ENGINEERING AND PHYSICAL SCIENCES RESEARCH COUNCIL

APPLIED MATHEMATICS EVIDENCE AND ENGAGEMENT WORKSHOP REPORT

Research, discover, innovate

EPSRC

Investing in research for discovery and innovation

CONTENTS

CONTEXT

Balancing Capability is one of three strategies in our strategic plan and is an important part of managing our portfolio of investments. It aligns our portfolio to areas of UK strength and national importance. Our strategy has enabled us to champion excellence and invest in research of the highest quality in addition to securing better value for the taxpayer. Through this strategy, EPSRC supports a balanced portfolio that nurtures both discovery and challenge led research – a balance that is achieved through our engagement with business and government to influence, respond and adapt to a changing research landscape. Balancing Capability has continued to use the research area trajectories of 'grow', 'maintain' and 'reduce' and this approach will continue to enable EPSRC to balance our portfolio in line with national need.

What is EPSRC doing now as part of the Balancing Capability strategy?

EPSRC are now reviewing the research area rationales to reflect how the research base has changed over the last five years. This will enable EPSRC to align these with future aspirations for the next five years.

Why are we reviewing our rationales?

- Our original research area rationales were published in 2012 but the science landscape has continued to evolve and we need to ensure our rationales reflect this.
- We need to ensure we focus on UK strengths and nationally important areas so the UK remains internationally competitive and builds strength in areas with potential in terms of national prosperity.
- In our delivery plan, we have identified four interlinked Outcomes which collectively underpin UK prosperity: Productivity, Connectedness, Resilience and Health. We want to ensure that our research area rationales link appropriately to this outcomes framework.

The Applied Mathematics Evidence and Engagement workshop was held to build upon work EPSRC has already undertaken and to gather further evidence to support the review of our research area rationales and to provide the community with an opportunity to feed into shaping our research area strategies as we move into the next delivery plan period. The evidence gathered will form part of an evidence base which will inform the development of our research area rationales in implementing the delivery plan.

OBJECTIVES

The objectives of the workshop were as follows;

- To collate evidence of the quality and international standing of each research area and to identify gaps in the evidence base.
- To establish the capacity of each research area.

- To identify the level of importance of each research area to other disciplines and to end users of research.
- To identify key emerging opportunities and priorities for applied mathematics.

DELEGATE SELECTION

Heads of relevant departments were invited to nominate up to two people, from with their department or from elsewhere, with expertise in each of Applied Analysis, Continuum Mechanics, Non-linear Systems and Numerical Analysis. This process produced a pool of 136 nominees (of which 120 were male and 16 were female). Attendees were invited from this pool to ensure a spread of expertise across sub-disciplines of applied mathematics as well as to, as far as possible, ensure demographic diversity. Invitees who were unable to attend were offered the opportunity to nominate potential alternative attendees and these were considered in the context of the expertise required for the workshop.

A separate process was employed to ensure representation of users (for example, industrial, government or other organisations which use the outcomes of research in this area) at the workshop. Potential user representatives were identified drawing upon expertise of EPSRC staff and advice from the Mathematical Sciences strategic advisory team.

Following this process, 27 delegates attended the workshop, of which 21 were male and six were female. Three delegates at the workshop were from user organisations whilst 24 were from academic organisations. A full list of delegates can be seen in Appendix One.

WORKSHOP PROCEEDINGS AND OUTCOMES

The workshop began with introductory talks from Mike Ward, Portfolio Manager for Applied Mathematics at EPSRC and David Abrahams, Beyer Professor of Applied Mathematics at The University of Manchester. The workshop then moved on to consider a range of aspects of six topics relating to applied mathematics; Applied Analysis, Continuum Mechanics, Industrial Mathematics, Mathematical Biology, Non-linear Systems and Numerical Analysis.

Strengths, Weaknesses, Opportunities, Threats

This session was designed to allow participants the opportunity to reflect upon the strengths and weaknesses of each research topic over the last five years and to consider what opportunities and threats faced each area. Strengths and weaknesses were defined as factors internal to the area which were supportive of, or detrimental to, its success respectively and opportunities and threats as factors external to the area which again were supportive of, or detrimental to, its success. Participants were asked where possible to cluster these properties as to whether they related to quality, capacity or national importance of each research area.

The full outputs from this session can be seen in Appendix Three, but the common themes are summarised here.

Strengths

The strength of the UK internationally across a range of research areas in applied mathematics was recognised and highlighted. Numbers of citations and the track record of UK researchers in winning high profile international awards were all seen as indicators of international strength. There are several areas or sub-disciplines where the UK is believed to be world leading in terms of research quality.

The potential for high impact research was seen as a key strength of UK applied mathematics and it was felt that the UK's tradition of mathematical research inspired by applications gave it a unique advantage in terms of such impact being realised.

Several research areas were understood to have strong communities often with a good balance between critical mass in large centres and high quality activities being undertaken at a wide range of smaller institutions.

Weaknesses

A consistent theme across all research areas was concern about the development of silos within disciplines and sub-disciplines and the maintenance of artificial barriers between disciplines. It was seen to be important that different communities work together to break down these barriers wherever possible.

Training and the strength of the people pipeline continue to be a concern in many areas. For example those areas which are inherently multidisciplinary faced challenges in ensuring people had the necessary training in the application area whilst still ensuring they receive a mathematically broad and rigorous training. The availability of PhD places was raised as a concern in several areas.

Opportunities

Several opportunities identified were common to many areas and included;

- The development of stronger links to other areas of applied mathematics and mathematical sciences more generally.
- The development of stronger links with application areas and the potential for diversification of funding this offered.
- Improved engagement with industry including small and medium sized enterprises (SMEs).
- The emergence of data science as an important theme with the establishment of the Alan Turing Institute was seen as a key opportunity for many areas.
  Evidence

Threats

A common theme across research areas was that negative perceptions of particular research areas from the wider mathematical sciences community, and sometimes from other disciplines, were a threat to the future success of all disciplines. Consequently there is a need to continue to promote communication between sub-disciplines of mathematical sciences and between mathematical sciences and other disciplines and to avoid the formation of silos. In a similar vein there was also concern around the structure and processes of funders and it was felt that there was a need to ensure that these did not disadvantage those areas of research which sit at the boundary of traditional disciplines.

For those areas of relevance to data science, the Alan Turing Institute was identified as a potential threat in terms of capacity. It was particularly felt that the potential strong demand for certain skillsets produced by the Alan Turing Institute may result in shortages of people in these areas. More widely, limited investment in training, particularly in some sub-disciplines was seen as a potential threat to the future of the people pipeline in applied mathematics and mathematical sciences more generally.

Landscapes

Prior to the workshop, authors of the landscape documents prepared for the 2010 International Review of Mathematical Sciences, or where the original authors were unavailable, their suggested alternatives, were invited to revisit those documents to identify any changes or updates which would be required for the documents to reflect the landscape in each respective area as they have evolved since 2010. This session provided workshop participants with the opportunity to consider this preparatory work and to provide input as to any changes to the original documents they felt were needed in preparing up to date community overview documents.

Scenarios

For each research area, participants were invited to consider plausible scenarios for how each research topic might evolve over the next five years and to identify the key factors associated with the best and worst case scenarios. The full outputs of this session can be viewed in Appendix Three, but the themes common across several research areas are identified below.

Best Case

The best case scenario for all research areas featured more effective practices for working with others outside the specific research community, whether they be researchers in other sub-disciplines of mathematical sciences, researchers in other research disciplines or end users of research. Furthermore, it was felt that improving such links would increase the opportunities for many areas of the Mathematical Sciences to make a greater contribution to key research challenges. Improvement of the people pipeline was seen as an important factor in achieving the best case scenario in several research topics, although what this meant in practice varied depending upon the specific situation of each research area.

Worst Case

A key feature of each topic's worst case scenario fell under the broad umbrella of retention of talent and related in particular to concern about possible net losses of talent to other countries, other professions or to retirement. The specific career stages of concern varied between topics and spanned all career stages from PhD level to established career stage. A second common concern was associated with the potential for different communities to retrench into silos and for decreased interactions with other disciplines and sub-disciplines.

Future Opportunities

The purpose of this session was to identify key longer term opportunities relevant to each of the areas of research. Naturally many opportunities were specific to each area and these can be viewed in full in Appendix Three, however several opportunities were identified which were cross cutting in terms of area of research including, Uncertainty, Data Science, improvement of links with other disciplines, closer links with end users including industry and increased integration of sub-disciplines within mathematical sciences.

FEEDBACK

Following the workshop the attendees were invited to provide feedback regarding the format and organisation of the workshop. Further details of the feedback received can be viewed in Appendix Four, but overall it is clear that the event was very positively received and that participants valued the opportunity to reflect on the current and future direction of applied mathematics and to feed in to the development EPSRC strategies.

NEXT STEPS

The immediate next step following the workshop was to invite the authors of the original 2010 landscape documents to co-ordinate the production of updated community overview documents of each research area, drawing on the original landscape documents, the outputs of the workshop and input from the wider community. These community overview documents will be published in due course and will form a key part of EPSRC's evidence base for the review of research area rationales.

A call for evidence has been opened to allow organisations to submit additional evidence to complement that already gathered by EPSRC through other means. The returns period opened on the 11^{th} April and will close on the 3^{rd} June 2016.

Following the call for evidence, EPSRC plans to hold regional meetings to update the wider community on EPSRC strategy and to provide a further opportunity to provide evidence as to the quality, capacity and importance of each of the Mathematical Sciences research areas which has not already been captured.

SUMMARY

The objectives of this workshop were to enable key stakeholders in applied mathematics to provide input and evidence regarding the quality, capacity and importance of six broad areas of research relating to applied mathematics as well as to identify key future opportunities in these areas. The six topics covered were applied analysis, continuum mechanics, industrial mathematics, mathematical biology, non-linear systems and complexity science and numerical analysis.

This workshop formed part of an ongoing process of engagement and evidence gathering ahead of the planned update of our research area rationales planned later in 2016. The advice and evidence gathered will, along with that received through other engagement activities, form part of an evidence base which will inform the development of our research area rationales in implementing the delivery plan.

APPENDIX ONE – DELEGATE LIST

David Abrahams	University of Manchester
Peter Ashwin	University of Exeter
Simon Bittleston	Schlumberger PLC
Ken Brown	University of Glasgow
Chris Budd	University of Bath
Matt Butchers	Knowledge Transfer Network
Ke Chen	University of Liverpool
Gianne Derks	University of Surrey
Charlie Elliott	University of Warwick
Melina Freitag	University of Bath
Nick Higham	University of Manchester
Nick Hill	University of Glasgow
Arieh Iserles	University of Cambridge
Anne Juel	University of Manchester
John King	University of Nottingham
Ben Leimkuhler	University of Edinburgh
Marco Marletta	Cardiff University
Paul Milewski	University of Bath
Alexander Movchan	University of Liverpool
Nigel Peake	University of Cambridge
Colin Please	University of Oxford
Ian Roulstone	University of Surrey
Alistair Rucklidge	University of Leeds
Carola-Bibiane Schönlieb	University of Cambridge
Anne Skeldon	University of Surrey
Valery Smyshlyaev	University College London
Helen Wilson	University College London
Louise Wright	National Physics Laboratory

APPENDIX TWO – AGENDA

Engineering and Physical Sciences Research Council

Mathematical Sciences Theme: Applied Mathematics Evidence and Engagement (AMEE) Workshop

03 and 04 February 2016 - Novotel Leeds Centre

03 February – Day One

11:00 – 11:30 **Registration (Tea/Coffee)**

Introductory Session

11:30 – 11:35	Welcome
11:35 – 12:15	Introduction
12:15 – 12:45	UK Applied Mathematics – Prof David Abrahams
12:45 – 13:45	**Lunch**

Session One

13:45 – 13:50	Introduction to the Session
13:50 – 14:50	Research Area Analysis – Quality, Importance, Capacity
14:50 – 15:05	**Tea/Coffee**
15:05 – 15:15	Feedback

Session Two

15:15 – 15:20	Introduction to the Session
15:20 – 16:00	Evidence Gathering
16:00 – 16:30	Plenary Discussion and Summary
16:30	End of Day One
19:00	**Dinner**

Engineering and Physical Sciences Research Council

Mathematical Sciences Theme: Applied Mathematics Evidence and Engagement (AMEE) Workshop

03 and 04 February 2016 - Novotel Leeds Centre

<u>04 February – Day Two</u>

<u>Introductory session 2</u>

9:15 – 9:30	**Tea and Coffee**
9:30 – 9:40	Overview of Day Two

<u>Session Three</u>

9:40 – 9:45	Introduction to the Session
9:45 – 10:45	Applied Mathematics Landscapes Part One
10:45 – 11:00	**Tea and Coffee**
11:00 – 12:00	Applied Mathematics Landscapes Part Two
12:00 – 12:15	Feedback from Landscape Authors
12:15 – 13:15	**Lunch**

<u>Session Four</u>

13:15 – 13:20	Introduction to the Session
13:20 – 14:00	Research Area Scenarios

<u>Session Five</u>

14:00 – 14:05	Introduction to the Session
14:05 – 15:00	Future Opportunities

<u>Finale</u>

15:00 – 15:30	Summary and Plenary Discussion
15:30	End

APPENDIX THREE - OUTPUTS

The raw outputs generated by participants at the workshop are included for information below. Please note that the views expressed are those of the workshop participants and are not necessarily those of EPSRC. Comments mentioning specific individuals and/or organisations have been removed.

Session One – Strengths, Weaknesses, Opportunities, Threats.

Applied analysis

- Strengths
  - Good interaction with other areas of maths, engineering and physics.
  - Analysis CDTs.
  - Area has made significant advances and is agile and adaptable.
  - Non-linear PDEs
- Weaknesses
  - Evolution equations might be better covered.
  - Poor personal contacts with industry.
  - Too much of an artificial divide between applied and computational analysis.
  - Few people working on inverse problems (c.f. Finland, US).
  - General lack of capacity compared with main EU/world competitors.
- Opportunities
  - Numerical analysis can be intrinsic to applied analysis.
  - Analysis of fundamental issues in data science.
  - PDEs in socio-economic sciences.
  - Great opportunities for impact, e.g. compressed sensing.
  - New applications of analysis; biology, materials, social sciences, nano-, climate.
  - Natural environment / life sciences.
- Threats
  - Quality / competitiveness of doctoral training not up to German / French / Italian standards; PhDs too short.
  - Need to improve links with application / continuum mechanics.
  - Alan Turing Institute might be dominated by stats and computer science.

Continuum Mechanics

- Strengths
  - Evolution of the discipline
    - Move towards stochastics.
    - Uncertainty Quantification.
    - Data
  - Homogenisation to attack discrete models
  - UK world leading
  - Diversity in subjects
    - Fluids
    - Solids
    - Bio
  - Large critical mass
  - Resilient progressive community

  - Underpins much of science

- Weaknesses
  - Experimental work not easily recognised or funded
  - Concentration of funding in few institutions
  - Connections to other sciences may be seen internally (within mathematics) as not creating new maths.
  - Should link more to analysis of PDEs
  - We are not good at lobbying and self-promotion as a unit.
  - Community in solid mechanics too small to guarantee sustainability.
  - Small communities → difficulties with continuity in people pipeline.
  - No CDTs focussing on solid mechanics.
  - Funding the people pipeline, especially fellowships.

- Opportunities
  - Some broad based CDTs cover continuum mechanics.
  - Cell biology.
  - Inclusion of uncertainties.
  - Traditionally deep engagement with industry.
  - High potential impact.
  - Engage with other sciences / engineering.
  - Industry knows that maths might solve the difficult problems, fatigue, damage etc.
  - New materials (modelling techniques).
  - Methodology should be useful for modelling in data science.

- Threats
  - Duality between science and mathematical methods.
  - Difficulty in finding interdisciplinary funding.
  - Need stability and greater infrastructure funding.
  - Mechanics weak in schools.
  - Large scale initiatives elsewhere e.g. the materials genome.
  - Misconception of "Old Mathematics".
  - Links between physics and Continuum Mechanics and engineering and continuum mechanics weak compared with other countries.
  - Mechanics is not selling but underpins a lot of applied sciences.

Industrial Mathematics

- Strengths
  - Tradition!
  - UK world leading and in demand.
  - Emerging capacity.
  - Young people attracted.
  - Broadening mathematical methods in recent years (e.g. networks, stochastics).
  - Experience.
  - Increase in centres.
  - Flexibility of engagement methods, studentships, workshops etc.
  - Impact!
  - Extra sources of funding.
  - Employability of PhDs.

- Weaknesses
    - Not regarded as real maths by our colleagues.
    - Hard to get recognised 4* papers.
    - Training might not be sufficiently mathematical.
    - Ad hoc approach to SME engagement, primarily local.
    - No national infrastructure.
    - Diversity and breadth.
    - Not enough engineering links.
    - Enough mathematical rigour?
    - Review process for funding potentially problematic.
    - Language gaps

- Opportunities
    - Strong demand from business.
    - Immediate external impact.
    - European Study Groups with Industry and derivatives.
    - Pure maths is now industrial maths.
    - More engineering links possible.
    - Financial maths.
    - Big data using maths.
    - Ever increase of good problems.
    - Industry appreciates mathematical training.
    - New areas of maths stimulated by industrial engagement.
    - Catapult network.
    - ICASE awards.
    - Excess industrial capacity to be tapped.

- Threats
    - Double jeopardy – Government wants industry to fund, industry wants government to fund.
    - Not regarded as real maths by funders.
    - Weak engagement with SMEs
    - Increasing international competition, e.g. India, Brazil.
    - Lack of SME capacity to absorb.
    - Big data not applied math.
    - Can we cross train?
    - Insufficient representation by EPSRC.

Mathematical Biology

- Strengths
    - Very active in applications / experiments underpinning application areas.
    - Can link to many areas of maths / stats.
    - Many organisations growing mathematical biology.
    - Attractive to PhD students – like link to applications.
    - Widely spread around the UK.
    - Strong community
    - Possibly the top community in mathematical biology in the world.
    - UK has more tools – other places reliant on simulation.

- Weaknesses

- Is UK competitive compared to US?
- Division between "stats" and "applied maths" mathematical biology.
- What is it?
- Lack of mathematical training of biologists and medics.
- Lack of CDT in mathematical biology (except one).

- Opportunities
  - Precision agriculture.
  - Biologists, physiologists, chemists looking for deeper understanding.
  - Extremely rapid growth of biological data that is increasingly complex.
  - Drug development (industrial collaboration)
  - Synthetic Biology.
  - Regenerative medicine.
  - Making sense of "omics" data.
  - Can maths connect with the tissue engineering catapult.
  - Funding from pharma.
  - Ageing population.
  - More joined up thinking between Research Councils.

- Threats
  - Lack of recognition from wider maths community.
  - Requirement to develop new maths.
  - Unrealistic timescale expectations – takes time to translate maths to e.g. clinic.
  - Good work may fall on REF boundaries.
  - Biologist: "This isn't biology." Mathematician: "This isn't maths."
  - Mathematical context may be perceived as "low level" so math bio may be under-appreciated.
  - Top research needs are model formulation and model validation making new maths virtually impossible.
  - Loss of pharma companies from the UK.
  - Are traditional maths bio people missing "omics".
  - Funding falls between gaps in RCs.
  - Disconnect between BBSRC and EPSRC – possible reductions in funding from BBSRC to systems biology.

Nonlinear Systems and Complexity Science

- Strengths
  - A capacity building area (attractive).
  - Many PhDs training in this area.
  - New but maturing area.
  - Relevance.
  - A bridge between pure and applied maths.
  - A number of internationally recognised centres and individuals.
  - Nonlinear pervasive and now incorporated into many areas.

- Weaknesses
  - Sometimes too thinly spread.
  - Taxonomy.
  - Complexity (the term).

- Mathematical quality can be erratic even if science is good (especially complexity).
- Does it exist?
- Can be descriptive rather than predictive.

- Opportunities
  - Stochastics
  - Interdisciplinary e.g. control, bio, climate, geoscience.
  - Inspiration for methods from applications.
  - New links to NERC, BBSRC, MRC (in new RUK?)
  - Applications to "big data".
  - Numerics / algorithms / computation.
  - Model reduction.
  - Low order modelling could help understand large scale computation e.g. direct statistical simulation.
  - Numerical modelling of complex systems (on the rise) vs low order modelling / analysis (on the decline?).

- Threats
  - Alan Turing Institute will draw resources away.
  - Abstraction sometimes reducing relevance.
  - Redefine non-linear.

Numerical Analysis

- Strengths
  - High international profile.
  - Embedding in mathematics.
  - Numerical linear algebra, Optimisation, Numerical PDEs are high quality.
  - Well connected to other applied maths areas.
  - Embedding analytical / other parts of maths in numerical schemes.
  - Few but large centres who work together.
  - Good links to industry across the board.
  - Needed for many applications e.g. industry, social, medicine, environment, energy, big data.
  - The community is good at spotting problems.

- Weaknesses
  - Perceived lack of prestige (compared to pure mathematics).
  - Where are the FRSs?
  - Insufficient capacity in inverse problems at all levels.
  - Small groups at some institutions.
  - Can be quite self-critical.
  - Insufficient links to Engineering.
  - Tension between Numerical Analysis and Scientific Computing.
  - Insufficient links to computer science.

- Opportunities
  - Uncertainty Quantification – many numerical challenges.
  - Link Numerical Analysis to applied analysis.
  - Low power large scale algorithms.
  - Interdisciplinary

- Some familiar links but there are new opportunities where more effort is needed.
- Vital to industrial growth.
- Industrially funded PhD.
- Data Science / Alan Turing Institute.

- Threats
  - Insufficient capacity (data science).
  - Renewal of optimisation, capacity.
  - Interdisciplinarity.
  - Perception that Numerical Analysis can be too analytical and not sufficiently practical.
  - Analysis / Computation balance. Threat: veering away from analysis.
  - Review process of interdisciplinary themes.

Session Two – Evidence Gathering

Industrial Mathematics

- Strengths
  - Maths underpins all eight great technologies.
  - Kaust OCCAM £20million+
  - ECMI success stories report
  - International study groups based on UK model (one per week!) & breadth of topics
  - Strong demand from industry
  - Funding of CDTs + other studentships, KTP, CASE, I-CASE, smith
  - Attendance at study groups
  - Employment of maths PhD
  - number of industrial people in IMA
  - International review of maths.
  - Deloitte Report
  - REF Impact Case Studies e.g. ASTON Book. Success Stories of UK industrial maths.
  - Leadership e.g. ECMI, KTN, Smith, COST (EU)
  - OCIAM, BIMI, ATI, ITN (FIRST)

- Weaknesses
  - ESGI unfunded by EPSRC!
  - Take up by SMEs
  - Stop of funds for SME engagement
  - Exit of short KTP internships
  - Stopping of MSc funding
  - Lack of short term funding

Applied Analysis

- Count appointments in (Applied) Analysis in UK since 2010 (say). How many have UK PhD?

- (Number of fellowship awards to analysts (ii) EPSRC willingness to invest in CDTs (iii) FRSs, Fields Medal in stochastic (harmonic) analysis.
- Would require data collection, e.g. survey of departments; survey of nationalities of editorial board members; survey of citation data (e.g. from Mat Sci Net on Google Scholar)
- Alan Turing Institute meeting in Cambridge revealed multiple opportunities in these areas.
- Representation on editorial boards of journals
- Some impact case studies already; some mentioned in national press were led by analysts.
- Strong industrial participation in Analysis CDTs
- £2million for a maths in healthcare centre for image processing
- There has already been sponsorship of applied analysis meetings from NA funds, e.g. the NA/HPC S&I in Edinburgh.

Non – Linear Systems & Complexity

- Strengths
    - Editorial boards (UK representation & editors - people who publish in pure + applied journal) Maths Bio textbooks containing non-linear dynamics language.
    - IRM 2010 – Philip Aston Impact case studies book (to be published ASAP)
    - CDTs (Planet Earth and In Forum) – proposals detailing business case.
    - FRS. LMS Senior Whitehead Prize
    - REF Case Studies
    - Opportunities
    - NERC investment (£1.8million) in data assimilation between 2008-2013. Ongoing
    - Look to MET office
    - Newton Programmes related to non-linear & applications
    - ICMS workshops related to non-linear & applications

- Weaknesses
    - REF Panel report on complexity

Maths Biology

- Excellence
    - Most UK maths biology academics are UK trained of other areas
    - History of subject leaders
    - Most EU funding includes UK maths biology
    - Membership of Editorial Boards & Editors
    - Representation at international meetings
    - Level of funding
    - Funding out with EPSRC
    - Metrics
    - REF
    - IRM
    - Number of international collaborations
    - 4 FRS's

    - 2 FRSE's since 2010

Continuum Mechanics

- Underpins deployment of advanced materials one of the 8 great technologies & energy & others.
- 2 of first 4 winners of Weissenberg Award (society of Rheology) UK based.
- JFM success rate of submissions
- Fluid Mechanics (Batchelor Prize) & Solid Mechanics (Rodney Hill Prize) both UK winners 2016
- International Review Maths Science
- Deloitte Report
- REF report & underpinning of Impact Case Studies
- Met Office – international representation; BAS, ECMWF, Hadley Centre
- Newton Institute programmes
- Aerospace Technology Institute Docs
- Smith Institute case studies/KTN?
- Count fellows of APS, FRS etc. SIAM fellows

Numerical Analysis

- 2 SIAM Presidents are from UK, out the last 4
- ICM, Speakers
- ICIAM – emath ENUMATH ECM
- Elected positions in SIAM activity groups
- ERC grants
- High numbers of UK publications in leading journals – authors & editors
- High citations
- Capacity far too small compared to other countries (e.g. Germany)
- American Mathematical Society Report
- REF Impact Case Studies – NAG-based in UK – use of software – largest
- Employment of NA PhD's in industry
- Few fellowships in NA – People Pipeline

Session Three – Applied Mathematics Landscapes

The refreshed documents for each research area will be published in due course.

Session Four – Research Area Scenarios

Applied Analysis

- Best Case
    - Analysis demonstrates that it can make serious progress on data science problems and entrains funding.
    - Continued growth in new (to UK) areas identified in landscape document.
    - Improved industrial contacts feed in exciting new problems.

    - Improved role for analysis as a unifying language across exciting, emerging areas in applied mathematics and RCUK portfolio more generally.

- Worst Case
    - Poaching of key staff by US/rest of the world.
    - Key people retire and we are unable to replace them.
    - Diversion of attention and funding away from fundamental research.
    - Continued gap in the pipeline from PhD to permanent post (i.e. not enough PDRAs/Fellowships)
    - Data Science money largely diverted to non-mathematical problems and activities.
    - Retrenchment of researchers into core sub-disciplines driven by REF / lack of time.

Continuum Mechanics

- Best Case
    - More resources!
    - Renewal of project studentships on grants – to support both areas of research and universities not covered (they are doing real research, not just being trained).
    - National spread of research funds – broad geography including small places.
    - Better postdoc pipeline.
    - Increased grant success rate and application numbers.
    - Increased industrial engagement (manufacturing, tech), beyond usual suspects: SMEs.
    - More stake in engineering, materials science, physics.
    - More experiments.
    - More stable funding for research infrastructure (INI, ICMS), e.g. 10 year timescales.
    - Ring-fenced funding for interdisciplinary – otherwise people on silo boundaries lose out.
    - There is already very strong demand for all maths PhDs from employers.
    - Regular / stable ESGI, SGIs

- Worst Case
    - Reduction in non-CDT places for PhD students.
    - Further concentration in large centres (CDT, Programme Grants).
    - As a minimum, maintain current level of postdoc support.
    - Cut in external engagement would be a disaster – must maintain interdisciplinary funding.
    - If funds are cut, could lose Programme Grants.

Industrial Mathematics

- Best Case
    - Broad base of diverse mathematicians – engages all communities to make industrial connections / benefits.
    - Stacks of cash and several Fields medals or Nobel Prizes.
    - Industry connections embedded in mathematical ethos.

- Broad collaboration across all Universities.
- We all just do mathematics.
- Many more students attend study groups / workshops as a matter of course.
- Broadening of engagement by interdisciplinary (academic) interactions with industry.
- Math modelling is key in all CDT training.
- Math modelling re-recognised as key.
- Specific recognition in EPSRC as bona fide activity.
- Connects maths to challenge themes.
- Connects with large investments e.g. Alan Turing Institute, Catapults.
- Good intern system to engage PDRAs with industry.
- Long term funding of mathematical infrastructure for connecting to industry, e.g. Study Groups, Turing Gateway to Mathematics, Knowledge Transfer Facilitators.

- Worst Case
  - Abandoned to computer science and engineering or industry.
  - Missed opportunities for new areas of industrial mathematics.
  - The pure/applied chasm widens.
  - Industry doesn't recognise benefits.
  - Just do a service for industry.
  - Failure to recognise as mathematics.
  - No impact is identified from research.
  - International study groups no longer led by UK.
  - No steady funding of engagement.

Mathematical Biology

- Best Case
  - New mathematics developed and proven to be successful.
  - Good links with Farr, Crick, Alan Turing Institute.
  - Sustained Cross Council Funding
  - "Sensible" people pipeline without blocks.
  - Mechanistic modelling and data use – work together.
  - Double jeopardy eliminated (e.g. new modelling recognised).
  - Success in translation e.g. links with medicine.
  - Links with experimenters e.g. active suspensions.
  - Lots in maths departments.

- Worst Case
  - (Over-)expectations in life sciences not realised.
  - Over-specialisation.
  - Failure to retain best ECRs.
  - Losing PhD students to other areas (with CDTs).
  - Failure to engage with nature and extent of 'omics data.
  - Widening gap between maths bio and rest of maths.

Non-linear Systems and Complexity Science

- Best Case
  - Breakthroughs in analysing stochastic systems

        - Societal interaction modelling
        - Biological / medical modelling
    - Data: The value of non-linear modelling of complex systems is recognised and leads to revolutionary new ways to make sense of data.
    - Attracting substantial funding sources from outside RCUK.
    - New links / understanding between statistics and non-linear theory e.g. non-linear Bayesian statistics.

- Worst Case
    - Failure to communicate between mathematical and applications end of the field (so we need broad training as the norm).
    - Progress on maths or applications becomes so hard people give up.

Numerical Analysis

- Best Case
    - Alan Turing Institute Fellowship in Numerical Analysis.
    - Increasing number of Newton Fellowships, URFs, Marie Curie fellowships in Numerical Analysis.
    - Establishing strong groups at the interface of data science and numerical analysis.
    - New Numerical Analysis groups being established in departments with little or no existing numerical analysis.
    - Strong Numerical Analysis groups in inverse problems, data science.
    - Increased recognition of numerical software development.
    - Embedding of Numerical Analysis in Continuum Mechanics, Mathematical Biology, Industrial Mathematics etc.
    - EPSRC Platform / Programme Grants with Numerical Analysis playing a central role.
    - Numerical Analysis considered by pure mathematicians as pure and by applied mathematicians as applied.
    - Continuing / increasing success in winning ERC grants especially at starter and consolidation level.
    - Royal Society supporting Numerical Analysis.
    - Biennial conference in Numerical Analysis continues to thrive.
    - Numerical Analyst as president of the LMS.
    - Growing number of KTPs based around Numerical Analysis research.

- Worst Case
    - Postdoctoral Fellows in Numerical Analysis constant.
    - Failure to embed Numerical Analysis in other relevant areas e.g. uncertainty quantification, data science, inverse problems…
    - Failure to capitalise on Alan Turing Institute.
    - Numerical Analysis considered by pure mathematicians as applied and applied mathematicians as pure.
    - Becomes disconnected from other applied mathematics.
    - Numerical Analysis not recognised by "outside" community.

Session Five – Future Opportunities

Applied Analysis

- Enlargement in fundamental research on PDEs motivated by recent & new applications: biology, medical & other imaging, data science.
- Improved interaction between applied analysis and stochastic analysis
- Inverse problems & imaging should grow (in the context of analysis).
- The interface with NA has been extremely fruitful & will continue to provide excellent opportunities – maybe including a route to better industrial contacts.

Continuum Mechanics

- Interface with – micro/nano/multiscale – biology & medicine – environment (climate, flooding, volcanology, glaciers, hi-tech agriculture, soil mechanics, seismology)
- Modelling advanced materials – involvement in Royce Institute
- Distillation of continuum models to their essence to provide high-speed calculations for optimisation & control.
- Interaction with experiments
- Uncertainty quantification (parameters, models)
- Interaction with numerical analysis/computation.

Industrial Mathematics

- Delivers Immediate Impact For Highest Priority Opportunities In Any Mathematical Area.
- E.g. Connection to data science: access to real huge data sets & real questions.
- Pan national network of mathematical expertise for triaging problems into community.
- Modelling of advanced materials (decision theory for design…) – reduce experimental effort – predict non measurable properties – insight beyond computational simulation.

Mathematical Biology

- Clinical/medical applications
- Interaction with omics
- Synthetic biology
- Agritech
- Regenerative medicine
- Antimicrobial resistance (AMR)
- Ageing
- Ecology
- Data Science
- Multiscale modelling
- Virtual organisms
- Neuroscience

- Uncertainty quantification

Non-linear Systems and Complexity

- Further engagement with applications – turbulence/weather/climate – societal modelling – biological/medical modelling
- Embedded in this are opportunities in data methods/stochastics.
- Further engagement with other mathematical areas e.g. analysis (applied & numerical) graph theory…

Numerical Analysis

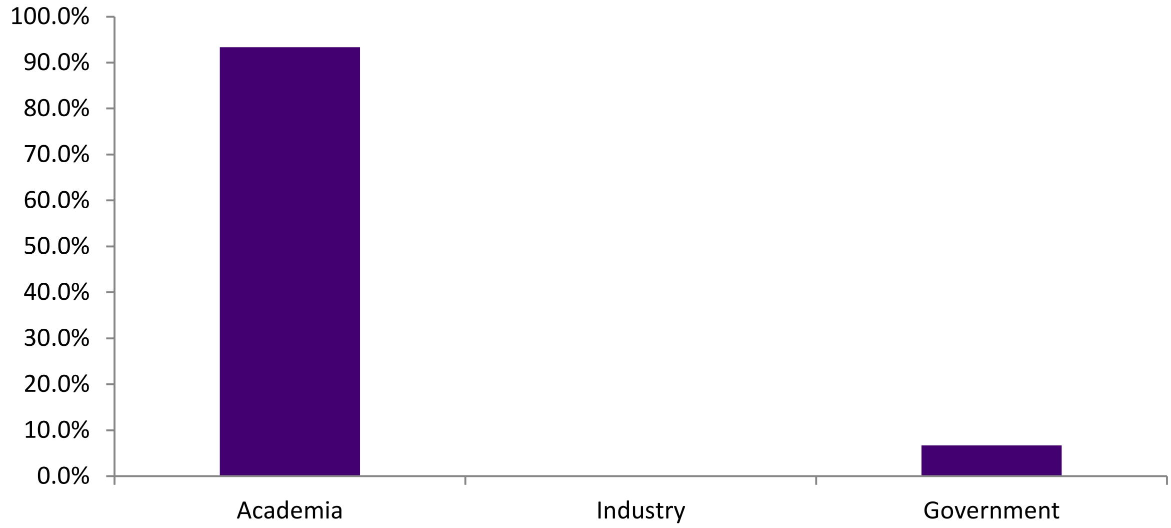
- Data science
- Optimisation, inverse problems, approximation
- Computational statistics
- Variational problems & algorithms
- High dimensional problems
- Algorithms for evolving computer architectures (many core, hybrid, accelerators, distributed, parallel)
- Mixed, continuous discrete problems linked to networks
- Compressed sensing for high NP hard problems
- Embed modern Numerical Analysis in all areas of applied mathematics
- Modern PPE approaches in cell biology
- Numerical applications in chemistry
- Uncertainty quantification

APPENDIX FOUR - FEEDBACK

Response Rate

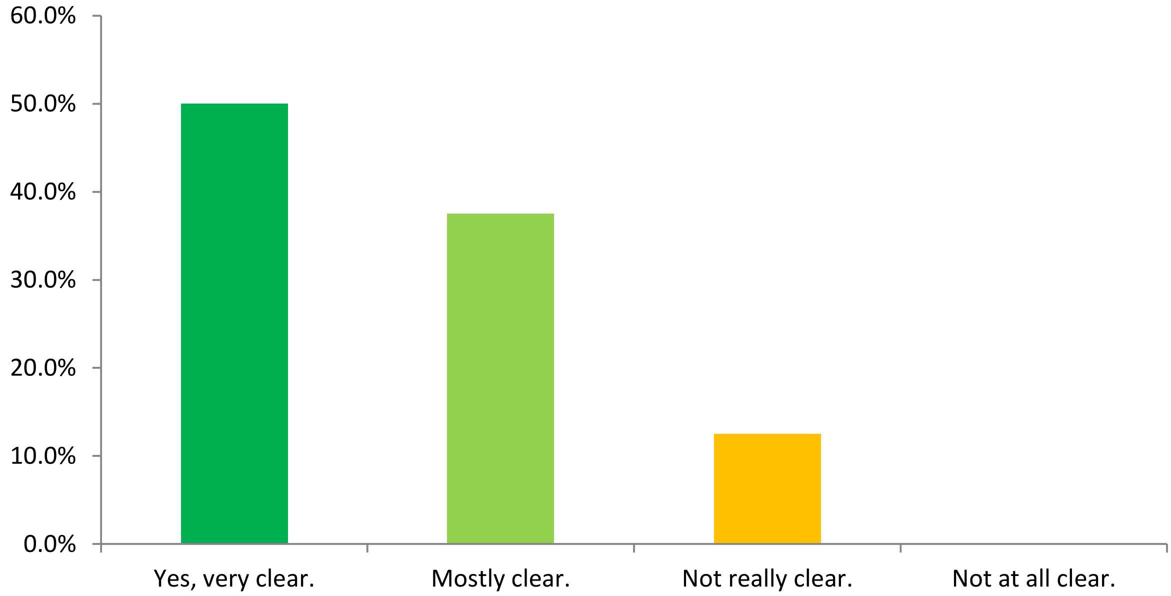
The overall response rate from delegates was 60%.

Sector of Respondents

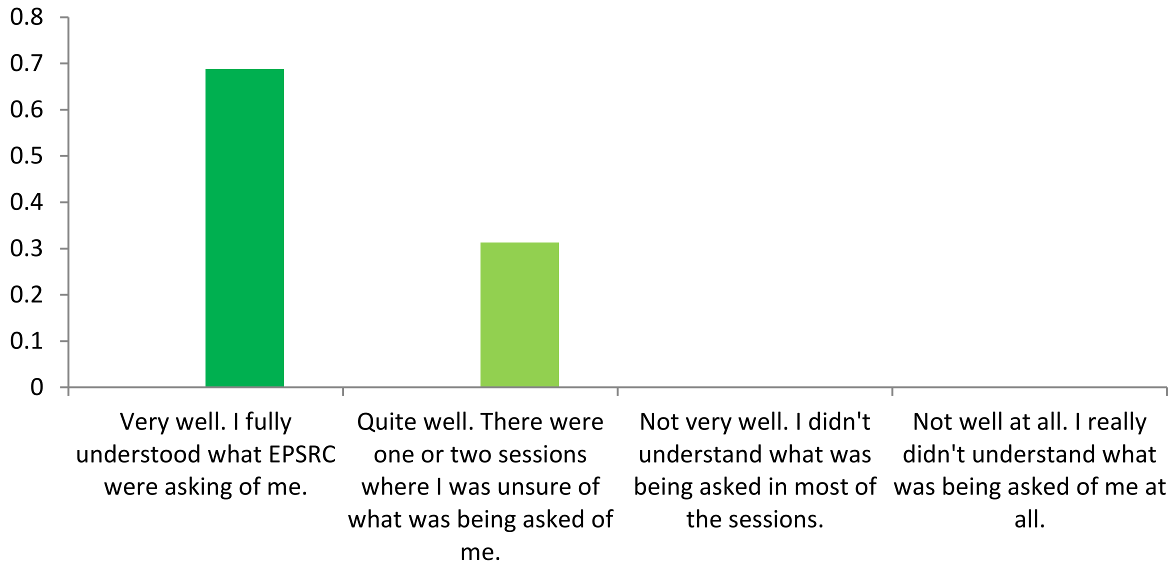


Provision of Information

Question: Do you feel the purpose of the event was made clear before you arrived?

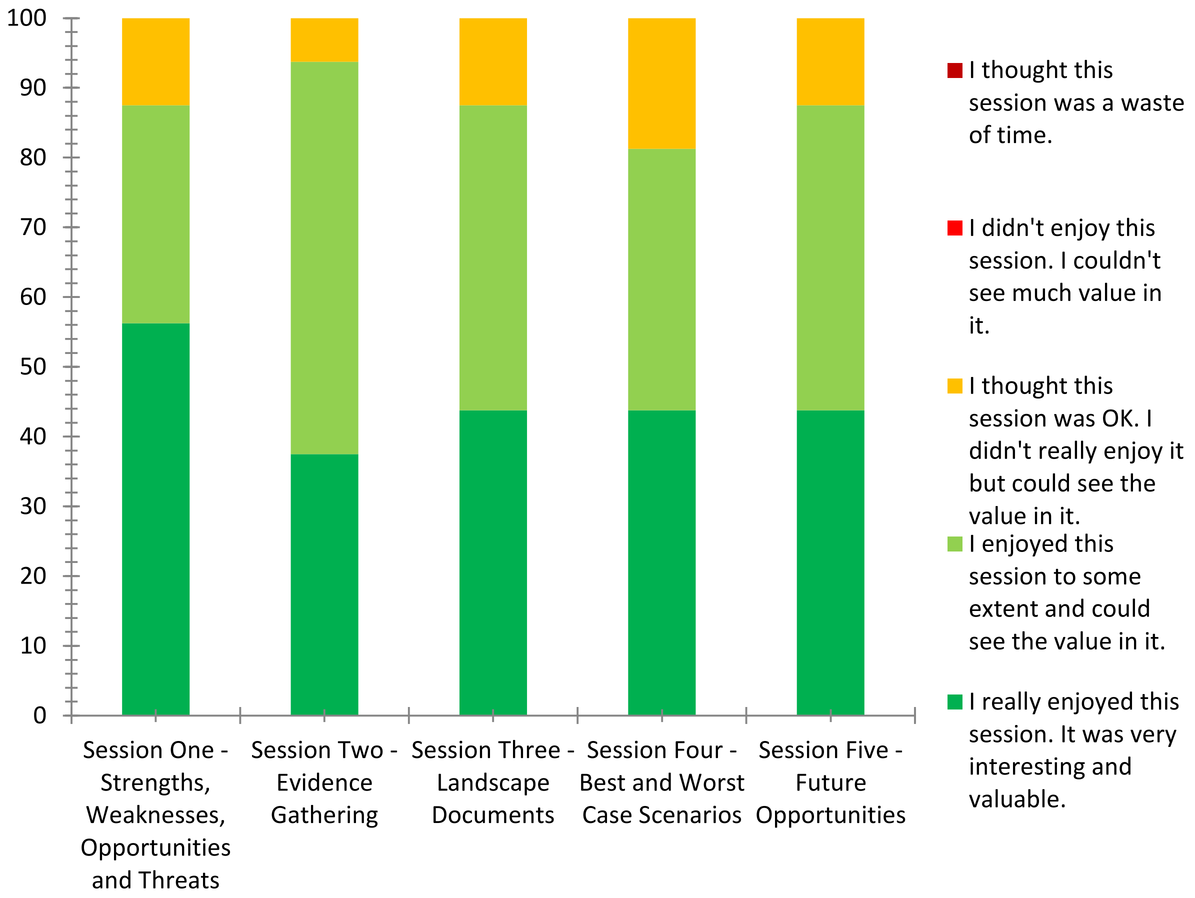


Question: How well did EPSRC explain what was being asked of you in each session?

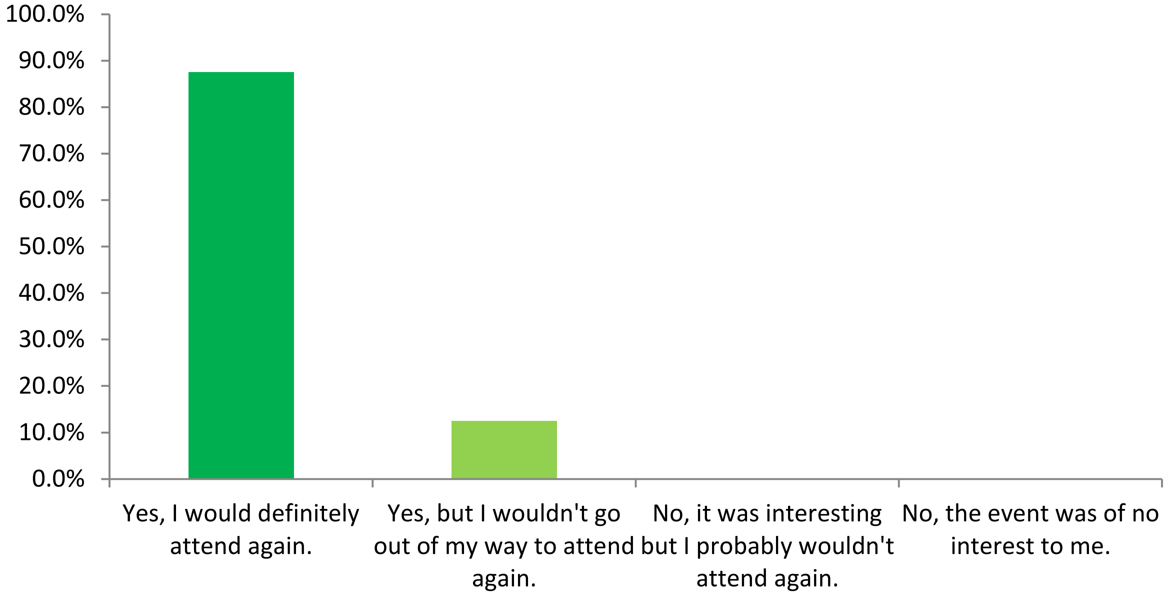


Overall Impressions

Question: How did you feel about each session of the workshop?



Question: Looking back on the event overall, would you say you are glad to have attended?


100.0%
90.0%
80.0%
70.0%
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Yes, I would definitely attend again.
Yes, but I wouldn't go out of my way to attend again.
No, it was interesting but I probably wouldn't attend again.
No, the event was of no interest to me.