

## **Embracing Complexity in Design: Emerging Perspectives and Opportunities**

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Embracing Complexity in Design (ECiD) is a unique interdisciplinary research programme with the objective of understanding the relationships between complexity and design in terms of scientific theories, methodologies, practice and social impact. The new science of complex systems is playing an increasingly important role in our society by providing radical new ways of understanding the physical, biological, ecological, and social universe. Design itself is preoccupied with envisioning the future of such complex systems, creating innovative products, systems, and solutions, and intervening in order to produce desirable effects. The Designing for the 21<sup>st</sup> Century research programme opened up this important new interdisciplinary research field and enabled our cluster to become world leader in this field.<sup>1</sup> This chapter discusses the main insights and results of the second phase of the ECiD programme, highlighting emerging perspectives and opportunities.

<sup>1</sup> JOHNSON, J. H., et al., 2007. Embracing Complexity in Design. In: T. INNS (ed.), *Designing for the 21<sup>st</sup> Century: Interdisciplinary Questions and Insights*. Aldershot: Gower Publishing, pp. 129–149.

## **Complexity Science and Design**

Both design and complexity have long research traditions complete with fundamental concepts, methodologies and distinct epistemological assumptions. They are also both very diverse. A major outcome of the ECiD project is the realization that design and complexity are inextricably entangled, and that combined they have a major role to play in designing the future.

Our programme of research began from the observations that: (i) many designed systems are complex and the science of complex systems is required to understand their behaviour; (ii) many design processes are complex, including methods of fabrication, materials, and supply chains; (iii) the environment of design is complex, including regulation, fashion

<sup>2</sup> SIMON, H. A., 1969. *The Sciences of the Artificial*. Cambridge, MA: MIT Press.

<sup>3</sup> JOHNSON, J. H., 2001. The 'can you trust it' problem of simulation science in the design of socio-technical systems. *Complexity*, 6(2), pp. 34–40.

<sup>4</sup> DORST, K. and CROSS, N., 2001. Creativity in the design process: co-evolution of problem-solution. *Design Studies*, 22(5), pp. 425–437.

<sup>5</sup> CALINESCU, A., et al., 1998. Applying and assessing two methods for measuring complexity in manufacturing. *The Journal of the Operational Research Society*, 49, pp. 723–733.

<sup>6</sup> SUH, N. P., 1999. A theory of complexity, periodicity and the design axioms. *Research in Engineering Design*, 11(2), pp. 116–131.

<sup>7</sup> AUSTIN, S., et al., 2002. Modelling and managing project complexity. *International Journal of Project Management*, 20, pp. 191–198.

<sup>8</sup> ECKERT, C., et al., 2004. Change and customization in complex engineering domains. *Research in Engineering Design*, 15(1), pp. 1–21.

<sup>9</sup> EARL, C., et al., 2005. Complexity. In: P. J. CLARKSON and C. ECKERT (eds.), *Design Process Improvement: A Review of Current Practice*. London: Springer-Verlag, pp. 174–197.

<sup>10</sup> MAIMON, O. and BRAHA, D., 1996. On the complexity of the design synthesis problem. *IEEE Transactions on Systems, Man and Cybernetics*, 26, pp. 142–151.

and the economy; and (iv) the design process itself forms a complex cognitive human system involving the creation and communication of voluminous heterogeneous information mediated by new ICT technologies enabling people to interact and collaborate locally and globally in completely new ways.

ECiD has shown that designers are masters of complexity. Designers manage large quantities of heterogeneous information: eliciting briefs from clients who do not know what they want or what are the constraints; creating new artefacts and systems using extensive domain-specific expert knowledge; managing external regulation and economic forces; managing the creative processes of generating and evaluating hypothetical possibilities, satisfying requirements and juggling constraints; and managing the uncertainties of building the new system. That many designers do this intuitively illustrates the amazing ability of human beings to assimilate and process huge amounts of heterogeneous, implicit and ambiguous information to create a synthesis that is adapted to needs. Even so, large complex systems cannot be designed by intuition alone, and the design professions are increasingly turning to the methods of complex systems science.

Whereas it is not surprising that complexity science is needed for the design of complex systems, our project leads us to the astonishing – and to some absurd – claim that *design is essential methodology in the science of complex socio-technical systems* and suggests that a design-driven scientific revolution is imminent; a revolution involving a culture shift that will surprise many working in complex systems science.

*Complex systems research* has a long and diverse history which can be conceptually traced back through cybernetics, general systems theory, information theory and even game theory. This history has also been built upon older, but more domain-specific traditions, such as thermo-dynamics in physics, evolutionary theory in biology, modelling in mathematics, computability and logic in computer science, distributed computing and multi-agent systems in artificial life and artificial intelligence, dialectics and social constructivism in social theory, and holistic approaches in philosophy. Planning and design have long been active areas in complex systems research.

Generally, complexity is seen as a characteristic of a system (and/or its observer) described on the basis of concepts such as size, variety, order and organisation. For instance, complexity is defined with relation to the size, or dimensions, of a system, the difficulty to model it, or the resources

<sup>11</sup> KOUTTAMANIS, A., 2001. Modeling Irregular and Complex Forms. In: K. NYS, et al. (eds.), *AVOCAAD, Proceedings of the Third International Added Value of Computer Aided Architectural Design Conference, Brussels, 4 June 2001*.

<sup>12</sup> GERO, J. S. and KAZAKOV, V., 2003. On Measuring the Visual Complexity of 3D Solid Objects. In: B. TUNÇER, S. ÖZSARIYILDIZ and S. SARIYILDIZ (eds.), *Proceedings of the 9<sup>th</sup> EuroPIA International Conference on E-Activities, and Intelligent Support in Design and The Built Environment, Istanbul, 8–10 October 2003*. Paris: Europia, pp. 147–156.

<sup>13</sup> KLEIN, M., et al., 2002. A complex systems perspective on computer-supported collaborative design technology. *Communications of the ACM*, 45(1), pp. 27–31.

<sup>14</sup> SOSA, R., 2005. *Computational Explorations of Creativity and Innovation in Design*. PhD thesis, University of Sydney.

<sup>15</sup> JOHNSON, J. H., 1995. The Multidimensional Networks of Complex Systems. In D. BATTEN, J. CASTI and R. THORD (eds.), *Networks in Action: Communication, Economics and Human Knowledge*. Berlin: Springer Verlag.

<sup>16</sup> JOHNSON, J. H., 2005. The Multilevel Multidimensional Networks of Complex Urban Systems. In: S. BATTY (ed.), *Proceedings of the Ninth International Conference in Computers in Urban Planning and Urban Management, CUPUM 2005, London, 29 June – 1 July 2005*. London: CASA.

<sup>17</sup> BATTY, M., 2005. *Cities and Complexity: Understanding Cities with Cellular Automata, Agent-based Models and Fractals*. Cambridge: MIT Press.

needed to describe it. Complexity is also identified with variety, diversity and multiplicity and is often linked to unpredictability or the degree to which it is possible to predict the possible future states of a system. Complexity is also seen as a critical state between order and disorder. The achievement of such states is typically associated with the critical capacity of a system to self-organise and adapt to changing environments.

The interpretation and understanding of these concepts varies across domains. However, despite the variety of the approaches, complexity is typically coupled with a ‘constructive’ stance in doing science: a disposition to focus on emergence rather than pre-determined order (that is, on order that is created from the bottom-up through local relationships and interactions) and to use generative methods and simulation instead of just decomposition and analysis. As a working position and for the purpose of this paper, we will identify this stance with an effort to study systems by preserving their organisation, or, to put it differently, to study complexity as a characteristic of the organisation of systems. This draws attention to the relational character of systems, the irreducibility of the whole into its parts, and the importance of the context within which systems are situated.

*Design research* also has a long standing history as a field of enquiry and has been studied from many different perspectives. Design research aims to develop theories about how designers think and work, but it also aims to develop methodologies and tools to support designers in their tasks. The most commonly quoted definition of design, ‘Everyone designs who devises courses of action aimed at changing existing situations into preferred ones’, comes from Simon,<sup>2</sup> who interestingly also pioneered research in complexity. This definition appreciates design as a natural activity which pervades all professional domains and disciplines. Most contemporary theories of design recognise that design involves an iterative cycle of synthesis, generation, analysis and evaluation through which design requirements and specifications co-evolve together with the solutions.<sup>3,4</sup> Design thinking is not simply about searching and generating solutions to a given problem. It essentially involves setting up a vision together with a possible realisation of this vision. The vision evolves together with the possible scenarios, processes and solutions that will satisfy it. Design thinking therefore requires an iterative process of understanding, generating, exploring, evaluating and reframing until there is a satisfying correspondence between the vision and the synthesised solution.

<sup>18</sup> MARSHALL, S., 2005. *Streets and Patterns*. London: Spon.

<sup>19</sup> BENTLEY, P. J., (ed.), 1999. *Evolutionary Design by Computers*. San Francisco: Morgan Kaufmann Publishers Inc.

<sup>20</sup> FRAZER, J., 1995. *An Evolutionary Architecture*. London: Architectural Association.

<sup>21</sup> RZEVSKI, G., 1997. A framework for designing intelligent manufacturing systems. *Computers in Industry*, 34, pp. 211–219.

<sup>22</sup> CAMPBELL, M. I., et al., 1999. A-Design: An agent-based approach to conceptual design in a dynamic environment. *Research in Engineering Design*, 11(3), pp. 172–192.

<sup>23</sup> COATES, P. and THUM, R., 2000. Parallel Systems and Architectural Form. In: *Proceedings of Greenwich 2000: Digital Creativity Symposium, Greenwich, 13–15 January 2000*. London: University of Greenwich.

<sup>24</sup> EDMONDS, E. A., et al., 1994. Support for collaborative design: agents and emergence. *Communications of the ACM*, 37(7), pp.41–47.

<sup>25</sup> GERO, J. S. and SOSA, R., 2002. Creative Design Situations: Artificial Creativity in Communities of Design Agents. In: *Redefining Content, Proceedings of the Association for Computer-Aided Architectural Design in Asia Conference, CAADRIA 2002, Cyberjaya, 2002*. New York: Prentice Hall.

<sup>26</sup> LECLERCQ, P. and JUCHMES, R., 2002. The absent interface in design engineering. *Artificial Intelligence in Engineering Design, Analysis and Manufacturing, Special Issue: Human-Computer Interaction in Engineering Contexts*, 16(3), pp. 219–227.

Design and complexity share many epistemological and methodological assumptions, attempting to take a constructive and holistic perspective of the world around us. The common emphasis on designing and constructing desired systems and properties is a strong motivation for attempting to establish stronger links between the two fields of design and complexity. However, we claim that there is an historical inevitability. Designers have to operate in an increasingly complex world in which everything is connected to everything else, and they have no choice other than embracing complexity to design and manage the new kinds of systems required to face the challenges of the twenty first century. Many scientists have yet to learn what it means to make a ‘prediction’ in the socio-technical world in which human beings *design the future*.

### Perspectives on the Relationships Between Complexity and Design

The emphasis of the research activities of the second phase of the ECiD project was to explore and synthesise different perspectives on the relation between complexity science and design by focussing on different domains of design practice. Specialised workshops were held exploring recent knowledge and advances in areas as diverse as service design, fashion, architecture, urban planning, art, digital media, performance, robotics, and policy design. This trans-disciplinary investigation unravelled the existence of multiple threads of investigation, partially conflicting and partially overlapping that from an extremely rich and dynamically growing body of research into complexity and design. Within these diverse fields of enquiry we can identify some common perspectives on the role and character of complexity in design.

#### *Complexity as a problem in design*

Complexity can be seen as a critical problem in design (whether it is the process or the product) that needs to be managed and reduced as far as possible. For example, complexity is associated with the difficulty of solving design problems, the combinatorial size of search spaces, and the variety of the generated designs. Notably, the complexity of solving design problems exists not only because these problems can be intractable, ill-defined or ill-understood, but also because they involve many different participants, with many different goals and needs. Examples include studying, measuring and managing the complexity of manufacturing,

<sup>27</sup> SAUNDERS, R. and GERO, J. S., 2002. Curious Agents and Situated Design Evaluations. In: J. S. GERO and F. M. T. BRAZIER (eds.), *Agents in Design 2002*. Sydney: University of Sydney, pp.133–149.

<sup>28</sup> ZAMENOPOULOS, T. and ALEXIOU, K., 2003. Structuring the Plan Design Process as a Coordination Problem: The Paradigm of Distributed Learning Control Coordination. In: P. LONGLEY and S. BATTY (eds.), *Advanced Spatial Analysis: The CASA book of GIS*. Redlands: ESRI Press.

<sup>29</sup> SAARLOOS, D., et al., 2005. A multiagent model for alternative plan generation. *Environment and Planning B: Planning and Design*, 32(4), pp. 505–522.

<sup>30</sup> BESUSSI, E. and CECCHINI, A., (eds.), 1996. *Artificial Worlds and Urban Studies*. Venice: DAEST, IUAV.

<sup>31</sup> WHITE, R. and ENGELEN, G., 2000. High-resolution integrated modelling of the spatial dynamics of urban and regional systems. *Computers, Environment and Urban Systems*, 24(5), pp. 383–400.

<sup>32</sup> PORTUGALI, J. and CASAKIN, H., 2002. SIRN (Synergetic Inter-Representation Network): An Approach to Design. In: D. DURLING and J. SHACKLETON (eds.), *Common Ground, Proceedings of the 2002 Design Research Society Conference, London, 5-7 September 2002*. Stoke-on-Trent: Staffordshire University Press.

<sup>33</sup> ZAMENOPOULOS, T. and ALEXIOU, K., 2007. Towards an anticipatory view of design. *Design Studies*, 28(4), pp. 411–436.

engineering and construction processes and projects, and looking at problems such as customisation, scheduling, or change management.<sup>5,6,7,8,9</sup> Undoubtedly, the complexity of processes is tightly linked to the complexity of the product itself and the way we analyse, synthesise and represent it.<sup>10,11,12</sup>

### *Complexity as a characteristic of design*

The second approach sees complexity as a characteristic or attribute of design and suggests design systems can be seen as systems that exhibit complex abilities or have characteristic complex structures. For example, design teams are seen and studied as complex networks with characteristic structures and rules of interaction.<sup>13,14</sup> Research here also includes studies which seek to understand and model design artefacts as special instances of complex multilevel systems<sup>15,16</sup> or measure and reproduce unique characteristics of designs – particularly urban forms and patterns.<sup>17,18</sup>

### *Complexity as a method in design*

A third view sees complexity as a set of methods and tools both for design practice and research. This induces methods for solving design problems or methods of simulating design phenomena. For example, methodologies that have now become central in complexity research, such as evolutionary algorithms,<sup>19,20</sup> or cellular automata and multi-agent systems,<sup>21,22,23,24,25,26,27,28,29</sup> have been regularly used to support the creative exploration of alternatives, solve multi-objective optimisation problems or evaluate design solutions, but also to model, represent, visualise and generally support complex design processes and tasks. There is a long tradition in using such techniques to model dynamical processes in cities, simulate the change of urban forms and visualise future planning scenarios.<sup>30,31,17</sup>

### *Complexity as a theory of design*

A fourth approach sees complexity as a theory of design. In this sense, complexity can be seen as a set of epistemological concepts that help us approach reality and understand design processes and products: examples include the use of concepts such as self-organisation, co-evolution, autopoiesis, or anticipation in the modelling of design processes.<sup>32,33</sup> Also there is a tradition in design disciplines (which might not be recorded in scientific papers) to use complexity concepts in design practice and discourse more loosely – as an inspiration and as a source for creativity and innovation.

### *Design as a method in complexity science*

<sup>34</sup> JOHNSON, J. H., 2008. Science and policy is designing complex futures. *Futures*, 40, pp. 520–536.

<sup>35</sup> HOWARD, E., 1902 [1946 ed.]. *Garden Cities of Tomorrow*. London: Faber and Faber.

An idea to emerge from the ECiD research is that the design and implementation of a new system constitutes *in-vivo* research into the theories behind their design.<sup>34</sup> It can be argued that the design process creates new systems, and that since there can be no empirical science of a system before it exists, designers are the first scientists of the systems they create. For example, the Wright brothers both designed the first heavier than air flying machine and initiated the science of aeronautics. The design and explosion of the atomic bomb during the Manhattan Project verified Einstein's hypothesis that such weapons could be made. Drugs are designed in medical research and tested to investigate biological processes. Ebenezer Howard's garden cities were design-driven experiments for social systems, and the creation and on-going design of our own city of Milton Keynes is a series of experiments in the design, planning and management of complex socio-technical systems.<sup>35</sup> Generally scientists have neither the mandate nor the money for the experiments they would like to do. Without policy makers in the public and private sectors, scientists cannot change taxation to investigate economic systems, cannot implement carbon policies to test their theories of human-induced climate change, cannot build cities to test their social theories, cannot design treatments to investigate cancer, and cannot do experiments in general. It is not just the money. The important thing is the mandate to make possibly damaging and *irreversible* changes that can affect millions of people on the basis of an unproven hypothesis.

### **New Interdisciplinary Research Directions**

Since 2005 the social and physical worlds have changed dramatically. The banking system that underlies much human activities has proved itself not fit for purpose and it urgently needs *redesigning* at micro and macro levels. Those responsible for parts of this system blame other parts for the problems – the system was more highly connected and interdependent than anyone realised. Climate change is no longer avoided by politicians as an inconvenient truth, and the urgent need to *design* new sustainable ways of living and consuming is now main stage. It is becoming obvious that the world is a complex system of systems **of systems**, and understanding how subsystems co-exist and co-evolve is essential to designing and managing them.

In the meantime, the *Embracing Complexity in Design* project has made a significant contribution in establishing new research projects and themes of investigation. By many interactions with many people from many backgrounds, new understanding has emerged on what it means for a system to be complex, and how this relates to and impacts on design. It may be obvious that the design of complex systems requires a science of complex systems, but it may be less obvious that a science of complex systems requires design.

Of many possibilities we select five key areas that emerged from our cluster's second phase:

- Metadesign
- Environmental change and sustainable design
- Art, science and performance interfaces
- Design and cognitive neuroscience
- Design, science and policy

### *Metadesign*

One of the main ideas in complex systems science is that top-down control does not work and cannot work for complex systems.

Even in hierarchical systems such as armies, the system works in practice by self-organisation and adapting to the environment based on individual intelligence and local information. Generals design the environment for the battle, but at the microlevel individual soldiers act according to unique sets of circumstances that no-one could have imagined. Military systems can be controlled by enabling measures such as training individuals, team building, creating a sense of mission and ensuring high morale. They can also be controlled strategically by harsh regimes that penalise individuals 'pour encourager les autres'. However, in the heat of the battle the action occurs bottom-up, from individual soldiers working towards – or against – the mission as established at higher and usually remote levels.

Increasingly in software engineering it is realised that designing large systems and testing them does not work. Not only is it impossible to test *a priori* all ways that software will be used, but the environment of software evolves allowing it to be used in new and unexpected ways. Designing functional and robust software remains a major unsolved challenge in Information and Communication Technology (ICT). Software engineers are increasingly looking to the science of complex systems for new ways to understand the way that complex engineered systems can be built

and maintained. In contrast to the rigid and brittle ICT systems that are currently designed, nature shows that systems can be much more resilient if they can adapt to their environment and co-evolve with it. Thus a major and important new idea is that of *metadesign*, where rules of assembly enable components to self-assemble according to changing requirements in changing environments. This is potentially a major contribution that complex systems science can make to design in the near future.

### *Environmental change and sustainable design*

Another theme of investigation which grew out of the project activities was the need to understand how complexity theories and methods can be applied to tackle the energy and climate challenges of our times and support sustainable design.

Sustainable design is a holistic approach to the development of artefacts, services and policies that does not simply look at recycling and the use of environmentally friendly materials, but also takes into consideration wider environmental, social and economic dimensions of design decisions. There is a natural connection between complexity and sustainable or ecological approaches, because they both take (or at least strive to take) a holistic view of phenomena. The ECiD project suggests that there are several potential synergies between sustainability and complexity for further exploration.

Methodologically, great benefits can be gained from using simulation, which is one of the most important tools of complex systems science, in order to generate and test alternative designs for sustainable development. For example, simulation can be used in order to explore different parameters that may affect individual behaviour related to energy use in buildings, and understand their interrelationship, their role and their importance. Equally, simulation may help generate alternative scenarios for intervention (at the level of the physical infrastructure and at the level of policy) and evaluate different ‘what if’ scenarios. Although simulation is not a panacea and has its limitations, it is still a very useful tool, especially because real experiments that have environmental and social impacts in the real world are often very expensive and, most importantly, carry immense risks. Simulation provides a means for scientists to work with policy makers.

A second way by which complexity science may be used to support the sustainable design enquiry is by focussing on new methods to engineer emergence through metadesign. Although most complex systems (especially social human systems) are volatile, unpredictable and difficult to control, understanding their dynamics and their multi-level structures may give us insights into making interventions that can produce desirable new behaviours, structures or functions. The fundamental issue then is exploring how we can combine design and complexity methodologies and tools, essentially in order to engender desirable effects.

One important and often overlooked way to achieve sustainable emergent outcomes is through collaboration, participation and engagement with local actors and stakeholders. Complexity studies have helped to better realise the immense capacity of self-organising distributed systems (whether these are physical, biological or social) to create beautiful sustainable solutions through communication and co-ordinated action. Looking at the formation of the built environment, for example, engagement with all kinds of groups like residents, clients, community groups and local authorities, is important for uncovering the important parameters and constraints of development, but also for exploiting the knowledge, experience and power that they hold as a distributed system. Collaborative solutions become self-sustainable when people are able to recognise positive changes, take ownership of the solutions and participate in their reproduction.

### *Art, science and performance interfaces*

Surprisingly some believe that art can contribute nothing to science, for example, on a recent BBC radio programme<sup>36</sup> the eminent biologist Lewis Wolpert proclaimed with great certainty that '*art has contributed zero to science historically. . . There are all sorts of images from science that can give artists something to work on, but it does not go the other way. . . The artist couldn't tell us a thing in that particular area*'.

We disagree, and so do many artists and scientists. 'Design' covers an immense variety of activity, from the highly subjective and ephemeral to the very objective and tangible. Art can be considered to be at one end of a spectrum that spans many creative disciplines through to heavy engineering at the other. Indeed, art can be considered to be a research laboratory for design, questioning the conventional and suggesting the new.

<sup>36</sup> *The New Two Cultures*, 2007. BBC Radio 4, April 25. Available at: <<http://www.bbc.co.uk/radio4/science/thenewtwocultures.shtml>>.

<sup>37</sup> MITLETON-KELLY, E., 2003. Complexity Research – Approaches and Methods: the LSE Complexity Group Integrated Methodology. In: A. KESKINEN, M. AALTONEN and E. MITLETON-KELLY (eds.), *Organisational Complexity*. Turku: Digistudio Helsinki Ltd.

<sup>38</sup> BOURGINE, P. and JOHNSON, J. H., 2009. Aesthetics at the Heart of Science. Submitted to: *European Conference on Complex Systems 2009, Warwick, 21–22 September 2009*.

Mitleton-Kelly<sup>37</sup> goes beyond this and uses art as a data collection instrument for complex social systems: ‘Julian Burton uses art to facilitate the process called ‘Visual Dialogue.’ This provides a visual perspective on important issues and challenges before, during and after meetings. The method can (a) capture the ideas, meanings, concerns and issues expressed in meetings, reflecting back emergent themes visually, as a catalyst for further discussion; (b) provide a visual overview of a current situation, expressing and conveying complex inter-related issues in context symbolically and engage a group’s attention thus enabling them to quickly grasp the main issues and focus on relevant elements; and (c) structure problems to facilitate shared sense-making, developing novel perspectives that can open up new possibilities in meetings.’ Mitleton-Kelly gives an example of a study of a company in which severe internal tensions made people reluctant to speak openly. Some of Burton’s pictures had been discretely placed on a wall before a gathering, and individuals looked at them, at first with curiosity and then with nervous recognition of parallels with their own dysfunctional organisation. The laughter of a senior manager was a pivotal moment, signalling permission for uncomfortable things to be said.

In Lythgo’s radio programme mentioned above, Christopher Frayling of the Royal College of Art gave the following example from the natural sciences:

*‘Fred Hoyle, [was] beginning to work in Cambridge in the late forties, on his theory of a cyclical cosmology that things don’t move in a linear way, they move in circles. He goes to see a film in nineteen forty eight made by Ealing Studios called Dead of Night. Dead of Night begins with someone pulling up at a country house – it ends with the same scene of someone pulling up at a country house. In between all sorts of things have happened but the entire movie is cyclical. It ends where it begins. It begins where it ends. And he went home and wrote in his diary ‘My God! It’s a cosmology. Maybe there’s something in this cyclical cosmology.’ The art had reinforced the idea in Fred Hoyle’s mind and off we go with Hoyle’s cosmology of the fifties.’*

Many scientists are very willing to embrace the importance of art and the need for science to innovate. Some mathematicians see their subject as art, for example, at a recent meeting on *Aesthetics at the heart of science*,<sup>38</sup> Gregory Chaitin said that the greatest compliment one mathematician can pay another is to say that they have created something *beautiful*. Mathematics is not passionless and works by creative leaps. For all its insistence on logic and proof by deduction, mathematical reasoning has

<sup>39</sup> GÖDEL, K., 1995. Some Basic Theorems on the Foundation of Mathematics and their Implications. In: S. FEFERMAN, (ed.), *Collected Works/Kurt Gödel, Vol. III*. Oxford: Oxford University Press, pp. 304–323.

<sup>40</sup> The principle that 'entities should not be multiplied unnecessarily', or that the explanation of any phenomenon should make as few assumptions as possible.

its own limitations since, as Gödel<sup>39</sup> showed, there are things that cannot be proved. Science is very much conditioned by aesthetics with high values being placed on minimality (*Occam's razor*<sup>40</sup>), symmetry, closure, patterns, randomness, harmony, consistency, complementarity, paradox, humour, surprise, and many other emotional and value laden concepts. At this meeting, Eve Mitleton-Kelly showed that artists and scientists have many things in common; for example, both explore spaces of possibilities, both use emergence, artists co-evolve with their artefacts as scientists do with their science, both art and science create new order, both are commonly engaged in collaborative emergence. The table below makes another set of comparisons, suggesting that art and science are highly related creative, cognitive processes.

Art	Complexity Science
Investigates relationships	Investigates relationships
Symbols communicate concepts	Symbols communicate concepts
Indifferent to consensus	Seeks consensus
Is subjective	Is objective [?]
Creates artefacts	Creates artefacts
Articulates theories of behaviour	Articulates theories of behaviour
Non-algorithmic search	Non-algorithmic search
Communicates ideas	Communicates ideas
World - Artist observational relationship	System – Scientist observational relationship
Artist as interpreter of observations	Scientist as interpreter of observations
Artefact – Viewer relationship	Theory – reviewer relationship
Stimulates new ideas	Stimulates new ideas
Obeys (and breaks) rules	Obeys rules (usually)
Avoids replicability	Seeks replicability
Builds on earlier work	Builds on earlier work

Table 1, Comparisons between art and science

Art emerged as particularly important during the ECiD project. Although it is clear that images, drawings and movies play a great role in science, it may be less obvious that the other senses may also play an important role. For example, can dance and movement have any value in science? Can music enable data to be perceived and interpreted differently? What roles can literature and drama play in the science of complex systems? And what of our senses of smell and taste? The science of complex systems needs new ways of thinking and engaging with the world – and art can play an important part in its development.

### *Design and cognitive neuroscience*

The ECiD project supported a pilot interdisciplinary research study carried out as a step towards understanding the neurological activity and organisation of the brain that is associated with the capacity to recognise and carry out design tasks. The study involved functional magnetic resonance imaging (fMRI) of volunteers while performing design and problem solving exercises. For more details about this research see Alexiou *et al.*<sup>41</sup>

<sup>41</sup> ALEXIOU, K., et al., 2009. Exploring the neurological basis of design cognition using brain imaging: some preliminary results. *Design Studies*, (in press).

The results of this study provide evidence to support the idea that design and (well-defined) problem solving are distinct cognitive functions, associated with distinct neural networks. Such evidence can have important implications for our theoretical understanding of the conditions that underlie our ability to design. For example, the association of design thinking with areas of the brain that essentially co-ordinate the processing of different cognitive functions or representations (like spatial, visual, verbal or sensory-motor information) points to the idea that design thinking is not a domain specific ability. This in turn may have important implications for design education and the development of teaching and learning curricula. The research also makes an important methodological contribution as it offers a first evaluation of how current advanced neuro-imaging techniques can be used in design research, highlighting problems and opportunities. Finally, the results can provide knowledge about the function of the human brain more generally and offer insights into the development of artificial design tools and methods.

Plans for future research involve studies that examine the dynamical properties of brain activation, mainly through electroencephalography (EEG). Complexity science can offer methodological tools for analysing and modelling dynamical systems and complex network structures such as those found in the brain, and existing research seems to be particularly promising in that respect.

Overall, this pilot study exploring design cognition from a neurological perspective is a unique example of how science and design can benefit from establishing frameworks for interdisciplinary collaborative research. We believe that extending this interdisciplinary collaboration between design research, cognitive neuroscience and complexity can offer important insights into the nature of design cognition and support the development of theories and methods for enabling and supporting design activity.

*Design, science and policy*

During the lifetime of the project a great number of activities were carried out, often striving to engage with communities outside the domain of design, including scientists and policy makers. These activities produced important insights about the relationships between science, design and policy more generally. While designers willingly embrace the science of complex systems, most scientists rarely give design a second thought and thereby miss one of the most revolutionary aspects of the new science – *design, in the context of policy, is an essential part of the experimental method of the new science of complex systems.*<sup>42</sup>

<sup>42</sup> JOHNSON, J. H., 2009. Policy, design and management: the in-vivo laboratory for the science of complex socio-technical systems. In: *Proceedings of the First International Conference on Complex Sciences: Theory and Applications, COMPLEX'2009, Shanghai, 23–25 February 2009*. London: Springer Verlag.

Currently few scientists today know anything about design as a process for understanding, creating and managing complex systems, but by the end of this century, if not by the end of this decade, design will be required study for complex systems science, alongside mathematics, statistics, computation, and other core topics. Many of the systems that we find hard to understand are socio-technical systems – systems of systems – with tightly coupled physical and social subsystems. Most of these systems are artificial meaning that they are in part, or wholly man-made – they are designed.<sup>2</sup>

It has become clear that some complex systems scientists are already deeply engaged in the design process, collaborating with policy makers over significant periods of time. In all these cases the scientists provide policy makers in the public and private sectors with useful theories that enable the future behaviour of the system to be predicted. It is clear that these scientists could not have done their research isolated in the laboratory and detached from policy and implementation of policy through design.

One of the main results of this project therefore is the argument that design as *in-vivo* experiment is at the heart of the methodology of the emerging science of complex systems and that it is essential to *embrace design in the science of complex systems*.

## Conclusions

Over the last five years the Designing for the 21<sup>st</sup> Century Initiative has given our cluster the opportunity to explore and develop the theme of 'Embracing Complexity in Design'. The golden rule of complexity science is that 'no-one knows everything about anything' and we have comfortably engaged in discussions playing many roles, professional and layperson, expert and ignoramus, student and teacher, guest and host, artist and scientist, citizen and policy maker. Complex systems scientists are a generous community, willing to share ideas and knowledge in the hope of discovering something new. ECiD has been a wonderful experience for all involved, and we feel it has generated important new insights into both design and science.

Currently the wider design and complexity science communities implicitly acknowledge their mutual relevance. Our research suggests that we are on the edge of a massive interaction between design and complex systems science. Can it be that design will give new understanding of how the brain works and what it means to be human, and brain science will give us new understanding of the social-cognitive process of design? Can it be complexity science will adopt design and even art as a fundamental part of its methodology, returning new principles for metadesign, with design and science merging into some new understanding of the ways that humans can live in their universe?

We believe that by embracing complexity in design, and embracing design in complexity science, humankind is better equipped for the unprecedented challenges for humankind to develop sustainable ways of living on an increasingly fragile planet.