



**Scottish Industrial Networking Initiative in Mathematical
Sciences (SINIMS) Workshop**

***Applications of Mathematics in
Technical Textiles***

Wednesday 16th January 2002

International Centre for Mathematical Sciences
14 India Street, Edinburgh EH3 6EZ

Delegates:

Dr Grant Andrews	SGL Technic Ltd
Dr Xiaogang Chen	UMIST
Ms Tracey Dart	ICMS
Mr Darren Fidler	Heriot-Watt University
Ms Kelly Filmer	Don & Low Ltd
Prof John Hearle	UMIST
Prof Robin Knops	Heriot-Watt University
Prof Andrew Lacey	Heriot-Watt University
Dr Gabriel Lord	Heriot-Watt University
Mr Brian McCarthy	TechniTex
Prof Sean McKee	University of Strathclyde
Ms Anne McWilliam	Ahlstrom
Dr Carmel Meredith	TechniTex
Mr Ralph Mitchell	Acordis UK Ltd
Dr Paul Moseley	Smith Institute
Dr Hilary Ockendon	Oxford University
Mr Alan Pietranek	Pail Containers Ltd
Prof Elmer Rees	Edinburgh University
Mr David Smith	Divex Ltd
Dr Jon Taylor	Acordis UK Ltd
Dr Heather Tewkesbury	Smith Institute
Mr Michael Treece	Assistive Technologies Ltd
Mr Reginald Treece	Assistive technologies Ltd
Mr Andrew Waugh	Heriot-Watt University
Mr Phil Wilkes	W.L. Gore & Associates Ltd
Dr Stephen Wilson	University of Strathclyde

Delegates will be referred to by their initials.

Programme:

- 10:30 Registration / Coffee
- 11:00 Welcome & Introduction (Paul Moseley)
- 11:10 Smith Institute (Heather Tewkesbury)
- 11:20 TechniTex (Brian McCarthy / Carmel Meredew)
- 11:30 Some previous applications of Mathematics in Textiles (John Hearle)
- 12:00 Analysis of a textiles problem using mathematics (Hilary Ockendon)
- 12:30 Buffet Lunch
- 13:15 Industry Presentation 1: *Acordis* (Jon Taylor)
- 13:45 Industry Presentation 2: *Divex* (David Smith)
- 14:15 Industry Presentation 3: *SGL Technic* (Grant Andrews)
- 14:45 Tea
- 15:15 Industry Presentation 4: *Don & Low* (Kelly Filmer)
- 15:45 Industry Presentation 5: *Pail Containers* (Alan Pietranek)
- 16:15 Industry Presentation 6: *Assistive Technologies* (Michael Treece)
- 16:45 Concluding Remarks (Paul Moseley)
- 17:00 Close

Meeting Notes

1. PM welcomed attendees to the workshop and introduced the programme for the day (see above). He explained that the objectives for the day were:
 - 1.1. to provide information for industrialists about the idea of Faraday Partnerships in general, and in particular, the Smith Institute and TechniTex Faraday Partnerships.
 - 1.2. to provide an overview of the range of applications of mathematics in the textiles industry over the last 30 years
 - 1.3. to listen to industrialists and provide academics with some ideas of the type of problems which are important in their businesses
 - 1.4. PM then gave an introduction to Faraday Partnerships (FPs) and their principles. These evolved from a series of Government white papers and investigations into maximising the potential of the UK research base for the benefit of the country's industry and academia, with specific attention being given to the industrial sectors identified by Foresight as of strategic importance to the economy. A full list of FPs is available on www.faradaypartnerships.org.uk. The principles are:
 - To promote active flows of people, industrial technology and innovative business concepts amongst the science and technology base and industry
 - To promote the partnership ethic in industrially relevant research organisations, business and the innovation knowledge base
 - To support core research that will underpin business opportunities
 - To promote business-relevant postgraduate training, leading to lifelong learning.
2. HT spoke briefly about the Smith Institute Faraday Partnership, and the way it aims to promote the use of mathematics and computing in industry with the aid of its team of Technology Translators (including PM and HT). The Smith Institute covers the whole of the UK, and is in contact with a large network of academics interested in industrially motivated mathematics problems.
 - 2.1. Some funding routes were highlighted including the Engineering and Physical Sciences Research Council (EPSRC) CASE and post-doctoral research awards, TCS (Teaching Company Scheme), LINK (several companies and universities collaborating) and SMART. Details of CASE awards which the Smith Institute have available to allocate are available on www.smithinst.ac.uk/news.
 - 2.2. A number of forthcoming events were also highlighted:
 - Flexible Photovoltaics – in collaboration with TechniTex, INREB and EPPIC Faraday Partnerships, 21st March, Cambridge

- Paper, 1st February, Arjo Wiggins, Beaconsfield
- Applications of Mathematics in Optoelectronics, 30th January, ICMS
- Applications of Mathematics in Medicine and Biotechnology, 13th February, ICMS
- Applications of Mathematics in Food and Agriculture, 25th February, ICMS
- Applications of Mathematics in Oil and Gas, 11th March, ICMS
- Applications of Mathematics in Semiconductors, 18th March, ICMS
- 41st European Study Group with Industry (ESGI), 2-5th April, Lancaster University
(further details are given at www.smithinst.ac.uk/projects/study_groups)

People requiring further details on these events should contact HT or PM, on the details given at the end of this report.

- 2.3 HT publicised the NOISE campaign (New Outlooks In Science and Engineering) and asked for first hand success stories of science and engineering in Industry, which might encourage 16-19 year-olds to consider careers or further study in these areas.
3. The Technical Textiles Faraday Partnership (TechniTex) was introduced by BMcC. He highlighted the decline in the traditional textiles sector and growth in Technical Textiles, even though some companies don't always realise that they can be described in that way.
- 3.1. Three University Textiles departments are part of TechniTex: UMIST, Leeds and Heriot-Watt, along with a number of Industrial members (membership is available at £500 per year). Members have the ability to participate in the Research and Development Programme planning.
- 3.2. The Industrial Advisory Board ensures that the core research areas are industrially relevant, and Technology Translators ensure that a flow of people, ideas and knowledge occurs between the academic partners, industry and BTTG (British Textile Technology Group).
- 3.3. Small amounts of funding are available from the Seedcorn Entrepreneur fund for ideas leading to innovative products. Other sources of funding include EPSRC and the DTI (up to £3 million).
- 3.4. Applications research can result from collaboration between similar companies (clusters), or by making use of supply chain networks, or non-competitive industries with similar problems, for example, automotive, medical and filtration industries. The research must lead to exploitable products and processes.
4. JH recognised that contributions in textile technology have been brought about by 10,000 years of craft and empirical development, with a general lack of mathematical engineering design culture. However, this has changed over the last 80 or so years.
- 4.1. Numerous examples were given, including: Taut-leg mooring for deep water platforms – typically 16 polyester lines to suction anchors moor platforms at sea level, to depths of 1400m below sea. A design guide for deepwater mooring textiles was developed including effects of viscoelasticity and non-linearities in the system.
- 4.2. Since the Industrial revolution, scientific research began to impact on the mechanics of machines. In the 1920s and 1930s, mathematics began to be included, then UK research associations and since the 1950s, UK universities too.
- 4.3. Statistics has seen a number of applications in the textile industry, including the following examples: variability in fibres, yarns and fabrics, interpretation of test data, empirical correlations, weak link theory (breaks at the weakest location – extreme value statistics) and bundle theory.
- 4.4. Work has also been done in the areas of twisted continuous filaments, yarns and ropes (using a helical model), compact staple fibre yarns (where the slip at the fibre ends reduces the contribution to the tension), bulky wool yarns (Carnaby looked at the shortest path and jamming of the fibres), friction twisting, fabric mechanics (extension, bending, flattening, using the energy minimisation method), compression of fibre assemblies dependent on the number of intersections of fibres, fabric buckling, two-dimensional elasticity theory, heat and water flow through fabrics, drafting of fibres, balloon theory and bifurcations, weaving mechanisms and weft projection, aerodynamics of processes, rheology, melt-spinning dynamics with steady state and transient conditions, mechanics of natural wool fibres (which exhibits differential contraction on drying due to its structure, mechanics of cotton fibres (and possibilities

- in genetic engineering to give internal structure to the properties of the fibres)... the list goes on!
- 4.5 Mathematically, JH found that traditional methods were unsuited to real solutions, that it may be beneficial to start with a computational approach, using simple relations to define the problem. Numerical methods and computer graphics also have a large part to play in the solution of these problems.
 - 4.6 One way of driving collaboration between industry and academia is to provide simple tools for industry, for example, software that is user-friendly. A software application called TechTex CAD (or TT CAD) was described. This centres upon a UMIST/DTI project, which has been developed in house at UMIST but isn't commercially available yet. The project is lead by Dr Tilak Dias, assisted by Dr Xiaogang Chen and Dr Prasad Potluri. It is able to predict the mechanics and other properties from the user-input fibre properties, yarn structure and fabric weave pattern.
5. HO agreed with JH that computational mathematics could be a good start to such problems, but moreover that mathematicians could bring with them skills in assessing and suitably simplifying problems (although not over-simplifying) in order to develop models to obtain a physical understanding of the issue. Useful predictions could be made from analysing the dependence on parameters of certain attributes, and exploiting certain aspects mathematically, for example, the microstructure vs. macrostructure, and the millions of thin, relatively long, fibres. HO has worked on numerous problems in the textiles industry, and outlined four:
 - 5.1 Spin bath: the problem is to design a spinneret so that fluid in the bath reaches all of the tow. The model developed was based on flow through an anisotropic (different properties in different directions) porous medium, with solidification of the fibre as chemical treatment progressed.
 - 5.2 Stretching: Instabilities were observed in the tow when stretching. A model including elasto-plastic effects was developed.
 - 5.3 Tow washing: The task was to find out how parameters affected the washing efficiency. Using an analysis of pressures and flows, it was found that the fluid in the bath develops regions of high pressure and low pressure at certain points, which causes flow through the tow, thus washing efficiency could be estimated.
 - 5.4 Carding: the problem was to try to quantify the effect of the carding machine, in terms of the "combed-ness" of the fibres. This was addressed as a free boundary model, and it was found to have one crucial parameter, a friction coefficient, related to the friction and elastic forces. Some experimental work on tuft extension was done at Leeds Textiles Department (Dr Abbas Dehghani), to estimate the value of this coefficient, and good agreement was found between the model and experiment, both exhibiting fibres aligning, then slipping.
 6. JT explained the business moves within (then) Cortaulds, (now) Acordis UK Ltd, resulting in a reduced number of people in R&D. Therefore they recognised the need to seek expertise outside of the company, particularly in blue-skies research where their employees just can't afford the time to develop potentially high-risk ideas. They find the involvement with FPs as a way to extend both skills contributing to the business and their budget for R&D, as they, along with many other textiles companies, face a race against manufacturers in the Far East.
 - 6.1 Their manufacturing process has many stages, which can overall be compared to paper production. It is a large process, built around craft, with the maths added after.
 - 6.2 JT showed a summary of the research projects which they have had involvement with over several years. These include at least four Oxford University Maths Study Groups (Folding of fibre in in-line dryers, Dr Penrose, Theory of Wedge washing, Dr Byatt-Smith, Dr C Robinson, Modelling of air gap in dry jet wet spinning, Tow crimping), a European Maths Study Group (J-Box performance) and an MSc project.
 - 6.3 HO agreed that the European Study Groups were a good way of getting some work done on an industrial problem, and that companies nearly always found it beneficial to have a number of academics concentrating on their problem for a full week.
 - 6.4 JT presented a problem that they would like to collaborate on: Product scheduling. At the moment they have 13 production lines, 4 polymer types and 12 key fibre variables, all of which have multiple possibilities (e.g. up to 10,000 colours, 9 types of crimp etc.). Changeover times are important as typically a 1 minute saving per colour change (for

example) could save the company £30,000 per year. An added complication is that the 12 key variables have varying degrees of effect on the changeover time – e.g. it is better to change from a light green dye to a dark green dye than it is to go from black to white, but presently, all 10,000 colours have names which can make it difficult for the scheduler to know exactly which hue it is. Quantities of product required also vary (in the example given, between 1 and 20 tonnes) There is also a time constraint, as the products have to be delivered on time to retain customer loyalty, yet lead times (the time between order and delivery) can vary as a function of customer location. SMcK commented that this kind of problem is seen in many manufacturing industries. Both he and HT have seen this in the food industry for example (although with much fewer variables).

7. DS, Business Development Director, described some of the equipment manufactured by Divex. These include diving chambers, rebreathers (including CO₂ scrubbers and O₂ injectors), compressors, gas reclaim helmets, harnesses, wetsuits and drysuits (including thermal barrier layers). Based in Aberdeen, they supply these products both commercially (e.g. offshore) and to the military.
 - 7.1 Saturation diving is one area they are working in. This is when up to 3 people at a time use a diving bell to descend from ships into water up to 450m deep. There is a control panel on the ship for the environmental systems of the diving bell, for example temperature and gas mixture. Hot water heaters can be used in the diving suits to maintain body temperature, at flow rates in the region of 30 litres per minute. At 450m depth, the gas mixture is up to 98% Helium, and the heat transfer during respiration is approximately 6 times that of air. Convective heat losses are also different from those in air. However, there is little driving force to research these areas as it is relatively safe (no fatalities this year). Having said that, experimental research causes problems on ethical grounds (i.e. sending people to deep water with conditions or equipment which has not been proven is both unpopular and expensive at ~\$50,000 per day). So some questions: How much heat is required to maintain the thermal balance of the diver? What should be the heat input (e.g. hot water)? What is the effect of breathing Helium? At depths of up to 450msw, a lost diving bell might contain 3 wet divers and equipment, be surrounded by an infinite layer of 4°C sea water, is uninsulated, has a volume of 6m³ and no heating capacity (all power is required to operate the CO₂ scrubbers). This combines to give the equivalent cooling potential of being in air at –166°C! So thermal protection in diving bells is very important. Currently, survival for people in 2 thermal suits and an outer shell is estimated to be limited to 24 hours at 250msw, only 8 hours with heating at 450msw.
 - 7.2 They are interested in finding ways to test new insulation materials. The cost of trials used to be part Government or Oil Industry funded, but this funding is no longer available, so they want to know if it is possible to model the effects mentioned earlier.
 - 7.3 Diving bells near the seabed can also suffer from problems of hydrocarbon contamination. There can be many different types, so is it possible to analyse which one quickly with the aid of some statistical modelling? It is important to know this as hydrocarbons can be volatile in warm conditions (e.g. in the bell), and can be detrimental to the health of the divers. They are also looking at fabrics for diving suits, which can resist the uptake or even get rid of such hydrocarbons.
 - 7.4 It was suggested (and widely agreed) that a multidisciplinary approach was required, and this was laid down as a challenge to Universities.
 - 7.5 Some of this technology has been used in, or even developed for, other markets, such as helicopter escape apparatus.
 - 7.6 SW commented that some of the problems, particularly heat transfer, are perfect for mathematical investigation, although the mathematics itself might not be novel.
8. GA explained that the Technology Group of SGL Technic Ltd have been in existence for 18 months and it is part of their philosophy to develop models to solve problems, and see Universities as a valuable source of expertise. The company makes 2 families of product; oxidised and carbon fibres.
 - 8.1 The polymer polyacrylonitrile (PAN) is the precursor to all products. This is oxidised at temperatures below 700°C to make PANOX, the oxidised fibre. Further heating at 1200-1500°C produces the basic material for their family of Carbon Fibre products.

- Sizing agents are used, then the fibres may be cut, milled or subjected to various textile operations to develop the full product range.
- 8.2 Panox is flame resistant, physiologically harmless, has a high moisture absorbency, high electrical resistivity and has good mechanical strength. Typical applications include thermal insulations, protective clothing, friction linings for brakes, interior furnishing and packing and gaskets. Subsequent customer conversion to carbon fibre can also take place, for example in aircraft brakes.
 - 8.3 Carbon Fibre has high tensile strength and Young's modulus and with >95% carbon has high electrical conductivity. Typical applications include thermoplastic compounds, anti-static and electrically conductive materials, and fibre reinforcement in cement and concrete.
 - 8.4 Manufacturing problems include fibre displacement within tows – slippage is possible, heat distribution through fibre bundle in ovens, even size distribution in tow, and uniform surface treatment for coatings etc.
 - 8.5 Sampling problems: is the sample representative? A 1m test piece is taken from the end of a box of product (typically holding 3.5km * 320,000 fibres), as customers want product that is continuous, i.e. with no breaks in it.
 - 8.6 Desynchronisation is a problem that appears to have a number of causes, non-uniform sizing is thought to be a key factor. The product is plaited into boxes, but when the customer removes the product, it can become uneven and looping, tearing and other disruptions occur. The dimensions of the box have already been changed to reduce the number of folds.
 - 8.7 Composites depend on the interconnectivity of short fibres. A low fibre loading can have a critical effect on conductivity. A model which predicts conductivity as a function of fibre loading would be desirable, to understand the dependence of the critical point on certain parameters.
 - 8.8 Processing involves heated ovens, and a model of heat and air distributions in ovens is desirable, including the inlet and extraction fans, heaters and oven geometry.
 - 8.9 Concrete can be reinforced with fibres, but they would like to know how to optimise the reinforcement by distribution of fibres through the matrix. Is an analogy to steel suitable?
9. KF recognised that some of the problems described earlier by JT and GA were replicated at Don and Low Ltd. They produce some 2.5million m² non-woven fabric per week and 4.5million m² woven fabric per week using a range of technologies for a range of markets.
 - 9.1 Non-wovens are produced using one main extrusion technology, for markets including construction, agriculture, work wear, bedding, medical, converters, airline, filtration and furniture.
 - 9.2 Wovens are produced using 3 extrusion technologies for markets including yarns, floor coverings, industrial and geo textiles.
 - 9.3 The challenges facing the business are those of raw material price, the exchange rate and competitors, leading to a need to make the products cheaper but keep the quality high. R&D has previously been as a result of customer demand, but might benefit from the systematic approach available using a bigger (external) research team of collaborators.
They want to know
 - 9.4 The effect of weaving on tape strength (JH can help here with TT-CAD, see item 4.7), also the properties of mixed technology fabric, and cross-directional strength. It was pointed out that this is one area of research that TechniTex are already interested in, and the company might benefit from becoming members of TechniTex.
 - 9.5 Mathematically, is it possible to predict the properties of materials achieved at different stages in the process by different processing conditions, and then predict the effect these conditions may have on the finished product?
 10. AP from Pail Containers Ltd uses polypropylene fabrics including woven in Carbon Fibre tapes to make bags for carrying bulk items (e.g. one-tonne bags). They have to be lightweight but strong, and the minimum industry standard is that a bag designed to carry 1 tonne of material must fail in excess of a 5 tonne loading.
 - 10.1 No R&D is carried out within the company, and due to competition from the third world countries, any development is in the area of automation (this minimises the disadvantage they face in labour and wage structure over the third world). For

example, a recent acquisition has been a machine which can do four tasks, where as competitors may have four machines, and therefore need 4 operators. *But is the same throughput achieved on this one machine as the four standard? Also, what is the risk of the one machine breaking down, versus one of the four standard machines breaking down? How many spares need to be kept?*

- 10.2 AP mentioned the recycling problem: that there has to be a 50% reduction in waste by 2005 (although this includes paper, wood, glass, cardboard etc, which should account for most of the reduction). Their products are difficult to recycle; so new fabrics may have to be found. HO asked if they were interested in predicting the load possible from the fabric strength (with new fabrics in mind), but AP thought that it was more appropriate to test the bags.
11. MT from Assistive Technologies UK described some of his ideas for developing smart textiles into wearable products, which could assist disabled or elderly people at home (a recent Foresight document identified the ageing population as an area which could benefit from collaborative research). The aim of this technology is to increase independency at home for the elderly or disabled. Detail is given in MT's handout at the meeting.
- 11.1 MT pointed out however, that at present no such fabric existed, which could record slight movements of the wearer. He has approached the Smart Optics Faraday Partnership, with an idea for using micromirrors (optical sensors) incorporated into fabric to record movement data. JT suggested a contact who had approached Acordis about integrating microtransponders into fabric.
- 11.2 One idea is that movement information can be sent to a remote therapist to suggest suitable treatment plans for the wearer, based on what they are and aren't able to do.
- 11.3 It might also be possible for the fabric to move in some way and support or enhance the movement of the wearer.
12. PM closed the meeting by summing up and thanking all speakers and contributors. Follow-up will take place between PM+/HT, CM+/BMcC and relevant industrialists and academics where potential research areas have been identified.

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Some useful websites:

www.dti.gov.uk
www.epsrc.ac.uk
www.faradaypartnerships.org.uk
www.foresight.gov.uk
www.ma.hw.ac.uk/icms
www.mediatex.co.uk
www.noisenet.ws
www.sbs.gov.uk/smart/
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