ENGINEERING AND PHYSICAL SCIENCES RESEARCH COUNCIL

FUTURE MANUFACTURING WITH MATHEMATICAL SCIENCES WORKSHOP REPORT

19 JULY 2017

Research, discover, innovate

EPSRC

Investing in research for discovery and innovation

CONTENTS

CONTEXT

In 2013, EPSRC invested approximately £3.5M through the Future Manufacturing with Mathematical Sciences (FMMS) call to support six interdisciplinary projects to carry out research that creates new links between its activities in Mathematical Sciences and Manufacturing the Future. The majority of these projects ended in the period between Autumn 2016 and Spring 2017, making it timely to bring researchers from these projects together in Summer 2017 to reflect on the progress the projects have made, share key challenges and successes and to consider emerging opportunities at the interface of the Mathematical Sciences and Manufacturing.

At the same time, developments in the strategic landscape have underlined the importance of the ability of the UK to draw on its research capability in the Engineering and Physical Sciences, including Mathematical Sciences, to address challenges in Manufacturing. Firstly, as part of its Industrial Strategy, the Government has announced an investment of £1bn in cutting-edge technologies in six key areas, including 'manufacturing and materials of the future', over four years through the Industrial Strategy Challenge Fund. In addition, EPSRC published its Delivery Plan for 2016-20, which emphasises the contribution of EPSRC's investment to four key outcomes which underpin UK prosperity; Connected Nation, Health Nation, Productive Nation and Resilient Nation. The Productive Nation outcome in particular highlights the UK economy's need for successful development of world-leading products, processes and technology based on the discovery and innovation in the mathematical and physical sciences, information and communication technologies, and engineering.

With these strategic developments in mind as well as considering the context of the FMMS call, EPSRC held this workshop on 19th July 2017 bringing together investigators from the FMMS projects, as well as other researchers with an interest in this area, to consider current progress and capability at the interface of mathematical sciences and manufacturing the future as well as emerging opportunities and next steps.

OBJECTIVES

The objectives of the workshop were as follows;

- To provide feedback from the projects funded under the 2013 Future Manufacturing with Mathematical Sciences call and to share key research outcomes, impacts and challenges encountered.
- To identify the ways in which the landscape in this area has evolved since the call and to identify current and emerging opportunities at the interface of mathematical sciences and manufacturing, particularly in the context of the Industrial Strategy and the Productive Nation prosperity outcome outlined in EPSRC's delivery plan.
- To consider how we can sustain momentum and encourage community driven research in the area

DELEGATE SELECTION

Each project funded under the 2013 FMMS call was invited to send one or more representatives to the workshop with additional attendees being invited on the basis of previous interest in activities in this area and with a view to ensuring an appropriate balance of expertise, experience and backgrounds. As there were no specific funding opportunities associated with this workshop, Expressions of Interest were not invited.

AGENDA

10:30 Arrival and Coffee
11:00 Presentations from projects
12:30 Lunch
13:15 Future Opportunities
14.30 Coffee
14.45 Industrial Strategy Challenge Fund
15:30 Plenary Discussion and next steps
16.00 End

WORKSHOP PROCEEDINGS AND OUTCOMES

Presentations from FMMS Projects

Representatives from each of the projects funded under the FMMS call were invited to provide a brief presentation on their project including; project activities, key outcomes, challenges and benefits. A summary of the FMMS projects is provided in Annex Three;

Future Opportunities

Participants were asked to highlight current and emerging opportunities for the Mathematical Sciences to contribute to addressing contemporary challenges in Manufacturing and to prioritise these according to their importance and the potential for researchers in the Mathematical Sciences to make a significant contribution.

The broad themes which emerged from the highest priority challenges identified were;

- Improved design of structures through novel mathematical optimization methods.
- Mathematical methodologies for modelling the behavior of complex fluids. This would have relevance to minerals processing (e.g. fluidized beds and foams) and food manufacturing (e.g. mixing, chopping, coagulation and fragmentation) for example).
- Mathematics for advanced materials, for example enabling more efficient design of novel and advanced materials such as composites.
- Statistical and data driven approaches to manufacturing, for example predictive modelling of rare events and tools for real time analysis of sensor data to aid decision making.

A full list of opportunities identified is presented in Annex Two.

Industrial Strategy Challenge Fund

The focus of the Industrial Strategy Challenge Fund session was to provide an overview of the Industrial Strategy Challenge Fund and forthcoming opportunities. The extra £2bn a year funding announced by government in Autumn 2016 is part of a wider programme to enable the UK to strengthen its economy. Robotics and Artificial Intelligence in Extreme Environments and the Faraday Challenge were announced in April 2017, both of which aim to support the government's efforts to increase UK productivity. More recently, an additional 9 challenges have been worked up. These challenges are due to undergo a series of deep dives, community engagement activities and other formal means. Participants were encouraged to engage with these activities to ensure Mathematical Sciences was appropriately represented.

Plenary Discussion

The plenary discussion focused on the current research community at the interface of mathematical sciences and manufacturing and how momentum from the FMMS call could be harnessed to ensure this community could effectively contribute to EPSRC's Prosperity Outcomes and to the government's industrial strategy. It was felt that a strong core community had been effectively established by the FMMS call but there was now a need to find ways to broaden engagement with challenges in this area. It was noted that no further managed activities such as calls in the area were planned by EPSRC but that there were nevertheless opportunities for community led activities to apply for funding through EPSRC's standard mechanisms. Participants discussed the possibility of developing a proposal for a network in the area which could then be submitted to EPSRC's Standard Grants scheme. It was agreed that participants would discuss ideas for such a network and would discuss any application with EPSRC prior to submission.

SUMMARY

The workshop provided the opportunity for key research outcomes, challenges and impacts from the projects funded under the FMMS call to be shared across the projects and for feedback from the call to EPSRC. It was clear that the FMMS call had enabled the development of new collaborations across academic disciplines as well as with industrial partners but that there was a need to engage a broader range of researchers with this area in order to enhance the mathematical sciences contribution to EPSRC's Productive Nation Prosperity Outcome as well as to relevant activities supported under the Government's Industrial Strategy. EPSRC encouraged participants to consider approaches to broadening engagement, and agreed to liaise with any attendees or members of the community wishing to submit a possible network application in this area.

In addition participants at the workshop identified a range of opportunities for the mathematical sciences to contribute to challenges in manufacturing and EPSRC encourages potential applicants to take inspiration from these in preparing applications in this area.

APPENDIX ONE – DELEGATE LIST

Hector Basoalto	University of Birmingham
John Billingham	University of Nottingham
Julia Brettschneider	University of Warwick
Chris Breward	University of Oxford
Colm Connaughton	University of Warwick
Jonathan Cumming	University of Durham
Tim Dodwell	University of Exeter
Matteo Icardi	University of Warwick
Marco Iglesias	University of Nottingham
Andrew Lacey	Heriot-Watt University
Bart MacCarthy	University of Nottingham
Anthony Mulholland	University of Strathclyde
Eleanor Stillman	University of Sheffield
Rhia Visavadia	EPSRC
Lesley Walls	University of Strathclyde
Mike Ward	EPSRC

APPENDIX TWO – OUTPUTS

Future Opportunities

The full list of potential opportunities highlighted by attendees is shown below. The numbers in brackets indicate the number of times each was flagged as a priority.

- Design of Structures (6)
    - Multi-level Optimisation
    - E.g. Shape optimisation
- Minerals processing (6)
    - Fluidised beds & foams
- Food (6)
    - Mixing, chopping, baking, drying/cooking
    - Semi-group methods in coagulation, fragmentation
    - Traditional British Applied Mathematics
- Room for traditional applied math modelling (complex manufacturing process) (5)
- Composite manufacturing (5)
    - Surrogate models
    - Mobile methods to immediately apply math method
    - Moving Boundary problems under uncertainty
- Integration of Materials and processes (4)
    - Theories of material defects etc.
- Multiscale in 3D printing (4)
    - Multi scale modelling
- Rare event modelling, need to be virtually modelled (4)

- 19th Century Theories still in use, need updating (3)
    - Underlying physics theories constricts alloys
- Robotics (3)
    - Control Theory
    - Design optimization
    - Motion Planning
    - Interesting modelling challenges
    - In situ Repair
- Big opportunities around contemporary stats (3)
    - Big data, metrology
    - Decision making
    - Sense data
    - Rare or extreme events (safe manufacturing design)
- Machining moving Boundaries (3)
    - (s)PDEs
- Automation of processes, process control (3)
    - Particle characterisation in drug manufacturing, inverse problems
    - Understand unwanted phenomena
- New Bayes from samples of one (3)
- Scale Up (3)
    - Nano
    - Machine
    - Process
    - Network
- Uncertainty quantification & analysis / Decision making under uncertainty (2)
    - Sensitivity analysis
    - Robustness
- Modern Computer Architectures / Numerics (2)
- Real time Modelling (2)
- Translation at physics laws into real world examples (optimisation) (1)
- Customisation of small manufactured goods, Reconfigurable systems (1)
- Batteries, required stats (1)
    - Robots, Data Science
- Digital twin/manufacturing (1)
- Speed up of data generation from numerical methods (1)
- Dirty Data (1)
    - Not recorded in a consistent way
- Cyber Security (stats), Industrial processes (1)
- Metrology (Additive Layer Manufacturing) (1)
- Rapid Prototyping speed up design (1)
    - Traditional British Applied Mathematics, modelling asymptotic provide insight
- Remanufacturing (recycling) (1)

- Reducing uncertainty in Large Volume (1)
    - Optimisation of welding processes, using inline sensing Data
- Supply Chain Integration (0)
    - Integration of manufacturing process & Supply chains
- Opportunities around complexity science (0)
- Performance based repair & maintenance (0)
- Opportunity for more rigorous quantitative research (0)
    - Increased confidence
    - Cost savings
- Design of Experiments (0)
    - Not a culture of experts in engineering

APPENDIX THREE – SUMMARY OF FMMS PROJECTS

EP/K031368/1 Butler, Professor R University of Bath	Whilst the basic advantages of composite laminates, such as carbon fibre-reinforced plastic, are well proven, they are often compromised by high cost, long development time and poor quality due to multiple defects, particularly in complex parts such as those found in aerospace applications. Within the aerospace industry, where safety is paramount, design changes require expensive programmes of empirical testing over a variety of length scales, the so-called "test pyramid". An important objective of this complex engineering system is to minimize the probability of failing the certification test. Modelling technologies and testing at various stages of development are all orchestrated toward this objective, which has been heuristically developed over the last decades without a clear understanding of how each player contributes to uncertainty reduction. This project will engage a multidisciplinary team of engineers and mathematicians to develop novel mathematical modelling tools to address this issue. An embedded university-industry partnership will focus effort on creation of new capability with underlying fundamental research to reduce design-to-manufacture time and increase quality in airframe and aero-engine manufacture, critically important to the international standing of the UK aerospace sector. We will systematically develop stochastic models that integrate uncertainties from simulations and empirical testing (at different stages of the test pyramid) and quantify their propagation through the system to provide effective and reliable quality control for high-quality carbon fibre manufacture. New and fully-validated, laminate designs will be developed that challenge the inherent conservatism and the expensive industry standard which predominantly uses empirical testing for structural integrity certification. A central theme to the project is the complex interaction of multiple scales within the structural hierarchy of an aircraft component. Interaction over all the scales strongly influences each of the three research areas addressed within this programme. Recently gained expertise in the modelling of folding in layered geological structures will be exploited to study the physically analogous formation of defects during automated manufacture of laminated parts. Multiscale structural performance models will draw upon novel numerical upscaling techniques to predict the strength of large aerospace components containing microscale internal defects. Novel probabilistic uncertainty quantification tools, such as multilevel Monte Carlo and multilevel Monte Carlo Markov Chain, will be brought to bear in performance analyses of entire sub-components. The data for these models will be inferred directly from images obtained using Computational X-ray Tomography (CT). Manufacturing practices will be informed by seconding team members to GKN Aerospace, located at the National Composites

	Centre, to explore the interaction between the technical and business objectives of the industry, assisting researchers in the use of the new modelling tools, and in the selection of optimal manufacturing solutions. Target components will be wing spars, skin-stringer panels, and engine fan blades. The development and application of the novel stochastic methods for failure prediction will be undertaken with expert guidance of visiting researchers from the University of Florida and Lawrence Livermore National Laboratory, CA. Our vision is to enable a greater than 50% reduction in design-to-manufacture time whilst ensuring predictable product improvement, amounting to significant (>10%) component weight saving.
EP/K031066/1 Kendall, Professor W University of Warwick	Additive layer Manufacturing (ALM) is a "3D printing" technique which develops products directly from their digital design data by the layer-wise addition of material. It is widely regarded as having great promise, especially for its capabilities to respond cost-effectively to changing customer demand and its ability to create objects with complex internal structure. At present a major difficulty holding back ALM is the problem of determining the extent to which the digital design has been correctly realized by the process: direct verification typically involves lengthy analysis of individual manufactured objects using Computed Tomography (CT) scans, tending to vitiate the advantages of ALM for general purposes. The purpose of this project is to explore methods by which this quality assurance process may be carried out more rapidly. The investigation will be carried out by a close collaboration between engineers and statisticians at Warwick using statistical techniques including random fields, false discovery rate methods, and ideas from stochastic geometry.
EP/K031686/1 Champneys, Professor AR University of Bristol	Efficient and effective manufacturing supply networks (MSN) are essential to the functioning of the global economy. In line with the EPSRC call, this proposal is premised on the strong belief that appropriate mathematical theory and methods can provide fundamentally new understanding on the behaviour of MSNs and provide an effective investigative toolset for MSN analysis, design and management. In particular we argue that the power of network science can be harnessed to underpin new thinking in MSNs for resilience and robustness. The work will be strongly embedded in real MSNs in three domains - producer-driven inbound MSNs and outbound distribution channels for industrial companies; global MSNs for critical products used in high-valued manufacturing (e.g. titanium or composite pre-preg materials); and evolving MSNs for emerging UK industries such as renewable energy. The project will develop and apply existing and new mathematics specifically in the theory of complex adaptive networks, drawing on techniques from game theory, dynamical systems and Bayesian informatics. It will also learn from related modelling approaches in ecology, metabolism modelling and utility grids. This grant will represent the first attempt to develop an integrated mathematical modelling suite to support effective decision

	making in MSNs in the context of risk and uncertainty. The work will build on disparate recent developments in network science and complex adaptive dynamical systems, Bayesian statistics and operational research to develop new models and measures to better understand and analyse MSN behaviour and performance. Multiple perspectives and a multi-level view of risks and vulnerabilities in MSNs will be taken, including physical, financial, informational, relational, and governance perspectives at the strategic MSN design and policy levels, and risk mitigating strategies at both strategic and operational levels to support MSN management. This is an adventurous and challenging proposal due to the following reasons: (1) The PIs based in have various domains of expertise, from theory of complex networks and nonlinear dynamics, to applied statistics in domains such as reliability and risk assessment, and development and application of operational research and operations management methods to MSN management and control problems. However, our expertise is complementary and will add a substantial body of new knowledge and bring novelties to the theory of complex networks, network dynamics and Bayesian networks, but also, applications of these new models to real-world MSN problems will ultimately lead to better understanding of complex MSN behaviour and will improve MSN management and control in the presence of risks and uncertainties. (2) This proposal will bring together PIs and PDRAs from 4 universities. The management of the resources involved is a challenge on its own. However, we believe that a very carefully designed project management plan can lead this research collaboration to its success. Furthermore, if funded, this research project can potentially secure the continuation of the collaboration among the four universities. (3) The project will involve a wide array of industrial partners from manufacturing primes (e.g. in Aerospace and Defence) to manufacturing trade organisations and consultants, to representatives of a brand new industry (offshore renewable energy) for which the in-bound MSNn does not yet exist.
EP/K031430/1 Skordos, Dr AA Cranfield University	This project focuses on the development of a manufacturing route for composite materials capable of producing complex components in a single process chain based on advancements in the knowledge, measurement and prediction of uncertainty in processing. The methodology proposed uses measurements of the instantaneous state of a component during production, predictive modelling of associated variability and numerical optimisation. These three are integrated in a control loop that allows the process to adapt in real time in order to compensate for deviations from its nominal state due to variability. This manufacturing philosophy accepts the existence of variability in these highly heterogeneous and directional materials and uses it in order to improve the product as the process evolves. The necessary developments comprise major manufacturing challenges, such as the real time measurement of fibre variability in robotic fibre placement and the processing of composite components involving areas of large thickness. These are

	accompanied by significant mathematical advancements, such as the numerical solution of coupled non-linear stochastic partial differential equations, the inverse estimation of composite properties and their probability distributions in different directions based on real time measurements and the formulation and solution of a stochastic model of the variability in fibre arrangements. The integration of these developments will be carried out on a single process chain of fibre placement, resin infusion and resin cure; however their applicability is generic in the context of manufacturing involving heterogeneous materials and variability. The outcome of this work will enable a step change in the capabilities of composite manufacturing technologies to be made, overcoming limitations related to part thickness, component robustness and manufacturability as part of a single process chain, whilst yielding significant developments in mathematics with generic application in the fields of stochastic modelling and inverse problems.
EP/K031406/1 Oakley, Professor J University of Sheffield	The aim of this project is to use statistical methods to develop "green button" manufacturing processes: processes that can be run without a human operator, and can respond to unpredictable variations in the properties of the materials that are being machined. We will be focussing on "high value, low volume" manufacturing: manufacturing relatively small numbers of very expensive components, where it is costly to have to scrap a component because of a fault in the machining process. We will work on a case study: machining the landing gear of an aircraft, which we will use to develop methods that can be applied more generally. The first step will be to build a computer model of the machining process. Given the computer model, we can experiment with different parameters of the machining process such as the speed at which the metal is cut, and the path that the cutting tool takes through the metal. In theory, we could then search for the best choice of parameters, such that the component is machined in the shortest time and is least likely to be defective. However, the properties of the metal to be cut will vary from item to item, so what is best for one item may not be best for another. We can't measure all the relevant properties, so we need to first assess how much variability we are likely to see, and then find parameter settings that best able to handle this variability without producing faulty items. Once we have determined the best parameter settings, we will then run a small number of machine cutting tests at different choices of machine cutting parameters. During these tests, we will take high quality but expensive measurements, telling us for example, the temperatures and forces exerted on the cutting tools. This information will tell us whether the process is operating satisfactorily, or whether there is a risk of tool damage and possibly a faulty machined component. We will also take lower quality, cheaper, sensor measurements, of the sort that would be available during the manufacturing process in the factory. We will study the relationship between all the variables that we have measured, so that we can construct a simulation

	model of the entire manufacturing process. (We can also make corrections to the computer model predictions, by inspecting how well the computer model predicts the cutting test outcomes). We can then use the simulation model to explore different strategies for modifying the process mid-production, in response to the cheaper sensor data, to avoid faults (eg "reduce the cutting speed by 10%" if a sensor reports vibration 5% above average"). It will be cheaper and faster to design the automated process using the simulation model, rather than conducting more expensive cutting tests. The end product will be a manufacturing process that can run efficiently without a human operator, making adjustments as the sensor data are observed, and will be configured in such a way so that it can deal with variability in the properties of the items to be machined. Our aim is to produce statistical methodology for configuring such a process, that can be applied in many different settings.
EP/K02826X/1 Axinte, Professor DA University of Nottingham	Techniques such as abrasive water jet machining (AWJ), pulsed laser ablation (PLA) and ion beam machining (IBM) are all methods of energy beam processing, by which energy is transferred to a surface and material is removed; this group of technologies can be employed to generate freeforms surfaces by controlled-depth machining. Although the way in which the energy is transferred in each of these methods is very different (AWJ: a high speed mixture of air, grit and water mechanically erodes the surface; PLA: laser pulses vaporize the surface; IBM: high speed charged particles erode the surface), they can be dealt under a unified mathematical framework whereby the rate of erosion of the surface is described by a partial differential equation. This equation relates the footprint of an energy beam (its instantaneous rate of removal, which may be a function of the geometry of the eroding surface, its distance from the source of the beam as well as position within the beam and beam orientation) to the evolution of the surface. The Investigators in this proposal have had significant success in using this mathematical framework to determine the final, machined surface for a given beam footprint and dynamic beam path; this is the forward problem. However, the problem that is of industrial interest is the inverse problem; given a required final surface, how should the beam be moved in order to accurately machine it? Currently, in both academic research and industry, this problem is solved by trial and error (craftmanship). The aim of this project is to develop methods for solving the inverse problem algorithmically, so that end users of this group of technologies (i.e. energy beam controlled-depth machining) can input their required surface into a software package and automatically generate a beam path. We will do this by tackling a series of increasingly realistic mathematical problems which can be related to real energy beam processes, backed up by an experimental programme against which our models can be verified.