Defining a Research Strategy for uncertainty

September 2015

Executive Summary

Uncertainty is a critical issue in a number of sectors and industries, with large implications on decision making, particularly in situations involving high potential costs. Although the UK has many world leading experts in uncertainty there is a need for underpinning research to support the rapidly changing environment resulting from substantial advances in both modelling and simulation capability and an increasing desire to mitigate risk. There is particular demand around for new models, data and methods required in the decision making processes.

Dstl and EPSRC held an event in September 2015 with experts from academia, industry and government to discuss real problems in uncertainty. The themes addressed were: industry problems in uncertainty, underpinning research challenges and methods for ensuring the benefits of uncertainty research are realised.

This integrated discussion demonstrated a need for coordinated, fundamental research and recommended that a cross disciplinary research effort into uncertainty should be initiated. This effort should be managed through a network of leading experts who liaise regularly with the wider community of practice. Additionally, a framework for communicating uncertainty is required which should inform best practice and facilitate the provision of consistent and verifiable advice for decision making.

Introduction

There is widespread recognition that uncertainty is an area of research which is rapidly growing in importance [1]. Effective methods for calculating and communicating uncertainty and its relationship to risk are required across government and industry. This recognition comes from the grass roots and is supported all the way to the Government Chief Scientific Adviser, who sees research in this area as a key enabler for solving many future scientific challenges. [2]. Currently, there are pockets of research looking at the problem of uncertainty; however, these tend to be disparate and unconnected. A focussed effort bringing these efforts together and extending them into areas which are currently under-funded is seen as crucial to meet the growing requirements from government and industry.

As a result Dstl and EPSRC held an event bringing together a range of experts within various fields relating to uncertainty across academia; industry and government. This event held in September 2015 was chaired by Prof. Muffy Calder (University of Glasgow) with the aims to uncover some of the big challenges in uncertainty, investigate the current research landscape and look at the common themes between the diverse interested parties.

Background

Irrespective of the area of science we work in, uncertainty is the single biggest underpinning issue that can undermine results, increase costs, limit the effectiveness of advice and ultimately cost lives. The rapid advancement of computational capability allowing complex modelling to be performed has outstripped our ability to calculate and combine the associated uncertainties. In addition, research into uncertainty communication is in its infancy in comparison to the fields which require it.

The last few decades have seen an incredible advance in scientists' ability to understand and model the world around us, with capabilities to predict the weather, to model armed conflict, to predict the effect of pollutants, to analyse human DNA and to cause widespread disruption via cyber influence. However, this rapid change has brought the impact of uncertainty to the

fore and research into uncertainty calculation and communication has not moved forward to reflect these advances. This capability gap is becoming an area of increasing concern, as highlighted by a recent call for research by the US Defense Advanced Research Projects Agency (DARPA).

"While the statistical analysis of output data from these [complex] systems has aided the quantification of uncertainty in experiments, a similar framework for capturing and managing uncertainties from all sources is still lacking for computational modeling. Without a mathematically rigorous and overarching framework for Uncertainty Quantification (UQ) in these models, the full promise of predictive power in computational science will continue to go unfulfilled."

Sources of uncertainty are seen to include human input, intrinsic and irreducible uncertainty in model inputs, calibration and tuning errors, model error, lack of training data and ill-defined or unknown problem spaces.

In order to model complex systems and to provide effective advice, each of these sources need to be explained and accounted for and their impacts communicated in a way that is easily understood by the non-expert.

Current research efforts in the area such as the EQUIP programme[1], the MUCM programme[2], Living with Uncertainty[3] and the Centre for Doctoral Training in Quantification and Management of Risk & Uncertainty in Complex Systems & Environments[4] as well as research into visualization techniques for example [5] are clearly having substantial impact. However, disparate areas could be brought together into a single holistic effort which has the ability to realise the full benefits from the research.

While uncertainty clearly underpins all of the eight great technologies[5] and will form part of the efforts of the Turing Institute, none of these efforts can realise the benefits of an integrated approach which ensures that research is not repeated and benefits from parallel efforts, nor will they address the gamut of basic research problems faced in the area.

Current Status

The UK has many world leading experts in calculating and communicating uncertainty, yet the community of researchers is small enough to form one integrated community. This research base has repeatedly expressed an interest in a more coordinated approach to research and is active in trying to move forward with the area. This provides a unique opportunity within the UK to capitalize on this drive and draw upon expertise to coordinate efforts in this area.

Initial work to outline whether additional effort is required to ensure a UK ability to support UK industry and meet government needs, was undertaken in a recent conference (CCU2015[6]). The large numbers of attendees and speakers demonstrated a pervasive enthusiasm and desire to push this area forward.

This desire was harnessed in a workshop of the key academics and users from industry and academia with the full list of delegates presented in Appendix A. The workshop examined the

[1] http://www2.warwick.ac.uk/fac/sci/maths/research/grants/equip/
[2] http://www.mucm.ac.uk/
[3] http://www.open.ac.uk/researchprojects/livingwithuncertainty/
[4] https://www.liv.ac.uk/risk-and-uncertainty-cdt/research/
[5] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/249255/eight_great_technologies_overall_infographic.pdf
[6] http://www.southampton.ac.uk/~ccu2015/

fundamental challenges which need to be addressed and explored the mechanisms which should be employed to meet these challenges.

Workshop and outcomes

After an initial introduction to the history and current landscape of uncertainty, the workshop was structured with four distinct sessions and finished with a roundtable discussion session. The four main sessions are as follows with the full workshop agenda in appendix B and the summarised outputs from the individual sessions in appendix C:

1. Current research challenges and applications of uncertainty as determined by industry and government
2. Discussion groups around the current research Challenges
3. Current academic research across a range of disciplines connected to uncertainty
4. Discussion groups looking at potential ways forward to address the previous outlined challenges

The outcomes from the sessions demonstrated some common themes around the challenges and problems with regards to uncertainty research independent of the specific applications. Some common research challenges discussed include communication, risk, modelling, data and decision making.

Conclusions

The result of the workshop was a number of conclusions and recommendations. These were agreed by the attendees and demonstrate that there is widespread recognition both that uncertainty requires a dedicated research initiative and that more effort will be required in order to support user requirements and underpin the eight great technologies. The conclusions and recommendations are detailed below.

- The eight great technologies and the Newton Institute, as well as several individual research projects are moving specific areas of uncertainty forward, however, they do not address the fundamental issues, nor can they ensure that the benefits of uncertainty research are realised through a unification of the uncertainty community.
- There is a very strong academic community in uncertainty within the UK, with many world leading experts who wish to work together to ensure best practice.
- There is no common approach to propagating and calculating uncertainty. There are pockets of best practice but no common standards. Without a common understanding and an acceptance of the provenance and integrity of uncertainty, it will not be accepted and will result in poor decision making and high risks for industry and government.
- A rapidly changing environment has stressed the current UK research capability, the explosion of the internet, super-computing and large scale models have all resulted in the need for new research into the area of uncertainty to support these efforts. Without a clear understanding of the uncertainty resultant from large scale models the outputs are difficult to justify and this can result in reluctance to base decisions on them.
- The main area of concern is in the area of uncertainty management where decisions must be made in highly uncertain environments. There is limited research supporting this kind of decision making and no common approach for communicating uncertainty

which can lead to confusion and a lack of understanding of the end user. Typically the decision makers are not experts in understanding or calculating uncertainty and difficulties in language and a lack of common understanding and policy leads to confusion, specifically between communicating the difference between uncertainty and unreliability.

- There is a recognition that a better understanding of uncertainty will allow for better planning and a balance of investment for low likelihood / high impact events.
- There are a number of underpinning areas which require further basic research these include:
    1. The effect of an ability to calculate uncertainty on decision makers
        a. Are there challenges in making clear decisions due to data overload?
        b. How much can uncertainty be reduced, is there inherent randomness or a lower limit beyond which no progress can be made?
    2. The language of uncertainty - how should uncertainty be effectively communicated to users who may not be familiar with mathematical concepts and terminology?
    3. Uncertainty in large, inter-connected and complex models including
        a. Rare events,
        b. Phase changes,
        c. Lack of experimental data,
        d. The requirement to infer across a number of scales.
    4. Uncertainty in decision making – is it possible to optimize potential courses of action under uncertainty?
    5. Communication of uncertainty to the non-expert / decision maker.
    6. Dynamic uncertainty – how are large scale, long running models reconciled with the requirement to make decisions in a rapidly changing environment with new data occurring in real time.
- There is a need for a framework for dealing with uncertainty that is broadly adopted as best practice and will lead to consistent and verifiable advice and recommendations under uncertainty.

Recommendations

This event has demonstrated a commonality in uncertainty across a range of sectors and highlighted the need for discussion between the interested and expert communities both within industry and academia. This event has taken initial steps towards developing the commonality around the big challenges in uncertainty. The next steps will be to build upon the expertise of the participants at the workshop as they represent diverse industry and research communities. This would provide a strong basis to continue the dialogue and investigation into the research challenges in uncertainty and how academic research may aid government and industry uncertainty problems. More development around the challenges and commonality between the sectors would provide a stronger basis for more long term recommendations.

A dedicated fundamental research effort involving a large number of research establishments should be initiated.

This effort should bring together academic researchers, government, business and others involved in decision making (such as the MOD, or charities). By researching foundational issues in a context of real-world problems, progress in finding ways of computing optimal

policy could be made. Research efforts should focus on the underpinning areas outlined in the conclusions and ensure that any projects are integrated across disciplines with statisticians, applied mathematicians, pure mathematicians as well as sociologists, economists and psychologists to ensure that research is focussed on how the outcomes will be understood and communicated**.** The mechanism for this would need to be developed as would the theme or themes of the research agenda. Some of the beneficial themes this research initiative could focus on are uncertainty management or data and modelling.

A cross discipline research effort into uncertainty, bringing together a community of researchers and practitioners, which should be managed through networking of the community.

This network would be capable of bringing the currently disparate research areas together to solve wider problems in recognized priority areas. The resulting new and improved techniques for calculating, propagating and presenting uncertainty would have wide ranging impact across government and industry. The network created would be a world class organization and would provide a focus for other research efforts internationally. The network would focus on the answers to the outstanding questions in uncertainty.

Bibliography

[1] D. Spiegelhalter, "The Future Lies in Uncertainty," *Science,* vol. 345, no. 6194, pp. 264-265, July 2014.

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[3] N. R. Council, Review of Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts, Washington DC: The National Academic Press, 1997.

[4] M. O. A. Kennedy, "Bayesian Calibration of Computer Models," *Journal of the Royal Statistical Society: Series B,* vol. 63, no. 3, pp. 425-464, 2001.

[5] D. P. M. S. I. Speigelhalter, "Visualizing Uncertainty About the Future," *Science ,* vol. 333, no. 6048, pp. 1193-1400, 2011.

Appendix A

List of Workshop attendees

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Appendix B

Workshop agenda

Agenda	
09.30	***Arrival and Coffee***
10.00	Introduction
	History and overarching aims The current uncertainty landscape
11.00	Application Areas and Current Challenges
12.00	Discussion Groups and Coffee (What are the current "Grand Challenges"?)
12.35	Initial Feedback (Feedback from teams of outlined challenges)
12.50	***Lunch***
13.30	Overview of Broad Challenges
13.40	Academic research and foci
14.40	Potential Funding Mechanisms
	RCUK Innovate UK
15.00	Discussion Groups and Coffee (Follow up workshop looking at potential ways forward to address outlined challenges)
15.45	Group Feedback
16.00	Overarching Gaps and Discussion
16.15	Summary and Wash-up
16.30	***Close***

Appendix C

Session Outputs

Session 1:

The current challenges and applications were presented from a number of industry and government representatives across a range of industries including actuarial, agricultural and statistics.

The key outputs from this session highlighted that there are a number of challenges that cross a range of sectors and that uncertainty is an issue for both government and industry. For example, some of the common cross-industry challenges included; simulation, quantification, optimisation and robust design. There were also common problems around communication, reporting and decision making in the face of uncertainty.

Session 2:

The objective of this group discussion session was to develop a Grand Challenge considering what the grand challenge involves and the application to real world problems. There were five groups which resulted in the following grand challenges:

- Large Multi-disciplinary multi scale decision making
- Propagation through chains and networks
- Communication objective networking
- Decision making under uncertainty
- Science of uncertainty

The outputs from this session demonstrated that the common themes in the research that is required for the grand challenges are:

- Communication (including engaging with the public, developing a common language and multi-disciplinary working)
- Risk (and assessing and managing risk)
- Modelling (including using the same model for different purposes and understanding trade-offs in the model)
- Data (including; what weight is placed on the data, where and how is it obtained)
- Time-scales (including real-time and decision making)

Examples of Real-world problems discussed in this session are:

- Capital Infrastructure
- Geophysical and climate
- Public Health
- Complex/complicated system
- Systems for decisions

Session 3:

Academics with a variety of different research interests presented current research related to the field of uncertainty including Mathematics, Statistics, Engineering and Economics. The key outputs from this session highlighted that there is a range of research being undertaken in specific application areas which could be developed and applied crossing boundaries. Current relevant research included working with the field of climate and weather, modelling people's behaviour and responses to uncertainty, optimisation in engineering, and understanding the geometric constraints of data. There were also commonalities between disciplines specifically around communication and language and decision making under uncertainty.

Session 4:

The objective of this group discussion was to develop the research challenges within the context of the grand challenges. The proformas which are summarised here considered the barriers and opportunities for the research challenges. The research required developed from session 2 specifically focussed around modelling and data. There are a range of challenges related to modelling including the need for better algorithms and developing real-time models. There is a need to understand the model limitations, boundaries and bias. How can data be collected in real time and can this data be extrapolated to the extremes of the model? In addition two common challenges is to provide a general language for uncertainty and a policy on uncertainty and decision making.

Key barriers to a number of the research challenges are:

- Communication and language (specifically between decision makers and academics)
- Time of decision making
- Cost of data

Key opportunities are:

- Alan Turing Institute
- Exploiting existing data sources
- Software engineering in the context of uncertainty
- Engaging other researchers and users (eg social sciences and other areas of science and industry)