assume that large corporations will not have an easy future, with the exception of those that manufacture uniform products exemplified by nappies or nuts and bolts.

However, big corporations have a remarkable ability to survive and many will re-invent themselves and continue in a more appropriate format. The organisational structure that is the most suitable for delivering to perpetually changing markets is a network of self-contained service units, each having a unique expertise (knowledge resource), often referred to as Virtual or Digital Enterprise.

The concentration of data on financial transactions, on communication with friends and business associates, and on individual mobility in huge “clouds”, by organisations such as Google, raises important questions on individual privacy. It is only natural to expect that those who have knowledge about us will try to use this knowledge to manipulate our behaviour. Knowledge is power. Who will exercise this power acquired by accumulation of digital data about every aspect of our life? Will a private company (possibly in collusion with a government intelligence service) manage to acquire sufficient quantity of data to establish monopoly of knowledge? Or, can we expect that the process of natural selection will ensure the distribution of knowledge? It is safe to be an optimist. Evolution favours complexity, which implies diversity and distributed decision making rather than centralisation, although the process is slow and by no means smooth.

People) and objects of practical importance to humans are furnished with electronic tags enabling them to communicate with each other bypassing their users (the Internet of Things).

Fig. 2 shows the emerging global network as all texts, images and videos/films are digitised (the Internet of Documents), more and more people are connecting through mobile devices and the Internet (the Internet of People) and objects of practical importance to humans are furnished with electronic tags enabling them to communicate with each other bypassing their users (the Internet of Things).

Figure 2

V. PROSPERING IN A COMPLEX ENVIRONMENT

We have been brought up in Newtonian deterministic tradition and feel comfortable in well-defined stable situations. We crave simplicity and predictability.

As it happens, complexity of the environment in which we live and work is relentlessly increasing and it now intrudes into every aspect of our existence. The increase in complexity is disruptive – by making our well-established systems and processes ineffective, it forces paradigm shifts *opening up opportunities for creating a new order in society, politics, law, policy, education, research, business, design, engineering and elsewhere.*

To take advantage of new opportunities it is helpful for individuals and organisations to develop the so called “complexity mindset”, which, in a nutshell, consists of believes, principles and methods that define the relation between an individual or an organisation and the ever changing world with which they have to co-evolve.

VI. MANAGING COMPLEXITY

A new scientific discipline entitled Managing Complexity contains a growing collection of concepts, principles and methods for successfully living and working with complexity [5].
There are two aspects of managing complexity:

- Coping with external complexity (complexity of the environment) and
- Creating and tuning internal complexity

Some of the key concepts and principles are briefly outlined below.

A) Coping with External Complexity

By definition we don’t have control over our environment and therefore we cannot control its complexity. The best strategy for coping with external complexity is to develop capacity for adaptation, which implies designing complexity into our processes and structures because only complex systems can self-organise and thus adapt.

To be adaptive means to be able to achieve desired goals under conditions of frequent occurrence of unpredictable disruptive events. Adaptability is achieved by rescheduling affected resources to eliminate or, at least, to reduce consequences of a disruptive event before the next one occurs.

Key requirements for adaptability are:

- Distributed rather than centralised decision making
- A sufficient redundancy of resources to enable unpredictable rescheduling
- Availability of technology capable of
- Early detection of disruptive events
- Real-time rescheduling of affected resources
- Continuous improvement of performance to avoid a drift into failure
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B) Tuning Internal Complexity

The level of complexity of systems/organisations, which we design or control, can be adjusted by changing

- Agent autonomy
- Agent connectivity

This is largely a trial-and-error process, informed by experience in designing and managing large-scale complex adaptive systems, as described in some detail in [5].

VII. COMPLEXITY AND SOCIETY

For the purposes of this paper I shall assume that any system in which large numbers of agents are people is a social system. Then we can postulate that any social system in which members (a) have a high level of autonomy, (b) are able to communicate with many other members and (c) can change established communication links easily, is a complex social system. Such a system is adaptive and therefore resilient to disruptions and attacks; it co-evolves with its environment and therefore it never becomes obsolete [6].

My analysis shows that in crisis situations, such as a military attack, many social systems, such as nations, tend to increase their complexity (for example, by allowing greater autonomy to constituent agents), which enables them to adapt to attacks and successfully defend themselves. Since the Napoleonic war against Russia, with few exceptions, defending nations have managed to win wars against the aggressors by various modes of self-organisation.

And yet, we continue to design organisations that are pseudo-deterministic and controlled by elaborate hierarchical management structures, rather than make them complex adaptive and capable of self-organising. Complexity releases human natural intelligence and creativity.

VIII. COMPLEXITY AND BUSINESS

A business is of course a social system. It is necessary to single out peculiarities of this class of social systems because businesses create wealth [5].

A great majority of businesses today participate in the Internet-based global market. Suppliers, customers, traders, investors, bankers, consultants and middlemen are negotiating, agreeing, modifying or cancelling transactions in unprecedented numbers and with unprecedented speeds. As a consequence, the global market has become volatile and the frequency of disruptive events is such that the market, once disturbed, has no time to return to stable supply/demand equilibrium. Complexity of the global market cannot be reduced or influenced in any way by any business, even by the biggest one. And, it has to be accepted that the complexity will not go away. In fact, there exists ample evidence that it will increase as more and more people and things connect to the Internet.

Businesses operating under such conditions have considerable difficulty in planning and managing their internal business processes. Traditional decision-making and resource optimisation approaches do not deliver expected results.

Clearly the solution is to develop capacity for adaptability.

Manufacturing of cars is an instructive example. One of leading European car manufacturers, for whom I worked as a consultant, still spends a large sum of money on out of date production optimisation software that requires eight hours or so to produce a perfect (deterministic) production schedule, which becomes obsolete couple of hours after it is implemented because changes to previously agreed orders arrive from dealers approximately one per two hours. As a result the company manufactures cars that are not wanted anymore and have to be sold with discount.

A real-time, complex adaptive scheduler such as one described in [6], would cost less and would be able to re-schedule affected parts of the production plan whenever a request for a change arrives.

IX. COMPLEXITY AND ENGINEERING

Engineering systems have been always designed to exhibit deterministic behaviour within specified operational range. To achieve this aim, dynamic engineering systems that have a variety of possible behaviours, such as machines, vehicles, aircraft, rockets and robots, had to be provided with a controller, human or automatic, to behave predictably.

In contrast, behaviour of complex systems is emergent (unpredictable) and these systems have no controllers – they are adaptable – they self-organise when disturbed to eliminate or, at least, to reduce consequences of the disturbance. And this is precisely why complex engineering systems are valuable when they operate in complex environments (such as military) where adaptation has an advantage.

A) Space Robots

Consider an example. The US sent a robot to Mars, which stop functioning after few weeks because space dust covered its solar cells. Then UK sent a robot to Mars, which fell into a crevice before it could even start to do some useful work. That was a massive waste of resources and time entirely due to outdated thinking of robot designers. A family of five smaller robots, as shown in Fig. 3 below, would be able to share workload, clean and maintain each other and either drag out the unfortunate family member that fell into a crack or abandon it and share its workload among those that survived. And that would be a perfect complex adaptive engineering system.

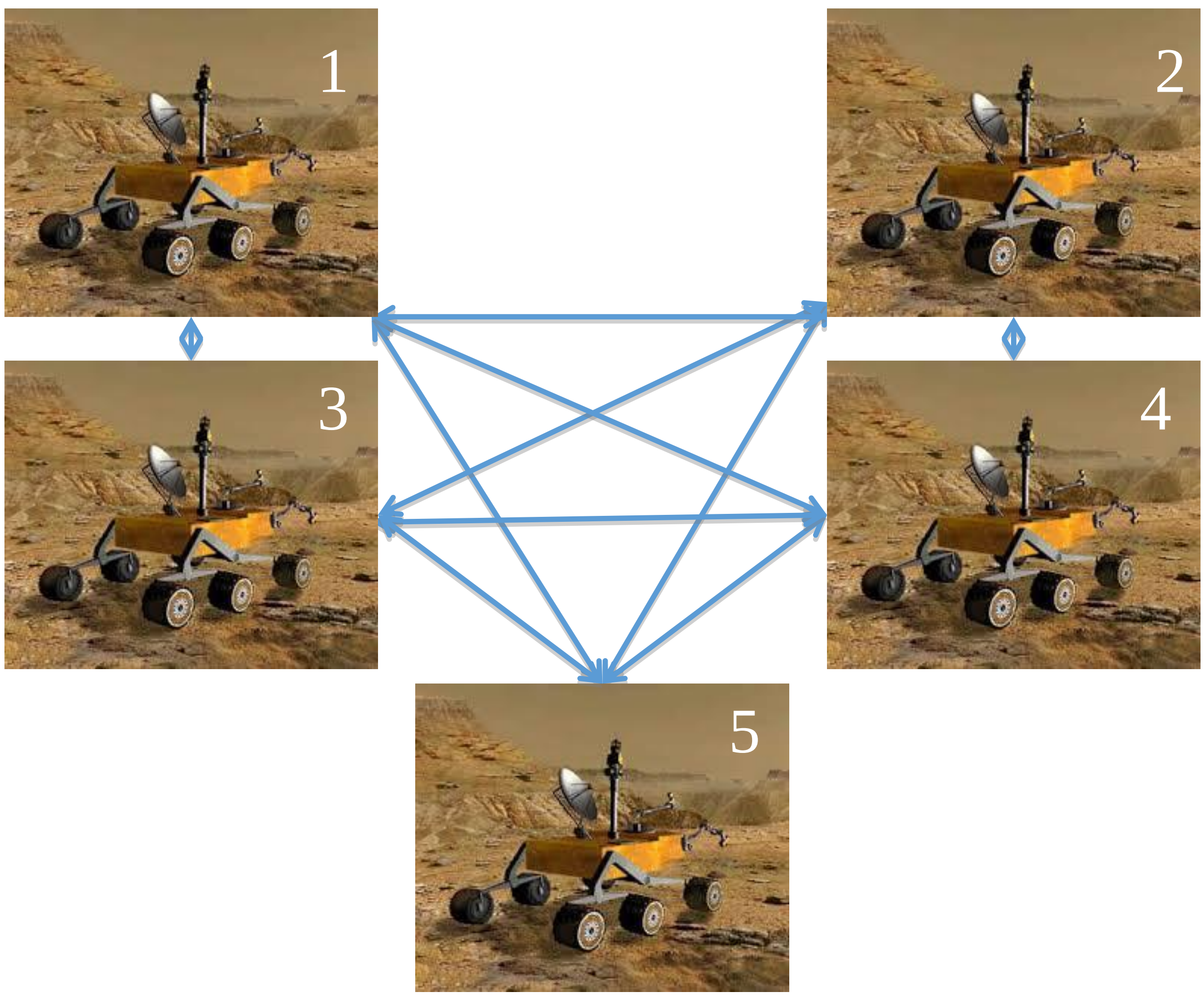

Figure.3. A family of five space robots

B) Adaptive Coordination of Power, Communication and Weapon Systems

To launch a rocket from a ship it is necessary to stop power and communication systems to ensure, for a very short time, a stable, non-moving and interference-free environment. Since in a conflict situation the ship must be ready to move and/or communicate at a very short notice it is essential to have in place a system capable of rapidly coordinating the three systems: weapons, communications and power. Coordination is notoriously difficult to achieve using conventional software technology. The best solution is to distribute decision-making and reach rapid decision which system is to be given control, at which point in time, by agent negotiation. Here is how such complex adaptive coordination system would work. Let's assume that a command is received to launch a rocket at a target at time T1. Weapon Agent then sends messages to Communication Agent and Power Agent requesting them to be ready at time T1 for action. However, Communication Agent may answer that it is not possible to interrupt the transmission of important messages in time and Power Agent may request few extra seconds for stabilising the ship. A rapid exchange of messages between three agents would continue until the conflict is resolved. A prototype developed by the author's team demonstrated superiority of coordination by negotiation over the conventional algorithmic solutions.

C) Defence against Cyberattacks

A cyberattack is an illegal entry into a digital system with intention of causing damage or stilling information. At present, although cyberattacks are relatively common, the overall costs for victims are manageable. All forecasts however envisage an alarming increase in electronic fraud and military strategists talk about future electronic wars in which cyberattacks will cause greater damage to the enemy than conventional weapons. It is essential therefore to invest into the development of cyberdefence systems.

It is interesting to note that highly adaptive systems are resilient and therefore have a natural defence mechanism. After all, adaptive systems, by definition, are capable of rapidly detecting a disruptive event and through a process of negotiation among affected agents deciding how to neutralise or at least reduce consequences of disruption. Precisely the same principle was used by author's team in developing a risk management system for reducing risk of fraud in financial industry.

X. CONCLUSION

There exist ample evidence that, driven by the rapid development of digital technology, complexity of our socio-economic environment is perpetually increasing and it has by now reached the level that no longer can be ignored.

It is therefore of paramount importance for all those who live in the new Global Village and work in the emerging Global Market to develop the appropriate Complexity Mindset, which would enable them to take advantage of fresh opportunities in research and practical applications currently on offer.

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