Report from the Scoping Workshop for the Review of Complexity Science as an EPSRC Research Area

Background:

Over the years, many definitions of complexity science have emerged, generally agreeing that complexity science studies the behaviour of systems consisting of large numbers of interacting components that interact with and adapt to their environments, leading to emergent behaviours.

Following significant investment directly into the area over the past decade, there is uncertainty about how best to continue to support relevant high quality research in this area in the future: Complexity is an inherent property of many large systems and aspects of complexity science can be regarded as integral parts of other research areas, such as non-linear systems, continuum mechanics, mathematical biology or operational research, as well as broader themes such as systems engineering, systems biology or network science. As such, work in complexity science and/or complex systems science can have an influence far beyond the remit of EPSRC supported research into biology, medicine, and the social sciences.

As the recognition of the importance of taking a "whole systems view" has grown across EPSRC's portfolio, complexity science approaches and methodologies have become ever more embedded in various aspects of our research portfolio. However, the big questions in complex systems research, such as the effects of climate change, questions around data science, population dynamics, biological systems, smart cities, etc. remain. At this stage, it is unclear whether these and other complex research challenges are best supported by a discrete research area of complexity science, or what would be a preferable alternative.

EPSRC therefore instigated a review into complexity science as a research area. By investigating our own data and consulting with the community, we aim to:

- get a better understanding of the research that is currently funded in complexity science across the EPSRC portfolio and its links to other parts of the RCUK funding landscape.
- understand how research in complexity science has changed over the past 5-10 years
- understand the effects that complexity science has had on the research landscape in the UK
- make a recommendation on how best to support excellence in complexity science and complex systems research in the future.

Aims of the Scoping Workshop:

On 25 April 2017, EPSRC invited a number of experts from a broad range of research disciplines that relate to Complexity Science to discuss the following:

- understand which major research challenges demand complexity science to be successfully tackled.
- define all stakeholder constituencies in order to involve them in the review.
- start thinking about how complexity science is best supported going forward and what work needs to be done to be able to answer this question.
- start thinking about how and when to involve the wider community in the review

This report summarises the outcomes from the workshop and gives a set of recommendations for the next steps of the review of Complexity Science as an EPSRC Research Area.

The report will be circulated amongst attendees of the scoping workshop and interested parties within the research councils, and an agreed summary will be published on the EPSRC website.

Summary

Complexity Science is intrinsically cross-disciplinary and relevant challenges in the real world require researchers from a range of disciplines to work together in a co-creative manner. This kind of working relationship requires time and effort to develop and a willingness from all parties to collaborate as equal partners.

Complexity Science at its best is ideally placed to break up silos. To do this it must look beyond the boundaries of simplistic models and seek to address real world challenges. There is a growing recognition that many long-standing problems faced by industry and society require complexity science approaches. Complexity is seen as an emerging topic in the engineering sector and in defence, and there have been recent substantial investments in research in this space internationally[1].

To be able to bridge the gap across disciplines as well as between researchers and problem holders, it is important that the UK supports the training of people with the ability and willingness to communicate beyond their domain expertise and understand how to work together to solve interconnected and complex problems.

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[1] [1] Examples include:
Complexity Science Hub Vienna: http://csh.ac.at/index/
New England Complex Systems Institute: http://necsi.edu/
NTU Complexity Institute: http://www.complexity.ntu.edu.sg/Pages/default.aspx
Future ICT: http://futurict.inn.ac/
Centro de Ciencias de la Complejidad: http://c3.unam.mx/

To best support research into complex global challenges, EPSRC should

- avoid perpetuating silos
- frame support for Complexity Science around real world challenges
- support longer, larger, co-creative, cross-disciplinary research endeavours alongside currently available standard schemes and allow for an appropriate level of risk to fulfil the high reward potential offered by such projects

All research councils should

- work together to allow support for research that addresses the complex global challenges faced by humanity in the 21st century
- train people who are able and willing to communicate and work across discipline boundaries

Next steps

- EPSRC will look at how previous large investments into Complexity Science have enabled change by mapping out follow on activities across research councils from initiatives such as Complexity Science for the Real World (2009), Energy Challenges for Complexity Science (2009), and the Centres for Doctoral Training (CDT) priority in Complexity Science.
- Together with the outputs of the scoping workshop, this will inform a set of recommendations on which EPSRC will seek input from the community through a smart survey.
- The results from the consultation will be discussed at a community meeting in 2017/18.
- Throughout the process, EPSRC will endeavour to work closely with its partner research councils in recognition of the cross-disciplinary importance of complexity science, complex systems research and systems thinking.

Annex 1: List of participants

Workshop attendees:

name	first name	affiliation	research interest
Cazier	Jean-Baptiste	University of Birmingham	computational and mathematical modelling of natural phenomena
Champneys	Alan	University of Bristol	applied dynamical systems, numerical bifurcation theory, localised phenomena
Connaughton	Colm	University of Warwick	Non-equilibrium statistical mechanics, fluid dynamics and turbulence, nonlinear waves, interacting particle systems
Gaertner	Thomas	University of Nottingham	efficient and effective machine learning and data mining algorithms
Galla	Tobias	University of Manchester	statistical mechanics of complex systems, stochastic and evolutonary dynamics, mathematical modelling in health, uncertainty quantification
Harvey	David	Thales	industry perspective
Hillston	Jane	University of Edinburgh	Quantitative modelling and verification with applications to collective adaptive systems and systems biology
Ison	Ray	Open University	systems thinking and practice, environment and sustainable development, social learning, applied technologies, and information systems
Kwiatkowska	Marta	University of Oxford	modelling and analysis methods for complex systems
Lacasa	Lucas	Queen Mary University London	complex systems science
Mobbs	Stephen	National Centre for Atmospheric Science	atmospheric dynamics
Moss	Guy	University College London	Interdisciplinary Research (computational, mathematical and physical sciences at the Life Sciences interface)
Penn	Alexandra	University of Surrey	Socio-economic-ecological systems; participatory complexity science; management, design and policy evaluation for complexity; evolutionary ecology/microbiology; synthetic and industrial ecology
Stepney	Susan	York	non-standard computation, complex adaptive systems and emergence, non-von Neumann architectures
Szymanska	Marzena	UCL	quantum collective dynamics in light matter systems

Additional participants of the pre-meeting activity:

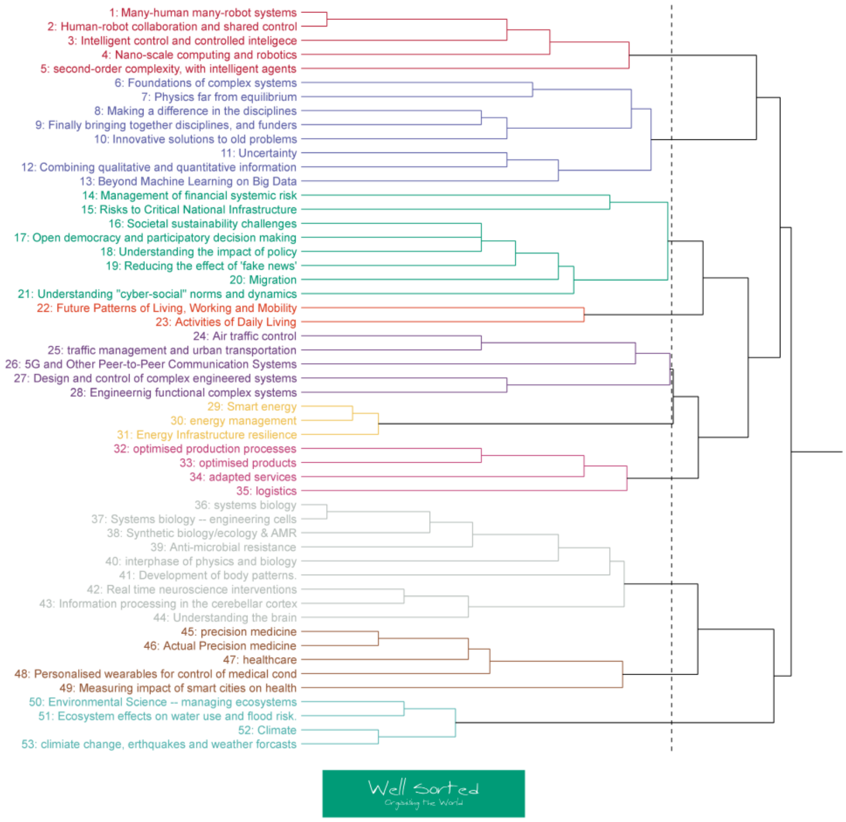
name	first name	affiliation	
Bijak	Jakub	Southampton	applications of quantitative methods in demography
Cohen	Netta	Leeds	AI, computational science and engineering
Dawes	Jonathan	Bath	applied dynamical systems, bifurcation theory, pattern formation, fluid mechanics
Gilbert	Nigel	Surrey	computational social science, policy
McCowan	Colin	Glasgow	health informatics
Nicosia	Vincenzo	QMUL	networks and data analysis
Wilson	Eddie	Bristol	intelligent transport systems

Annex 2: Outputs from the pre-meeting work

In preparation of the workshop, the attendees as well as a set of interested parties who were not able to attend the workshop, were asked to complete the following task via the web-based well-sorted tool[2]: "Casting your eye into the future, please submit 3 challenges to which you believe complexity science will have made a major contribution." 18 people contributed to this stage.

In a second stage, the attendees were asked to cluster the anonymised inputs, based on a short description provided by the initial contributor. 20 people contributed to this stage.

"Well-sorted" used the individual inputs to the clustering phase to sort the contributions into a number of groups and provided a set of visualisations of those groupings. Depicted below is the dendrogram, which shows each submitted idea and its similarity to the others. The lower two ideas 'join' the more people grouped those two ideas together. For example, if two ideas join at the bottom, every person grouped those two together. A full set of visualisations together with the descriptions for all individual headings is available as a separate document.



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[2] Methven, T. S., Padilla, S., Corne, D. W., & Chantler, M. J. (2014, February). Research Strategy Generation: Avoiding Academic 'Animal Farm'. In Proceedings of the companion publication of the 17th ACM conference on Computer supported cooperative work & social computing (pp. 25-28). ACM.

Annex 3: Outputs from the facilitated sessions

Session 1: Future Research Challenges for Complexity Science

The attendees were asked in groups to discuss in more detail two of the clusters from the "well-sorted" pre-meeting work. The following questions were to guide the discussions:

- Which overarching title would you give the challenge in your cluster(s)?
- What is a feasible timescale needed to solve this challenge and what would be key milestones?
- Who are the stakeholders/stakeholder communities with interest in this challenge?

The following clusters were identified:

Challenge	**Stakeholders**	**Timescale**
Natural and social earth systems	Environmental management, climate and earth systems sciences, risk management and mitigation	5 – 10 years to see some initial benefits
Systems biology and neuroscience (understanding the fundamental biology of the brain)	Academia, biotech industry, AI industry, communications industry	open-ended
Systems medicine	Healthcare industry and agencies, government, society	5 years – open-ended
Antimicrobial resistance	Biotech industry, healthcare services, healthcare agencies (WHO etc.), government	0 – 20 years (urgent!)
Engineered networks and infrastructure Challenges therein: - Autonomous air traffic control - Autonomous urban vehicles - Modular engineered complex systems - Measure and costing of real design complexity - Interactions of critical infrastructure - The physical side of IoT	Big engineering companies, governments, engineers, computer scientists	0 – 30 years depending on the challenge
Managing changes in energy infrastructure (incl.	Energy companies, consumers, government	0 – 5 years as of immediate importance; possibly up to

economic incentives and market design)		50 years for whole energy systems
Goods and services - Distributed manufacturing - Logistics and supply chains (risk/optimisation) - Personalisation of products	OR, network science, economists, manufacturing, game theory	5 – 10 years
Socio-economic technical systems - Risk management - Policy making and societal dynamics	Government, social scientists, citizens, policy makers	open-ended (the timescales are moving as the problems evolve. Complex problems that can't be solved but have to be managed)
Multiscale intelligent systems and their interactions - Shared control - Human computer interface - Molecular robots - Molecular programming	Physical sciences, engineering ICT	20 – 50 years
Foundations of complex systems	Mathematical and social sciences (physical and behavioural aspects)	open-ended
Novel applications of complexity science	Cross-disciplinary, academic-private partnerships	open-ended

A roundtable discussion concluded the session:

Two important aspects that had this far been missing from the discussion were identified as:

- Defence and cybersecurity
- Complexity in economics

Reflecting on the session, the attendees commented that

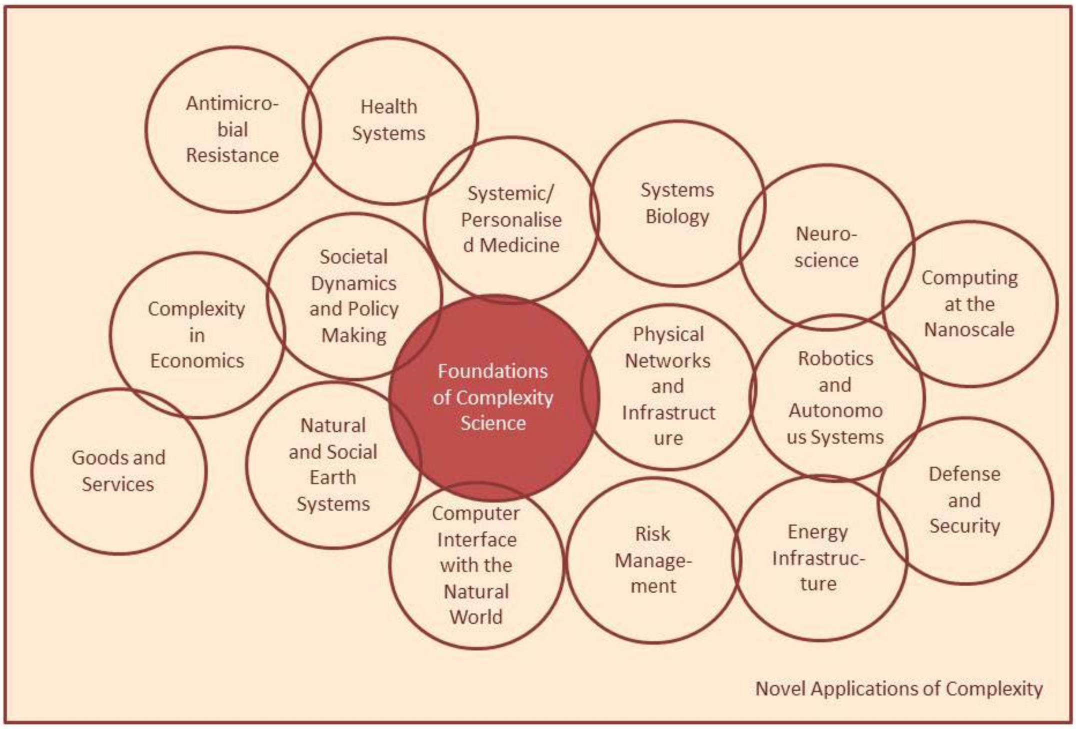
- There are common questions about the fundamental nature of complexity that underlie all identified challenges, such as: Does control work? How are we dealing with emergence?
- Most Complexity Science challenges are cross-disciplinary. It may therefore be valuable to think of ways that require and enable disciplines to work together when designing ways to respond to these challenges.
- Complexity Science clearly sits at a level above an individual EPSRC research area. An argument could be made, that systems engineering should also sit at the same level.
- The behavioural aspects of complexity science must be taken into consideration. As an example, understanding the pressures that lead doctors to over-prescribe antibiotics is key in solving the problem of antimicrobial resistance.

- It is important that people are trained who understand complexity and are proficient in developing and applying tools and methodologies to handle complexity in a system. In addition, these researchers must be able to communicate with a wider audience and work across disciplines. In the past, EPSRC has championed the development of these skills, for example through their fellowships and Centres for Doctoral Training. In future, it is hoped that these skills will be supported across all disciplines.

Session 2: The Flower Challenge

After EPSRC presented data from supported grants over the past 5 years, attendees were asked to take all that was heard so far into account and name the most important research topics connected to Complexity Science. EPSRC staff wrote the challenge on “flower petals” and attendees were then asked to split up according to their expertise and interest and fill the individual petals with keywords relating to the topic. At the end of the session, with the “fundamentals of complexity science” at the centre, the petals were arranged in clusters with the distance from the centre reflecting the breath of the topic (the further away from the centre to broader). The list is not considered exhaustive, but is meant as a means of concretising some of the main research challenges which require a Complexity Science / systems thinking approach.

The “complexity flower”:



List of topics:

Topic	**Keywords**
Foundations of Complexity Science	Co-evolutionary dynamics Managing for emergence Governance Self-organising processes Measuring complexity Misplaced understanding of control Defence Academic Pathways Implications of boundary choice / neglect Relational / systemic dynamics Information theory Strange-attractor properties of technology Incorporation into Systems Engineering approaches / processes Application to “real problems” Application to autonomous systems / AI Co-creation The goal is to keep laying the game while the game changes/adapts Spatio-temporal location Understanding interconnectivty/interdependence Stochastic processes Non-equilibrium dynamics
Health systems	Individual-environment-society Lifestyles-economics

	Health economics Heterogeneity of systems: fitbit vs primary care General knowledge from Big Data Associated cost of IT Multi-scale Whole systems Connected health and social care Data driven (real-time) healthcare
Systemic medicine	Personalised medicine Beyond Omics Diversity of data types Integration Live and past data Missing data Visualisation Ontologies Population diversity Fake news / bad science Diversity / specificity Systems medicine Nonlinear biomedical systems Personalised delivery of therapy Working with data companies Slow feedback loops uncertainty quantification in modelling physiological systems Confidentiality in a systems context Multiscale modelling subcell-cell-tissue-organ-patient-population Cohort vs individual interplay Learning from cohort but tailoring to individuals
Antimicrobial resistance	Technology to identify diversity Socioeconomic factors Ecotoxicity dimension Systems approach - not just killing everything Dynamics – selection pressures, creating and modifying Whole systems: setting boundaries correctly (e.g. inside / outside farm buildings) Mobility of vectors Spatial effects (e.g. manure spreading) Multiple scales Co-evolution Farming practices and microbial evolution
Systems biology	Drug resistant bugs Visualisation Integration of Omics Systems models based on real data
Neuroscience	Brain functioning Brain-machine interfaces Brain algorithms Form vs function – neuroscience vs psychology

	Non-invasive diagnosis (fMRI etc)
Complexity in economics	Systemic risk Social networks and norms Individual behaviour vs social practices Networks Game theory Dynamic bottom-up modelling Agent cognition Bounded rationality Agent based modelling
Societal dynamics and policy making	Interdisciplinary social and natural sciences Data availability “common sense” complexity Science and narratives Public acceptance Short timescales for policy making Complex adaptive systems Learning/adaptive policy
Natural and social earth systems	Co-evolutionary dynamics of human and natural systems Emergence Systems dynamics approach to big data Post-carbon society Data Accessible narratives and examples of complex systems (participation) Boundaries Complex adaptive systems approaches Tools for systems management / steering Systems risk Networks Game theory Dynamic behaviour of modelling
Computer interfaces with the natural world	Internet of Things Hybrid: digital and analogue
Risk management	How to calculate systemic risk empirically? Prediction in open loop systems
Computing at the nanoscale	Molecular programming DNA computation Molecular robotics/machines Drug delivery Cell interaction Stochasticity as a resource not a problem
Physical networks and infrastructure	Security designed in from the start Reconfigurability Internet of Things
Robotics and autonomous systems	Towards many human – many robots sytems Shared control Brain-computer interfaces Molecular robotics

	Control of molecular structures Swarming Self-organisation Heterogeneous systems Designing emergence Reconfigurability Internet of Things
Energy infrastructure	Resilience to targeted attacks Resilience to random fluctuation, e.g. with more renewables, small scale generation, etc. Rapid change in energy distribution Optimised restoration Agents of energy systems Adaption at multiple scales e.g. supply demand balance during operation vs pricing and incentive policies to change behaviour over longer scale to avoid the need for short term interventions Complexity toolbox
Defence and security	Building up capacity / expertise Social impact Liberty New routes of attack via online and information world Peace negotiations International studies
Goods and services	Distributed manufacturing Logistics and supply chains Product personalisation Service aggregation whilst maintaining “enough” individual satisfaction Distributed approach to stock / logistics
Novel applications of complexity	Genetic algorithms for science discovery New methods for data analysis: dynamics and networks

A roundtable discussion concluded the session:

- Looking at the “flower”, one could conceivably identify clusters that sit in the remit of a number of research councils (EPSRC, NERC, BBSRC, MRC, ESRC), reflecting the cross-disciplinary nature of Complexity Science.
- The clusters could also be mapped on EPSRC’s Outcomes Framework for a productive, resilient, connected and healthy nation, indicating the high relevance of many of these challenges for the real world.

Annex 4: Summary of the final roundtable discussion

The workshop attendees were asked to discuss the following questions:

1. Is there value in having something called "Complexity Science"?

Yes, many research challenges of fundamental importance for society exhibit a high degree of complexity. To have any hope of solving these challenges, we must aim to understand the role of complexity in those systems and its consequences.

Complexity Science is an important field of research at an international scale and complexity is an emerging topic beyond academia (examples mentioned were Thales, Boeing, dstl). EPSRC would send out the wrong message by abandoning support for Complexity Science at this point in time.

2. If Complexity Science as a research area disappeared, what would happen?

That would very much depend on what came in its place. The workshop attendees were very clear in that a rethink of the mechanisms by which EPSRC and the wider research council family aim to support the best Complexity Science is important and timely.

3. At what level should Complexity Science be supported?

The research area of Complexity Science has come out of a number of big initiatives by EPSRC in the 2000s. There is doubt in the community about the ability of EPSRC to fund truly cross-disciplinary research by having Complexity Science as an individual research area, and there is a wide-spread misconception that all Complexity Science proposals are assessed through the Mathematical Sciences. In addition, there is a danger of perpetuating a silo by not requiring researchers to interact with problem holders.

All attendees agreed that Complexity Science, while important in its own right, should be supported in a challenge-led, cross-cutting manner and not through its own research area.

It was suggested that Complexity Science challenges could be supported as a theme across research councils or at UKRI level.

Most importantly, it is important to have access to a high-quality pool of relevant reviewers who understand cross-disciplinarity to assess research proposals.

4. By what mechanisms should Complexity Science be supported?

An ideal funding mechanism would

- Incentivise true cross-disciplinarity
- Connect researchers and problem holders
- Take account of the need for substantial investment of time and effort to create real partnerships
- Be prepared to invest in projects of substantial risk to reap the potentially high rewards.

Contact for any queries:

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