global system dynamics and policies

Collated and written by
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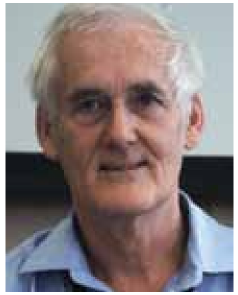
"Systems thinking can help in exploring and defining the multiple and competing goals of nations, organisations and communities."

Foreword

by Professor Lord Julian Hunt FRS



To formulate policies for the future of the globally connected world, and for responding to today's crises, requires the simultaneous consideration of many factors, different types of data and how these interact. Increasingly, a systems approach, in conjunction with latest developments in ICT, is providing understanding and an accepted framework for enabling different disciplines and organisations to collaborate in decision-making, policy and operations. Systems thinking helps in exploring and defining the multiple and competing goals of nations, organisations and communities. These can include minimising risk (whether endogenous or exogenous) and maximising sustainability, prosperity and well-being.

In the past two years systems analysis has been applied, using international language and methods, to deal with climate change and both technical and organisational arrangements for responding to new kinds of large environmental hazards. It is looking increasingly likely that systems analysis will be needed to address the systemic problem of the international financial markets. Governments are responding with new task forces and study groups, many using so-called complex system methods.

The coordinated action project Global System Dynamics and Policies (GSD), funded by the European Commission, has brought together some of the leading experts in complex systems modelling specialising in different aspects of research and applications. GSD, together with other European projects, has been exciting, surprising and broad ranging. Ideas and techniques from different academic disciplines, from physics and engineering to social science and linguistics, have contributed to new insights and software for the major problems of our time. These problems include global warming, energy strategy, economic stability, improving urban planning, energy management, crisis response in organisations and understanding mental stress. The next phase of this international collaboration will have to find out how best to explain the thinking and methods of systems analysis to decision-makers and enable them to utilise this approach more effectively in the future.

Julian Hunt is a Professor at University College London, a member of the UK House of Lords, chairman of Cambridge Environmental Research Consultants Ltd. and former director-general of the UK Meteorological Office.

Introduction
by Giles Foden

This book is concerned with the value of 'systems thinking'. The idea has been around for a long time. It goes at least as far back to Ludwig von Bertalanffy, who began developing his 'allgemeine Systemlehre' (common systems teachings) in about 1937. In fact, humankind has been developing systems since the dawn of intellectual life – and before that, too. Early on, human survival itself developed on systems. Systems of hunting, systems of avoiding being hunted oneself (how to avoid that lion on the grassy plain?), systems of agriculture, systems of barter and trade – and so through history to the interlocking, complex and often conflicting systems of custom, culture and identity.

When we talk about identity, we must start or end by talking of the individual. Yet that word, **system**, often seems at odds with an idea of the individual. What can a system do for me or you? How does the individual user, consumer or citizen fit into the system of which they find themselves part? How does the reality organizing itself inside our heads cohere with what's being organized outside? These are hard questions to answer.

As a species among other species, as a set of societies existing within the atmosphere – that is another reality in which all of us live – we are again facing situations that may be survival-critical. If the possible risks ahead were figured in the shape of that lion on the savannah, as faced by our forebears as they journeyed to new phases of organized life, it would be a large and forbidding animal. At such a time, perceptive of but by no means fully alert to such threats, I find that I have fallen in with systems thinkers.

Mostly, they emerged from natural or social science disciplines, bringing intellectual cargo of different types. Three things held them together. One was that they were all interested in crossing borders. The second was that they wanted to join their cargo with that of others. The third? They wanted the scientific product of that freighted union to be of some social utility; they wanted it to have users.

As for myself, I am a novelist. Author of novels such as *The Last King of Scotland*, I stumbled into the world of complexity and systems when I wrote a book called *Turbulence*, which was about the D-day weather forecast. Some of these scientists helped me. So in a way I am just one of those users, someone who with a small bit of scientific knowledge and almost no scientific ability, has found systems thinking extremely helpful. Engaging with other disciplines, far from eroding my own individual sphere, has strengthened and grown it.

Yet I must confess that I remain entranced by the continuing emergence of systems thinking. I have learned many things coming to the meetings of the group whose activities are outlined in this document.

One simple lesson is that what happens at the edges of systems is important. Another is that we should take note of what disappears from systems. Time, perspective and feedback factors (positive as well as negative) are also significant.

These and other aspects of systems thinking enhance its ability to identify the sometimes robust, sometimes fragile, always potentially fugitive patterns that characterise human experience. Charting those patterns can help alert us to the dangers and opportunities that lie ahead. But the processes by which those patterns are charted could do with a little advertisement, and I think that is one of the purposes of this book. For systems thinkers, there is at present a need to gain authority and support from policy makers and the media.

Part of the advertisement is about opportunities that will add value and spur sustainable growth across many dimensions of our economic and social life. For one mustn't see systems thinking as having only a negative benefit. It's not just about the lion on the plain eating us, it's about how we might grow food on the plain, and ensure that the lion or its descendants nonetheless survive that transformation of the environment.

So, as well as warning us of risks, systems thinking can also help identify latent value. To do this, systems thinkers must (to quote the Nobel laureate Seamus Heaney) be 'adept at dialect', charting a cunning middle way between the various disciplines their work comes from and the various uses to which it will be put.

That variety of uses demands good integration. It demands good data, good metrics and good governance. And it demands clarity. Those offering system thinking to policy makers should be clear – clear about what is possible and clear in the language they use to describe it. They should also be clear about what is not possible, about all the scales and connections we can't even measure, never mind model. The currently irreducible areas of experience can change – other patterns can show us how they might be brought into the fields of knowledge and usefulness – but their presence must always be acknowledged.

Increases in computer capacity mean that real-life systems of great complexity can now be represented digitally and different scenarios run on them, and that is important; but the principal future value of systems thinking is, to my view, more likely to lie in teaching humanity how to extract fairly simple lessons from the data sets feeding these system representations and then apply these lessons to the system in question.

It is a big challenge. The field of data is already vast. It is getting larger by the day. But how should we make sense of it? And, having gained some understanding, how should we change our societies as a consequence of that wisdom? What would be the effect of the change, were we to effect it? It is these sorts of question that systems science can begin to help to answer.

Systems thinkers must not soar into illusion, claiming too much for what they do, but nor must they continue to hide their secrets under a bushel. It is not my job to lobby for the brilliant scientists whose work is summarised in this document. All I can do is to appeal to policy makers' best instincts and self-knowledge, offering them my own positive exposure to both the elastic mental attitude (it involves a conception of the total effect of any action) and, most important of all, the sound science that are at the heart of systems thinking.

I can tell them that it has been an exhilarating as well as a valuable experience. I genuinely believe that there are many millions of other ordinary people who are potential enthusiasts for this co-ordinated approach to solving our problems and bettering our lives. One scientist involved in the EC programme outlined in the following pages told me, at one of our gatherings, 'we are on the verge of a new Enlightenment, the first of a series of cognitive leaps'. These seem like grandiose statements, but I agree with him wholeheartedly.

The next step in that process of enlightenment will be engaging the wider public through web applications. For it is not just those who make policy who can benefit from this co-ordinated action, it is all of us. That is because the most exciting border crossing of all will occur when we reach a step-change both in social process and in the possibilities of individual subjectivity. I hope that, reading this document, you too want to join in this doubly ameliorative journey.

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His novel Turbulence is published by Faber and Faber in the UK.
In Germany, it is published by Aufbau under the title Die Geometrie der Wolken.

Overview

This book discusses the recent advances in complex systems modelling and analysis for policy and decision-making purposes. It aims to offer ways of dealing with the urgent societal and technical challenges of our time. A **complex system** is composed of many interacting and interdependent entities where the emerging behaviour of the system as a whole cannot be completely determined from the behaviour of its individual components. Indeed many social, natural and technical systems are complex and there are many popular introductions to the subject for example Mitchell (2009) and Johnson (2009). **Systems thinking** or a **systems approach** is a method of investigating a problem or potential decision using the tools from complex systems science.

This book is based on the meetings and papers of an international coordinated action called Global System Dynamics and Policies (GSD), which was funded by the European Commission and guided by the Scientific Officer Ralph Dum. The purpose of GSD was to review how systems analysis and modelling can be applied now and in the future to policy and decision-making, with a focus on climate change, sustainability, energy and socio-economic risk. GSD has connected the different methodologies of multi-scale physics modelling, engineering dynamics, economics and organisations modelling, with the aim of producing integrated applications for decision-making.

For more information, see **www.globalsystemdynamics.eu**.

The superscripts are used to refer to the work of the partners of the GSD project shown at the end of the book.

“Can democracy survive complexity?”

Stephen Schneider
(Nobel prize winner and former advisor to successive US Presidents from Nixon to Obama) speaking after the COP 15 United Nations Climate Change Conference.

Themes

We begin by introducing the main themes of the GSD project.

- Increasingly the modelling of dynamical systems (social, political and economic) is being applied to qualitative and quantitative decision-making and policy planning in the political and corporate arenas. For example, the French utility company Veolia uses system models to advise on optimum policy options with city authorities. In that context, a demand for integrated civic policies points to the need for integrated system models ('Towards a Science of Global Systems' meeting, Brussels 2009).

- Modelling for decision-making differs from the analysis of complex self-organising systems, in subjects such as biology and physics, to reflect the wide range of societal inputs and types of behaviour and also to understand how outputs need to be appropriate to users of the information[2] (BIG-STEP meeting, Brussels 2010). It requires research experience from the academic community and practical experiences from business, industry and government to ensure models and data address the problems to be solved. Disease and epidemic modelling is a well-established example of this collaboration.

- Global problems not only involve many disciplines but also lie at the interfaces between different academic subjects where the concepts of one subject provide the critical input to another, as climate change models have demonstrated. This requires that the study of global systems encompass the natural sciences, social sciences and the tools of mathematics and computer science. Part of the task ahead (and an important reason for adopting a systemic approach) is to construct an authentically holistic approach building on the strengths of many disciplines. We must explore how this approach can overcome the limitations of the excessive specialisation of our science and the compartmentalisation of our decision process.

- Advances in information science (software engineering, model specification, formal methods) and their applications can lead to greater systems reliability and widen the range of application. This is particularly true for models requiring the gathering and managing of large-scale, heterogeneous sets of diverse data and large computing requirements.

- Developments in Information Communication Technology (ICT), in combination with system dynamics, are leading to new communication channels between policy, science and society[5]. The effectiveness of data within public policy decisions is greatest when society has wide access to the data and models that inform policy and when the implications of model results, including uncertainty, are openly and intelligibly explained. This crucially depends on how logically and rationally information and model outputs are translated into words and pictures. Reducing the uncertainty in this process is of great importance for effective use of systems in decision-making. An example of rapid communication of data is the use of Twitter by environmental agencies to send out topical warning messages.

- How can systems modelling help the decision-making process? Studies of complex systems show how the models can be simplified in order to simulate several possible states of the system and different types of decision. As is well known in economic and environmental planning, such simplification is also necessary where the model output is connected to other models and decisions and planning are made on an assembly of systems. Emergent behaviour might push the system into a new state and also profoundly affect the connections with other systems. Actions to curb anthropogenic climate change for example can inhibit economic growth[3,4]. System models can also be used forensically to determine interdependencies of elements with and within complex systems.

- In connected systems ICT enables an increase in the speed and complexity of decisions, as financial organisations have demonstrated so powerfully. Both of these factors can make systems prone to instabilities, leading to the collapse of individual organisations and major changes in the overall behaviour of financial markets, which may not be understood by managers or factored into the controls of the system ('Is there a Mathematics of Social Entities?', 98th Dahlem Workshop, Berlin, 2008).

- Analysis of system behaviour can indicate whether disturbances result from instabilities and therefore are inherent, or are driven by external influences. Changes both in physical systems (such as giant waves) and in social systems (such as sudden fluctuations in financial markets) are often attributed to external factors but in fact may result from implicit non-linear instabilities of the system that are generally not well understood. The volcanic eruptions starting in April 2010 and its impact on airline operations across Europe is an example of where connections between models of complex systems are applied to estimate risks – in this case the effect of ash on safety of aircraft engines – and also in real time for warnings and estimation of likely impacts using data and rapid communication from remote sensors and local coupling of physical and social systems.
- As more data becomes available about how people and organisations behave, representative system models can be built based on simulation of interacting agents, leading to agent-based modelling. These models will be useful for improving practices for societal problems.

"We know astonishingly little about global systems and thinking we know more than we do is very dangerous."

Carlo Jaeger
(Chair of the European Climate Forum and GSD partner)
speaking at the GSD BIG-STEP conference in Brussels, April 2010.

Connectivity and holism in complex systems

In recent decades, interrelated factors including the widespread use of the Internet, rapidly rising population and expanding globalisation of our economies, societies and cultures have led to an exponential increase in the connectivity of our global systems. For certain processes or for making certain decisions (such as limiting climate change) it is necessary to consider the whole system and holistically model many subsystems as an integrated system.

Some of the broad features of systems are determined more by the connectivity between their elements than by the detailed dynamics of the elements themselves. This connectivity aspect of dynamic systems is one of the reasons why they have ramifications for complex policy actions in an often uncertain and rapidly changing global context. In global systems, high system interconnectivity is a key aspect leading to uncertainty and instability. But it is also crucial to understand how a system may, or may not, be sensitive to critical behaviour of its elements (Hunt *et al*, 2010).

Models of dynamic systems tend to develop on multiple scales in space and time, which depend on the individual elements and on how the overall system is aggregated. Indeed models of more complex or larger dynamic systems can highlight previously unseen connections between patterns on different scales. Modelling this wide range of spatial and temporal scales is needed to study essential system properties such as (in)stability, resilience, vulnerability and regime shift tendencies in multi-physics systems or organisational networks.

The holistic approach for large systems is based on modelling contributions from diverse backgrounds. The IPCC reports (IPCC, 2007) on climate change scenarios drew on physics, chemistry, biology, earth science and economics. Models and prediction about future scenarios for the global environment have led to quantitative recommendations on mitigation and adaptation strategies for policy-makers. The very recent controversies over climate models have exposed the difficulties in validating complex system models using uncertain and incomplete data. Therefore, future scenarios and plans based on these models have to be explained transparently to the decision-makers and the public.

> "Can nine billion people be fed? Can we cope with the demands in the future on water? Can we provide enough energy? Can we do it, all that, while mitigating and adapting to climate change? And can we do all that in 21 years time? That's when these things are going to start hitting in a really big way. We need to act now. We need investment in science and technology, and all the other ways of treating very seriously these major problems. 2030 is not very far away."

John Beddington
(Chief Scientific Advisor to the UK Government)
addressing SDUK 09 conference in March 2009.

Agents and dynamics in systems with application to economics

Many systems have large numbers of elements or agents where the connections are temporary and random but they exist within some overall framework such as vehicles on a highway, people in an office or companies in the economy. Diverse multi-agent systems have been studied using modern ICT techniques (e.g. remote sensors for individual agents and large simulations). For some applications real-time predictions and control are needed to simulate quasi-independent interactions. By both observations and simulations, more is being learnt about inter-agent interactions.

During the period of the GSD project, the collapse of banks and unpredictability of the financial markets led economists and system modellers generally, to recognise that the current quasi-equilibrium models are not appropriate for rapidly changing economic conditions. Perhaps, as was suggested at the 98th Dahlem workshop entitled 'Is there a Mathematics of Social Entities' (December, 2008), dynamical system models should be considered again (as they were when economic modelling began in the 19th Century). National governments and international bodies have been engaged in the long-term task of deciding on what should be the most effective policies to deal simultaneously with climate change and sustainable economic development. Some major countries have decided on their policies (notably the EU and China), but these significantly differ. Other countries have been unable to decide. For both of these reasons there has been no internationally agreed plan for future action. GSD workshops (some of which were held with other organisations) have modelled how governments and organisations are addressing these challenges and could do so in future. These workshops, held in Berlin[4] (Mathematics of Social Entities); Venice[4,5] (Agent-based Modelling for Sustainable Development); Bekkjarvik, Norway[3] (System Dynamics Models of Coupled Natural-Social Systems) and Utrecht[2] (Elementary Models for a Sustainable Economy), have shown the need for new approaches to modelling global socio-economic systems. The results of integrated, multi-agent, evolutionary modelling methods in conjunction with ICT should in future be integrated more effectively into the decision-making domain[3].

"It's about listening to what our scientists have to say, even when it's inconvenient – especially when it's inconvenient."

US President, Barack Obama

The role of ICT

The role of ICT is growing in the deployment of dynamic systems models as they are being applied to larger numbers of elements in the systems, operate with vast quantities of data (such as financial or climate models) and provide output to large numbers of other systems, people and organisations. These developments require provision of large-scale computing infrastructures, in some cases for real-time modelling. Advances in collective and interactive web infrastructures enable stakeholder participation and interaction between different stakeholders in society. Better storage and access to large-scale data infrastructures, data mining techniques and interactive sensor networks are enabling the gathering of data on the behaviour of individuals and groups of agents in ecological and social systems such as animal movements in changing situations. Online monitoring and prediction, for example, of social or natural crises, with feedback from individual citizens, are already contributing to dynamic systems modelling of the environmental and political developments but this will inevitably change how the models are developed and used in future. Determining the metrics to be used to monitor interactive systems will be critical to their further development.

Technical advances in information science have to go beyond software engineering, model specification and formal methods in order to determine the safe speed limits for man-machine interactions, which when exceeded can cause so-called 'flash-crash' disruptions, such as those seen in the financial markets. There are also other limits to the complexity and size of the models that are used. Firstly, system models that rely on the gathering and managing of large scale, heterogeneous sets of diverse data use ever larger and more energy consuming computing capacity. Secondly, as computer programmes become larger and more complex, their reliability can become questionable since the only evidence to confirm that they are correct is verified by the highly skilled, but unsystematic process of looking at the results of thousands of calculations and studying their patterns. Computer science has not yet been able to find a fool-proof proof!

One method of presenting interactive models and data to decision-makers is through innovative ICT tools with which decision-makers can investigate data, models and even the assumptions and limitations of the models themselves: so-called serious gaming. These tools need to be constructed closely in collaboration with computer scientists and the practitioners themselves to find innovative methods for understanding, managing and disseminating the scenarios and data. There is a delicate balance that needs to be struck between the details of the models, the method of dissemination between these models and the policy-makers themselves. The GSD workshop 'how can IT help enhance uptake of scientific advice in complex policy decisions' at the European Conference on Complex Systems addressed these issues.

One vision of future ICT tools to aid the policy-making process has been developed by Arizona State University. The Decision Theater (**www.decisiontheater.org**) is an interactive environment incorporating computational and visualisation technologies to address public policy issues in four areas: Urban growth; public health; education and environment. This facility uses models, data and simulations to visualise future scenarios to aid decision-makers. There are now some research projects which intend to build upon this concept and develop large-scale software tools using new ideas of complex systems modelling.

The GSD project helped develop the interactive web model GETOnline[5] (available at **www.chalmers.se/ee/getonline**), which allows the user to select different conditions for the development of the energy system, such as access to resources, demand for energy and political decisions. The underlying calculation model combines energy technologies with energy sources, bioenergy, fossil fuels, solar energy and nuclear energy, to satisfy needs as cost-effectively as possible. The model was presented at the COP15 conference in Copenhagen. Other examples of interactive models for policy-makers include the Climate Interactive C-Roads project (**www.climateinteractive.org/simulations/C-ROADS**) and the Chalmers Climate Calculator[5] (**www.chalmers.se/ee/ccc**).

Systems models for operational and policy decisions

Methods currently used in policy-making involve more data and evidence than in the past, for example for economic and health planning. On the one hand the advantages of using data and models to develop evidence based policy is clear (for economics, health, agriculture and natural disasters, for example) however, on the other hand, there are very large differences in how countries manage resources, regulate economies and govern themselves due to differences of opinion/prejudice, lack of data or inadequacy of models. This is why both organisations and individuals differ so greatly in their decisions. This level of objectivity is why GSD is accepted as a framework for frank discussions of policies about climate change and sustainability as was made evident at the EU-China GSD seminar in May 2009, when Chinese specialists explained how their country's policies were more biased towards economicgrowth over the next 40 years rather than suppressing greenhouse gas emissions. The difference between this policy and that of the EU was discussed on the GSD blog (available via **www.globalsystemdynamics.eu**) and in New Scientist (Hunt, 2009). It is interesting to note that UN administrators, politicians and experts at COP15 in Copenhagen could not reach a legally binding international agreement concerning climate change. As the GSD programmes move forward it is essential to show objective dialogue with politicians and improve international understanding leading to harmonisation of international policy.

Data and system models are becoming closely integrated with policy development. GSD partner Tarmo Soomere[7] has used this approach in the Estonian parliament, the Riigikogu, to determine suitable policy concerning the environmental risks related to a gas pipeline planned in the Baltic Sea. After data models were presented, the Riigikogu noted that previous environmental assessments had 'not sufficiently taken into consideration all the risks connected to the project'. In Cyprus GSD partner Anastasia Sofroniou[6] has had success engaging the Water Development Department in a data and model-led debate regarding water scarcity (Sofroniou and Bishop, 2010).

The GSD conferences in Brussels[1] (BIG-STEP: Business, Industry and Government: Science and new Technology for Enhancing Policy) and the UK House of Lords[1] (Dynamics for Policy Making) have had great success in engaging policy-makers from commercial business, industry and government in a discussion on how systems thinking can help their decision-making process.

We present some of the methods and applications relevant in the current context in Table 1, however for a more complete description of complex systems science tools as well as a catalogue of elementary models and integrated assessment models, we refer the reader to the report 'Interacting with complex systems: models and games for a sustainable economy'[2] written as part of the GSD project (de Vries, 2010).

Methodology	Related modelling approaches and applications
Integral-differential equations	Physical and engineering sciences; pollutant dispersion
Optimisation and control theory, linear/dynamics programming	Physical and engineering sciences; resource depletion; least-cost abatement strategies
Systems science, systems dynamics, cybernetics	Resource systems; environmental economics and management
Catastrophe theory	Ecosystem dynamics; social (r)evolution
Network (graph, neural theory)	Foodwebs; economic input-output theory; social and information networks
Game theory	Common property resource management; social dilemmas
Cellular Automata (CA)	Land-use and land-cover dynamics (geography)
Genetic Algorithms (GA)	Optimal strategy search in complex systems
Multi-agent Simulation (MAS)	Systems science and ecology; resource and ecosystem management
Complex Adaptive Systems (CAS)	Ecosystem dynamics; socio-natural system (co)evolution (archaeology)
Scenario analysis, Narratology; figurative language study	Connecting qualitative story-telling, metaphor use and quantitative modelling (management science; futurology; textual analysis)
Simulation gaming and policy exercises	Resource management

Table 1.
Methods and tools and application fields along the complexity dimension (de Vries, 2010).

Simplified models for decision-making and games

For very large complicated problems it is not possible to model every element and sub-system in full detail because of time and data storage capacity. Another disadvantage of complicated but detailed models is that it is not practical to vary the parameters to understand the implications and predictions of the model. Quite reasonably, policy-makers are sceptical of any results, especially those that do not conform to their world-view. The balance between comprehension and comprehensive has led to the construction of integrated models with simple components and interactions between them (e.g. the economic climate modelling of Stern, 2007). Sometimes these models are constructed to simulate serious games. Though simplified models and games may not be as complete as the full models, they do allow decision-makers to interact with simulations, and thus they can illustrate some of the implications of their decisions. The way a model is simplified for decision-making depends on what kind of decisions are to be made, as well as data availability. Simple models backed up or verified by larger models may be best for fast response to disasters or other situations where there is a requirement for speed and simplicity of solution. Model simplification is not simply a matter of reducing data or structure for the sake of it; it needs to be thought through pragmatically, on a case-by-case basis. However it may be that, in an era of vastly increased data flow and complexity, model simplification-customisation also needs to be employed as an ethos, with modellers asking themselves always, what is the purpose of this model and how can I accurately reflect the world, my experience or available data?

If we can simplify the model, we may focus on the interface between, on the one hand, the (knowledge about the) system being investigated and, on the other, the person (user: policy analyst, business leader, member of the public, …) who tries to grasp the system dynamics in order to design desirable and effective interventions. In this way the scientific observations incorporated in the model and the personal observations of the user are linked in flexible ways, which allow positive interactions and learning experiences. This approach has been consolidated into methods like simulation games and policy exercises[2].

From a social science point-of-view, the approach may also serve as a laboratory in which human behaviour can be examined under more or less controlled circumstances – as carried out in experimental economics, or in military exercises for instance. The CLIMEX-project (Apetrei, 2010), for example, focuses on the user interaction with an extremely simple model.

Games and interactive simulation and visualisation technologies also appear to be an effective method for engaging the public. If the public can interact with the models, simulations and visualisations that are being used to formulate policy then there may be more debate, a stronger consensus and therefore a greater chance of achieving sustainable policies.

Science of global systems: A research agenda

During the GSD workshop in Brussels Towards a 'Science of Global Systems' a research agenda was established to develop the progress made within the GSD project. Some suggestions have emerged about fruitful directions for future research endeavours.

Our challenge has three components:

- Firstly, to understand the dynamics of global systems. Also to understand how future outcomes are affected by uncertainties in the model and in the initial data, especially where the systems are affected by humans (e.g. climate emissions). Uncertainty leads to risk and it is the understanding of the levels of risk that often drives policy.
- Secondly, to investigate how decision-makers, in business, industry and government, can understand and make better use of these models, firstly by addressing the question of how data and models can be incorporated into the decision-making process and secondly relating in more detail the subjective, responsive and random elements when decisions are made about complex systems;
- And finally, to incorporate future and emerging technologies into this global systems approach to policy-making by developing new and innovative methods for data collection, simulation, visualisation, management and dissemination.

We need to integrate in novel ways the four cornerstones of research in global systems science – i) **data** ii) **models** iii) **people** and iv) **policy**.

"Policymakers face a task of unprecedented complexity and difficulty: the transformation of our present unsustainable global socio-economic system into a sustainable system that will maintain the planet Earth sufficiently close to its present state to ensure the welfare and security of future generations. Moreover, this transformation must be brought well underway with one or two decades."

Klaus Hasselmann
(GSD Partner)

DATA

In general the data challenge is concerned with developing new methods of better user-centred modelling techniques for gathering and incorporating user pertinent data into models, together with novel ICT-enabled methods to use and interact with this data and subsequent models (e.g. visualisation, online access, etc.).

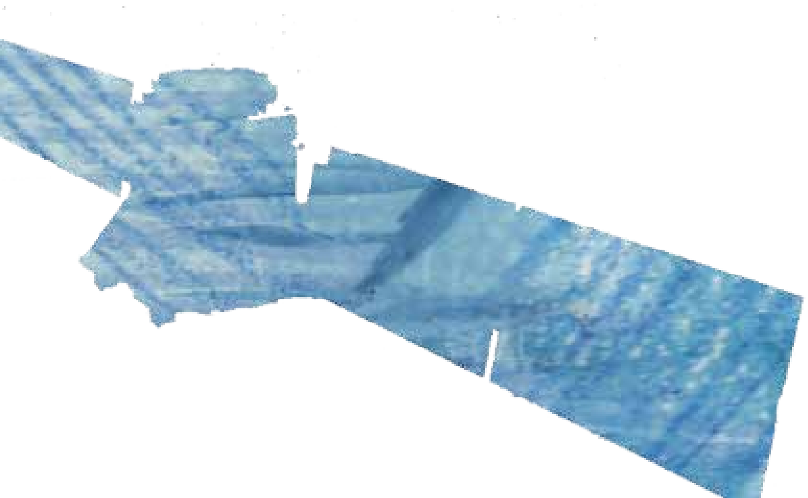
Another task is to utilise and publicise data that is held across different systems and in different forms. Data exchange limitations between countries are holding up possible applications of GSD to many social problems.

We need new methods for validation in real-time so we are best placed to react to drastic change. Firstly the data must be collected - we have never had better access to vast amounts of real-time data through new technologies, particularly mobile technology and so called Web 2.0 concepts (interactive web usage rather than passive information gathering use). These technologies must be integrated into the data and the modelling process – but in a secure way that protects the privacy of the individual. Mobile networks must be incorporated to generate geographical based information. The recent trend for on-line social networking can provide data on how certain groups of society interact with one another; real-time eyewitness information on sudden events; and data on public perception and opinion. Recent examples of the development of highly focused data provision is the use of Twitter or SMS by environmental agencies to send out topical warning messages or the web application Survey Mapper (**www.surveymapper.com**) developed by the Centre for Advanced Spatial Analysis at UCL which gathers geographical opinions on a subject of choice through online surveys.

Research needs to be directed at model and data management. This is one aspect that is often overlooked and concerns the use of the model by practitioners. Running models for the purpose of policy-making often involves thousands of parameter sets, thousands of subsequent model output data and perhaps several different model components from around the world which all need to be recorded, versioned, stored, annotated, visualised and compared. How do we design software systems and databases to manage this data? New software systems, which enable decision-makers to intuitively investigate model scenarios, are required.

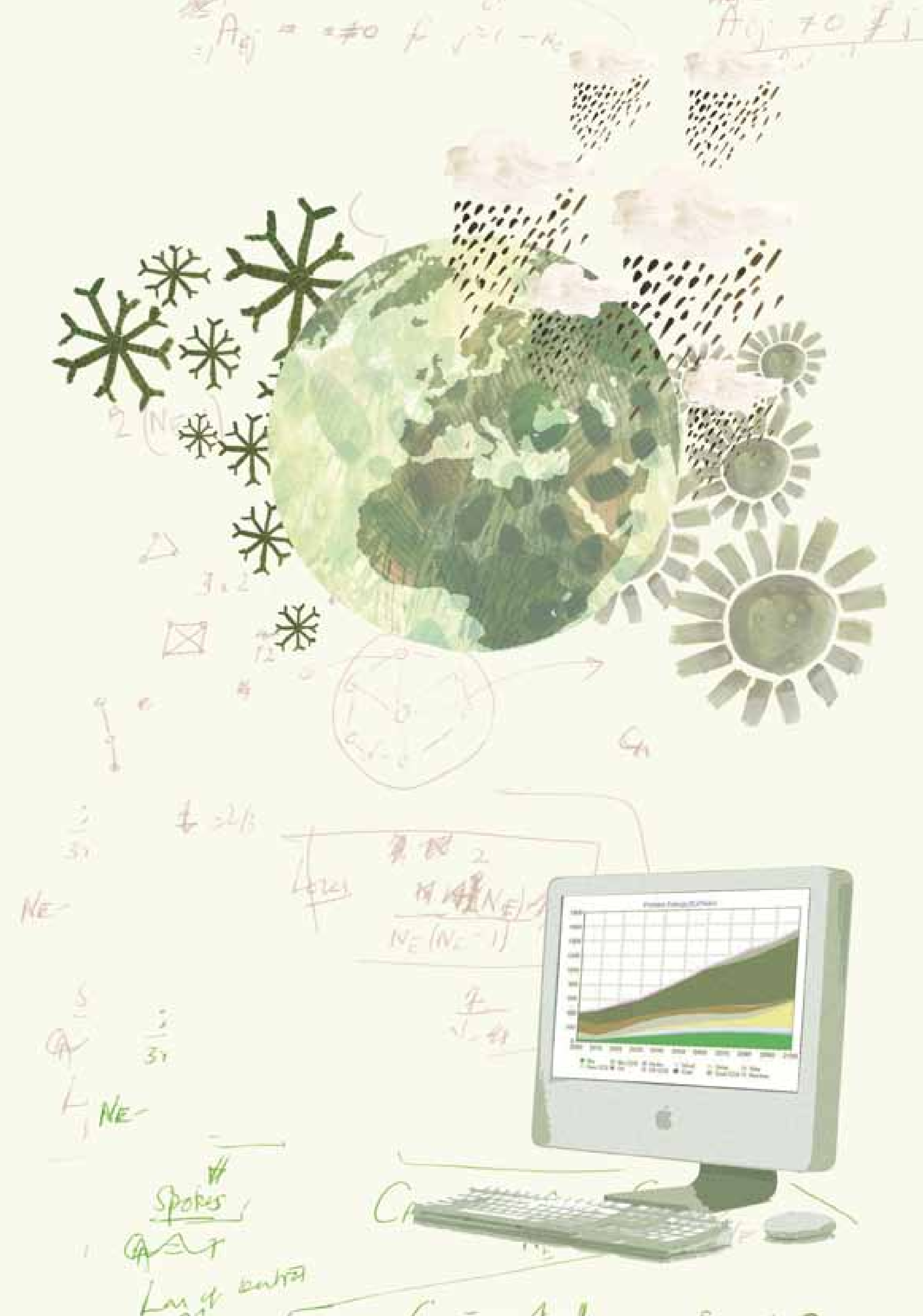
A recent trend for data storage is the move away from localised closed storage devices to network-enabled decentralised data facilities known as cloud computing. This has shown great promise in increasing the accessibility of data to both academics and decision-makers. Care must be taken however to ensure such facilities are secure, especially when handling personal or politically sensitive data.

We need novel and innovative methods for visualisation. Some of the current state of the art visualisation techniques that would benefit the policy-making domain include virtual reality (for example Virtual London, which has recently been developed by the Centre for Advanced Spatial Analysis (CASA) at UCL using Ordnance Survey data), augmented reality (the most widely known example of which is in sports broadcasting to describe team tactics but it is gaining momentum within the mobile technology industry by incorporating geographical information systems), as well as simply novel methods for producing two-dimensional diagrams which might engage decision-makers and society (see, for example **www.informationisbeautiful.net** or **www.gapminder.org**). The EC FET funded project Vismaster (**www.vismaster.eu**) is focused on the research discipline of visual analytics to effectively utilise the immense wealth of information and data acquired, computed and stored by modern information systems.



"I don't know all the answers but what I do know is that leaders in the 21st century must be systems thinkers."

Jeff Immelt
(Chief Executive Officer of General Electric)



MODELS

To fully integrate system models into decision-making, research needs to be focussed on the development of techniques, tools and concepts for an integrated system model in order to arrive at a system-wide view (rather than using linked sub-systems). To verify the results of integrated models one approach is to establish an over-riding systemic-view to ensure that all interactions between sub-models are configured at the right level. This would build on existing work in the environmental and health sciences.

Other research approaches include the development of formal methods and ICT tools to reduce/simplify models in ways that address their application/use in a decision-support and/or training context, rather than the scientific description of the phenomena involved and the development of infrastructures for big models used for ongoing questions about output (e.g. changing rainforests, changing CO_2 emissions), where the whole model is run for each scenario/decision on a GRID infrastructure, and the models being able to deliver scenarios in real time.

We need a better understanding of the boundaries between models; what are the implications of linking existing models of systems into a co-ordinated whole? How far do we need to move beyond integration of current models towards conceptualisation of truly holistic models that not only combine but actually fuse knowledge from different domains, points of view and disciplines? What are the dangers of such fusions?

Can we learn about coherent model interfaces and how can we make adaptable models? This may involve new software for a flexible conceptual analysis that enables users to examine problems across a variety of systemic domains. Useful policy interfaces require for instance the capability to modify conceptual structures in the course of negotiation processes.

Finally, can we improve our understanding of the relationships between cognitive models of the past (ex-post, 'closed' cause-and-effect models which reduce the number of dimensions of reality to represent it) and cognitive models of the future (ex-ante, 'possibilistic' models that encompass unknown dimensions of reality by assuming indeterminacy)?

PEOPLE

Understanding the dynamics of our society is difficult. Often as soon as we get a consensus of opinion some take the opposite stance, initially without full justification, which can unbalance the system. People do not always act rationally and it is very hard to perform controlled experiments to investigate hypotheses. We should be concerned with the behaviour of individual people emanating from the behavioural sciences (psychology, anthropology, sociology) but also the aggregation of this behaviour over our society. Does the apparent intelligence and variety of the human individual evaporate in the crowd or are our systems more complex? Should we not delve for 'deeper' mechanisms behind the observed aggregate system behaviour? As Bentley and Ormerod (2009) propose, perhaps it is a good idea to start with the 'zero-intelligence' model as the null-hypothesis. We could begin by representing human individuals as if they are billiard balls, or ants, or social atoms. Then, as our understanding advances, we add 'depth' in the form of cognitive processing, memory and so on.

It is the consideration of our social systems – such as our energy use, our economy and those of developing nations – that will enable effective mitigation and adaptation strategies (for example as in the 2007 IPCC Fourth Assessment Report, the now famous Stern Report (2007) or in the accessible text on energy use by MacKay, 2008). More immediate effective policies for crime prevention can also be greatly helped by modelling social behaviour[9].

Identifying socially accepted data relevant to policy decisions requires developing a theory of social and economic experiments (how to set them up, what data to gather, how are privacy and security issues addressed, etc.), developing theories of the determinants of perceptual change in societies and understanding the role of present ICT in this process.

We need to set up continual people-based monitoring, for example networks of focus groups that are maintained over time and allow us to study the changes in social values that hinder or facilitate specific policy solutions. Studying the use of Web 2.0 based opinion dynamics and developing individualised models adapted to individual citizens and focused according to the interest of the user is another aspect. In limited ways this is already being exploited commercially. Finally, can we developing non-aggregated data: information (e.g. warnings) more closely related to the needs of the recipient (e.g. health or farming), whether for individuals, specific social groups, geographic localities, or regions.

"People are smart – they know the world is complex."

Jacqueline McGlade
(Executive Director of the European Environment Agency)
speaking at the GSD BIG STEP conference in Brussels, April 2010.

POLICY

The policy cornerstone concerns the relation between scientific data and models and the decision process in society. In order to make existing scientific insights and models more useful for decision-making, it will be necessary to analyse how to incorporate human decision-making in the models (agent-based) and how to validate their representation. This entails, inter alia, a 'mathematics of social entities' to capture underlying social processes, understanding problems of agency and the social acceptance of scientific reasoning, including models. For example, experimenting with decision-making processes in different individual and group contexts. We also require an understanding of the dynamics of conventions and conceptual structures, strengthening of existing and development of new forms of participatory modelling and model analysis (decision theatres, online web-based games, etc) and improving the study of the role of conflict in decision-making, notably by using models of such situations.

The role of design has a large part to play in ensuring policy-makers are best placed to reap the benefits from such tools and models. How do the policy-makers develop a symbiosis with such ICT tools and how can art, design, language and visualisation be used both to engage policy-makers in models but also to enhance understanding? The inter-relations between design, language and science in the policy-making domain are little understood.

Narrative, analogy and interactive communicative technology have been identified as important factors in increasing the applied potential of systems modelling[8]. Indeed these factors are commonly used in describing model options to policy-makers for example through maps, betting and similarities in biology. Can we develop analogies for specific system behaviours? This is a lexicon that could be extended and put on a better linguistic footing. There may be a lot to learn from translation studies in considering the translation into verbal outputs. Should we consider the coming together of art, language, science and policy on a more formal platform?

Conclusion

Society faces many risks and challenges in both the short and the long term. A systems approach, with multi-disciplinary quantitative modelling and with ICT at its core, can help us to better understand the evolution of such risks and point the way to resilient, sustainable futures through new and, above all, evidence-based methods for developing policy. The GSD project has shown where more focus is needed to develop a science of global systems for decision-making.

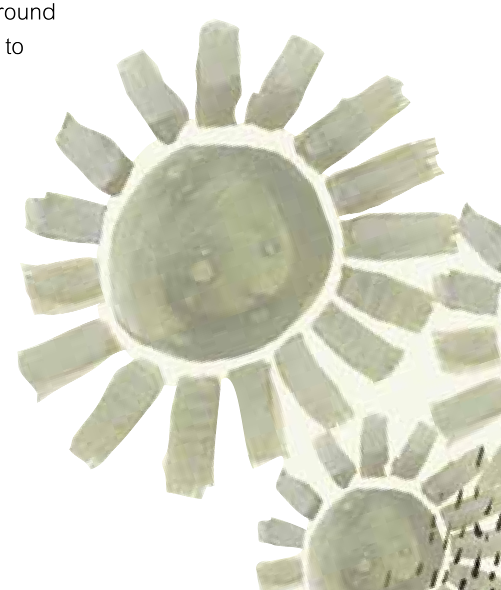
Indeed, a consideration of policy is vital in developing a science of global systems. Regulation of global systems is required but we are perhaps unable to mitigate long-term problems without collective action. While part of the solution lies in providing the public access to models to make them more informed and engage in local and community level action, national and international governments have a large role to play in developing sustainable policies aimed at keeping our global systems in good health. A future challenge that has been identified is to provide a framework to enable a systems approach to policy-making not only for governance but also for business and industry. In particular, a set of guidelines for decision-makers, in a similar vein to the Best Practice Guidelines for Industrial use of Computational Fluid Dynamics which was produced by the European research community on flow, turbulence and combustion (see **www.ercoftac.org/index.php?id=77**), might usefully be developed. These guidelines would aid both decision-makers and scientists through a systems based consideration on various issues.

At the heart of a systems approach to policy-making there needs to be a multidisciplinary framework for developing models incorporating the latest developments in complex systems science as well as vast amounts of relevant, accurate and real-time data, collected using new technologies. The science in developing such a framework however is not yet complete and significant funding for research directed at global systems modelling is required. As well as the science of such a modelling framework, there are other issues that need addressing – one of these is model and data ownership. Ownership of a model by one group may lead to distrust of results by other interested parties.

To fully verify results we need a way of cross-referencing models so that data inputs to one model can be tested and results extended via another model. Furthermore general acceptance of results will only occur if others can perform their own computer experiments giving legitimacy to policy decisions. Therefore open access systems need to be tested. Do we need to provide a common science framework to allow interaction between models?

What has become clear is that a systems approach to policy-making will only be established in close collaboration with future and emerging technologies. Indeed ICT is at the core of this new research agenda. Supercomputers or grid technology are required to run necessarily large models and simulations, the evolution of which will enable more accuracy and richer dynamics to be investigated. Large-scale models can even show up connections and consequences that we have not envisaged. Data collection techniques will become more sophisticated through mobile technologies, geographical information systems and a greater understanding of the Internet but this may possibly lead to a deluge of data. To counter this issue distributed ICT systems will be used to connect local devices in order to identify trends in real-time without the need to store huge amounts of data. The understanding of human behaviour will be enhanced through the emerging field of web science and innovative visualisations, games and interactive simulations will not only aid the modelling process but also allow decision-makers to investigate scenarios.

Such a systems approach has the capability to allow us to get away from 'pin-ball policies', which bounce around between fixed-time decisions, and can lead to sustainable policies, increased resilience and scientific advancement which, above all, will enable society to overcome some of the biggest problems it has ever faced.



GSD Partners

Partner number	Partner organisation	Country
1	Prof. Steven Bishop and Prof. Lord Julian Hunt, University College London	UK
2	Prof. Bert de Vries, Copernicus Institute for Sustainable Development and Innovation of Utrecht University	Netherlands
3	Prof. Klaus Hasselmann, Max Planck Institute of Meteorology	Germany
4	Prof. Carlo Jaeger, European Climate Forum and Potsdam Institute for Climate Impact Research	Germany
5	Prof. Kristian Lindgren and Claes Andersson, Chalmers University	Sweden
6	Dr. Anastasia Sofroniou, EDEX-Educational Excellence Corp. Ltd (now at Frederick University)	Cyprus
7	Prof. Tarmo Soomere, Tallinn University of Technology	Estonia
8	Prof. Antonio Ruiz de Elvira, Universidad de Alcala	Spain
9	Prof. Henri Berestycki and Prof. Jean-Pierre Nadal, Centre National de la Recherche Scientifique, Ecole Normale Supérieure and Centre d'Analyse et de Mathématique Sociales, and Ecole des Hautes Etudes en Sciences Sociales.	France

Workshops

The following are just a selection of workshops that took place during the GSD project and are referred to within the above text. For details of other GSD events see **www.globalsystemdynamics.eu**

'Is there a Mathematics of Social Entities?',
98th Dahlem Workshop, Berlin. December 14–19, 2008.

'Agent-based modelling for sustainable development',
a joint GSD and ECF workshop, Venice. April 2–4, 2009.

'System Dynamics Models of Coupled Natural-Social Systems',
a joint GSD and ECF workshop, Bekkjarvik, Norway. June 22–26, 2009.

'Dynamics for Policy Making',
London GSD Conference, House of Lords, London, UK. July 2, 2009.

'Towards a Science of Global Systems',
GSD Meeting in collaboration with INFSO/F2 and RTD/I2, Brussels. December 15–16, 2009.

'Elementary Models for a Sustainable Economy',
Utrecht, Netherlands. January 21–24, 2010.

'BIG-STEP: Business, Industry and Government – Science and new Technologies for Enhancing Policy',
Brussels. April 14–15, 2010.

'How can IT help enhance uptake of scientific advice in complex policy decisions: The GSD network', Workshop of the European Conference on Complex Systems, Jerusalem, September 15th, 2008.

'EU-China GSD Seminar',
Beijing, May 11–16, 2009.

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The project **Global Systems Dynamics and Policies** has considered new ways to model the dynamics of systems that develop on multiple scales in space and time requiring careful system aggregation. Comprehensive models, which take economic and social factors into account, will allow us to highlight previously unseen connections and causal relations. At the same time, in order for policy-makers to be able to make clear judgments, this project has shown the need for comprehensible models that can be operated at different scales of user knowledge. The initial focus in this study has been on sustainability where these models will help us understand the interplay between local actions and global effects that is becoming ever more prominent today. The project has interacted with leaders from government and industry to identify the key areas that need to be further addressed.