Techno-mathematical Literacies in the Workplace

RESEARCH REPORT

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Prefatory note

The main body of this report, together with Annexes 2 and 3, describes the research of the Techno-mathematical Literacies in the Workplace project (RES-139-25-0119). A small supplementary collaboration Enhancing and assessing Complex Reasoning through Models and Modelling (RES-139-25-0119) was carried out by the research team, with US and UK researchers. Funding was integrated with the TmL project, and the work is reported in Annexe 1.

Background

Over the last two decades, the nature of mathematical knowledge required in workplaces has been influenced by two significant changes. Firstly, the adoption of information technologies has led to modern workplaces being increasingly highly automated. Secondly, there has been an increasing focus, both in manufacturing and service industries, on flexible response to customer needs (cf. Victor & Boynton, 1998).

These two changes have impacted on the nature of the mathematical skills required in modern workplaces. Employees at many levels in a company need to understand some elements of what is behind the interface of the IT systems, so they can communicate with others in different parts of the workplace, and with customers who are demanding more information and more transparency. Thus, new work practices increasingly require what we term Techno-mathematical Literacies (TmL), that is, being able to reason with quantitative or symbolic data processed by information technology as part of decision-making or the communication process.

Previous research (e.g. Hoyles, Wolf, Molyneux-Hodgson, & Kent, 2002; Noss, Pozzi & Hoyles, 1999; Noss & Hoyles, 1996) led us to propose this research and argue that much of the discussion around “skills gaps” and the non-transferability of school mathematics had missed essential characteristics of the new knowledge required in technology-mediated work, and its central role for effective boundary crossing (Tuomi-Gröhn & Engeström, 2003).

Objectives

The original aims of the project were:

1. to understand the techno-mathematical literacies (TmL) — fusions of mathematical, IT and workplace-specific competencies — required by managers at different levels to operate in workplaces in at least three different industrial and commercial sectors;

2. to design iteratively, evaluate and disseminate — in collaboration with companies, sector organisations and training organisations — a set of multimedia-based training resources to help experienced employees acquire appropriate techno-mathematical literacies;

3. to evolve a set of measures for evaluating the learning outcomes of the training resources from the point of view both of individual and group learning;

4. to contribute to the emerging theories of learning transfer in relation to the development of subject-based modes of expertise among individuals and communities;
5. to work with sector organisations, training organisations and Sector Skills Councils to address issues concerning the forms of qualification and accreditation that should be made available to employees that will support progression for experienced employees, and strengthen existing forms of work-based training.

Re 1, we have identified and characterised the TmL required within workplaces in three sectors, packaging, automotive and financial services (a fourth, pharmaceuticals manufacturing, was partially investigated).

Re 2, in each sector, we co-designed with employer- and trainer-partners training resources (renamed “learning opportunities”) and appropriate software, and participated with these partners in training sessions.

Re 3, having achieved Objectives 1 and 2, the evaluation of our co-designed learning opportunities had to be undertaken with our employer-partners. This entailed working with companies’ evaluation metrics, rather than developing our own measures. We did, however, extensively follow-up the training opportunities with targeted interviews with individuals and groups (see e.g. interview schedule in Annexe 3), and collected evidence as to the ways in which engagement with the learning opportunities had influenced participants’ practice.

Re 4, see publications and activities below; notably our contributions to discussions on the subject of abstraction and transfer (e.g, Symposia at EARLI conference, 2005, and AERA Annual Meeting, 2006).

Re 5, we worked throughout with several sector-based vocational and professional organisations, for the purposes of validation and (where possible) discussion of the implications of project results for vocational qualifications and accreditation (main organisations: SEMTA sector skills council, the Financial Services Skills Council, and the Institute of Packaging).

Methods
We undertook our research in two phases, as summarised in the research process diagram (Figure 1)\(^1\).

In Phase 1, we derived ethnographic case studies in companies in order to identify and characterise the TmL needed to function effectively. Methods used included work-shadowing, analyses of documentation and semi-structured interviews with a wide range of employees, from shop floor operators/customer service agents and first-level managers through to senior managers. We progressively focused on probing the meanings held by different groups in the work process of the symbolic outputs of IT systems that were supposed to convey information between groups within and beyond the workplace: putative “boundary objects”, where our ethnography indicated that communication was problematic. (Boundary objects are artefacts that exist in several communities of practice and satisfy the informational requirements of each; cf. Bowker & Star, 1999). We also joined team meetings and process improvement teams (in manufacturing) and listened to conversations with customers (in finance) to ascertain if and when problems of communication might be arising and how employees reacted to these.

\(^1\) Full details of our fieldwork in each sector/company are given in Annexe 2.
In Phase 2, we carried out iterative design-based research with our employer-partners, to design and implement “learning opportunities” aimed at developing the TmL identified in Phase 1.

Learning opportunities incorporated interactive software tools that modelled elements of the work process, or were reconstructions of the symbolic artefacts from workplace practice, called “technology-enhanced boundary objects” (TEBOs). TEBO development was a major activity in Year 3 of the project, involving many cycles of collaborative design, implementation, evaluation and re-design. The learning opportunities were embedded in activity sequences based on authentic episodes recorded in Phase 1 or reported by employer-partners.²

Evidence of learning was derived from evaluation forms (some employer-designed), follow-up interviews and questionnaires with participants (see Annexe 3 for a sample interview schedule) and their managers, and (where possible) observation of participants’ work following our intervention. Email threads between company trainers/managers and researchers were an important form of data collection in co-design and evaluation phases.

The project set out with a particular interest to investigate time-served upwardly-mobile employees (TSUMEs), who had been in a particular employment for several years, and who aspired to upgrade their skills. In preliminary investigations in manufacturing contexts, we identified these roles as mainly connected to the “first level” management of shop floor operations, managing the day-to-day operation of one or more production lines/areas. Initial ethnography focussed on these managers, and relevant TmL were identified. But, in moving to Phase 2, our work had to be aligned with company training policies, which led us to broaden our methods to include groups other than TSUMEs, whilst maintaining a focus on intermediate-level employees. We also found that

² See Annexe 3 for details by sector.
‘intermediate-level TmL’ were in fact key to a population of employees broader than originally envisaged, encompassing both shop-floor operators and mid-level managers.

In collecting data, we continuously sought to triangulate views of the same workplace activity, seeking the perspectives of different groups of employees. In analysing data, we triangulated interpretations of the raw data (audio transcripts, etc.) amongst the project team. We further triangulated with experts in the company through presenting reports, and with the appropriate sector through validation meetings, and the project’s advisory group. All these interactions provided information on the validity and generality of our findings.

The iterative co-design of learning opportunities involved a further set of triangulation points for the project. Validation of policy implications was sought from appropriate post-16 education and training organisations, particularly the Sector Skills Councils (SSC) for the sectors studied in our research.

Results

We report the major findings from the research overall; results from each of the workplace sectors; and finally, elaborate the major cross-cutting concepts that emerged. Please note that we do not report here on the Pharmaceuticals Manufacturing case studies, since (as noted in form, section 6) it was not possible to fulfil the second phase of the project with these companies. The broad findings in pharmaceuticals are subsumed into the work described for automotive manufacturing.

4.1 Overarching Findings

1. It is simply not true that the IT presence in workplaces removes the need for employees to interpret and understand the output of the technologies. On the contrary, this research characterised new kinds of literacies and new ways of acquiring them. From a theoretical point of view, the research also indicated some problematic aspects of situated theories of workplace learning, in particular in their lack of emphasis on the role of disciplinary knowledge, such as mathematics.

2. IT systems are based on models involving mathematics that is largely invisible. This means that TmL were seldom picked up on the job and needed to be developed explicitly. It was difficult for managers and trainers responsible for skills development to recognise the nature and scope of the TmL that impacted on their business. Even in sites that were most involved in widespread change arising through the introduction of e.g. process improvement techniques, we found that the need for new knowledge in the form of TmL was insufficiently recognised, and there was limited capacity amongst trainers and managers to communicate with companies’ own technical experts to develop appropriate training.

3. Symbolic information in the form of numbers, tables and graphs was often understood by employees as “pseudo-mathematics” — as labels or pictures with little, if any, appreciation of the underlying mathematical relationships. Information thus failed to fulfil its intended role in facilitating communication across “boundaries” between communities.

4. Effective learning of TmL challenged pseudo-mathematics by making work-process models more visible and manipulable through engagement with TEBOs. This necessitated determined efforts in iterative co-design of TEBOs and authentic activities that used the complementary expertise of employers and educators. Collaborative design involving researchers and employer partners has received little attention in workplace
research. Our research points to its considerable potential in bringing together the range of expertise essential to address the TmL skills gap, and in starting the process by which employers can take control of, sustain and extend what begins as a researcher-led intervention.

4.2 Results in each sector

4.2.1 Results in manufacturing industry

Our research in manufacturing – Packaging and Automotive – developed along two themes, both connected to the drive for greater quality and productivity in manufacturing processes: (1) modelling manufacturing processes, and (2) statistical process control.

Modelling manufacturing processes

In a packaging factory making plastic film by an extrusion process, we investigated how the computer control and monitoring system served as a boundary object between managers, engineers and shop-floor machine operators. The extrusion process involves about twenty stages. The plastic starts from raw granules, is melted to form a thick tube, which travels through several stages as a flat “tape” and is then extruded (stretched) at different temperatures and tensions that need to be very precisely controlled, becoming thinner at each stage until the desired thickness (gauge) is reached (e.g., 19 micrometres). The most sensitive stage of the process is at “the bubble” – where the tape is inflated with compressed air so that it rapidly expands and the film thinned down to its final thickness.

Figure 2: a screen-shot of part of the computer control system for the film production process; white “thread” shows the flow of the film through various production stages, with temperatures, pressures, etc. displayed, terminating in the bubble, the white hexagonal shape in the centre.

Each extrusion line is controlled by a computer system that monitors and records numerous process parameters – typical display screens (see Figure 2) present flow
diagrams representing actual quantities and flows, e.g. temperatures and pressures at
different points in the line. The computer system records and stores all these process
data, which is presented in graphical form (see Figure 3). Although these records are
accessible to all, our ethnography indicated that shop-floor operators and line managers
rarely looked at them. Managers were convinced that if shop-floor employees were able
to engage with these data, they would have a much-improved model of the process,
which would lead to more effective operator control of the process and more efficient
production.

We identified the following TmL: understanding systematic measurement, data collection and
display; appreciation of the complex effects of changing variables on the production
system as a whole; being able to identify key variables and relationships in the work flow;
and reading and interpreting time series data, graphs and charts, some of which are
standard and some idiosyncratic and company-specific. We also noted the need for
employees to be able to control the process for target mean and minimal variation and to
communicate about these values with other employees and with management. Finally, we
identified a need for employees to appreciate the role of invisible factors – such as the
cost of raw materials and selling price of the product – in determining the target mean
and variation of the physical film, none of which were evident in the computer-generated
data available.

TEBO: Simulating and “opening up” a model of the process. We co-developed a software simulation of
the production process of making plastic film by extrusion (see Figure 4). Numbers in the white boxes
are inputs or parameters that the user can modify. The goal was to achieve stable running of the
process with film gauge at a required target. It was crucial not to make changes that “burst the bubble”
on the right (this in practice stops the production process). The graphs in the middle show historical
data for 9 variables.
The learning opportunities were highly rated by the participants, and will be adopted by the company in future induction and training. A process engineer commented:

“If every operator and shift leader went through training using the tool there would be a baseline level of understanding that we risk not getting with the observational style training we currently use. I think the tool also helps identify people’s strengths and weaknesses not only in terms of film-making process understanding but also logical problem-solving ability. I didn’t expect this!”

**Figure 4: TEBO to model the production of plastic film by extrusion**

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**Statistical Process Control (SPC)**

SPC is a set of techniques widely used in workplaces as part of process improvement activities. Using such techniques requires many employees to interpret and communicate one-number process measures – “process capability indices”. We found that in training, the usual introduction of these measures deployed statistical and algebraic symbolism as well as laborious manual calculations that seemed universally to hinder employees’ understanding of the underlying mathematical relationships. The indices were mainly understood as ‘pseudo-mathematics’: as labels for “good” or “bad” processes without meaningful connection to their basis in the manufacturing process. Yet the company wanted the indices to be meaningful as prompts for appropriate action.

*We identified the following TmLs:* understanding systematic measurement, data collection and display; appreciation of the complex effects of changing variables on the production system as a whole; being able to identify key variables and relationships in the work flow; reading and interpreting time series data, graphs and charts; distinguishing mean from target and specification and control limits; knowing about the relation between data and measures and process and model; understanding and reducing variation, and appreciating the basis of process capability indices and how they are calculated.

*TEBOs:* explaining core statistical concepts through visual interactive software. We developed software tools (Figure 5) to be used in conjunction with existing SPC courses, to make the statistical concepts more understandable by a) simulating the physical experiments that trainees did to generate sample process data, so that after doing them manually they were able to generate larger data sets, making statistical patterns and trends easier to perceive, and b) allowing direct manipulation of capability indices with visual feedback layered over algebraic formulae.
Our activities and tools were extremely positively evaluated by the company’s SPC team. They were subsequently taken up for supporting communication in unpredicted ways (see Impact, below).

An SPC specialist engineer commented:

“One of the hardest things we have to get across is what the Cpk means – once you're familiar it becomes trivial, but to translate that to someone who doesn't know is really difficult, the tool enables you to show in a dynamic way – if I move this then this moves. It's like creating a cartoon from a load of slides. When the operators chart data they are taking little snapshots in time and your tool brings it all together like a cartoon, animating it.”

Figure 5: (a) and (b): Software tools which model Cp and Cpk, “capability indices” for how well a process is under control and meeting required targets.

Figure 5 (c): The simulation allows the user repeatedly to generate trials of 50 pushes of a coin in shove ha’penny, plotting where the coin lands each time on the three charts. The player attempts to improve the process by altering several process parameters.
4.2.2 Results in the Financial Services sector

Financial Services is a substantial sector of the UK economy. Our focus was on employees working in the customer-focused areas of pensions, investments and mortgages. In the face of increasing competition for customers, and the increasingly complex nature of financial products, we found that employees who were unable to understand how the numbers that formed the output of the computer system were derived, were often unable to communicate the benefits of their products to potential or actual customers.

We observed the phenomenon of “pseudo-mathematics”: numbers such as interest rates were labels attached to a financial product (e.g., “a 5.9% APR mortgage”), not elements of the underlying financial-mathematical models which make the products work. This mattered because customers have particular needs and backgrounds, and successful communication involves being able to adapt the standardised responses to customer queries written by technical experts to the individual customer’s needs, or to know when a particular customer query required an expert investigation.

We group our findings under two headings: (1) modelling pensions and investments, and (2) modelling mortgages.

Modelling pensions and investments

Our research was undertaken in customer enquiry and sales teams in two large financial companies dealing with pensions and investments. We investigated the meanings of putative symbolic boundary objects e.g. the annual pension statement (Figure 6), various other financial statements directed to customers, and explanatory letters sent to customers in response to enquiries.

We identified the following TmLs: appreciating the existence of a mathematical model underlying the output in, for example, financial statements (e.g. pension statements) or interest on loans; and understanding growth (compound interest) and “present value” of money (including frequency of interest payments, management charges).
**TEBOs** we developed comprised:

- spreadsheet simulations of symbolic boundary objects;
- specially-written software (Figure 7, a and b) that allowed direct manipulation and engagement with the key variables (time, frequency of payment interval, principal value) underlying the financial concepts of compound interest and present value, and provided visual representations of how the variables interconnected and changed over time.

We found that after engagement with the TEBOs and the accompanying activities, customer enquiry teams were able to appreciate that the “numbers were not just magic”. They were beginning to develop mental models of the products and use them to interpret outputs and respond to customer queries.

A Manager commented:

> “I was concerned that people would find it interesting but would think it had no practical use. But the comments I got were that people had learnt stuff about Excel that they didn’t know, but also that they had understood some of the processes behind the pensions products which they could use [with customers] … The overall feedback has been excellent, in lots of ways: content, pace, support – I thought there could be a lot of theory work, people sitting and not interacting with each other, so that was a surprise the level of debating exercises. There was debate and that challenged people, more than I thought there would be.”

An employee commented:

> “When I’m talking to people on the phone now, it makes more sense in your head, how the calculations are arrived at… Rather than reading from a script, as if that was in German, just pronouncing the words but I wouldn’t have a clue of what it means in English… It then means you can understand your speech as well sometimes, rather than sounding like a dummy, and saying to them, oh we’ll get someone to ring you back, or write to you about that. Now you can more or less satisfy the caller’s queries, at that first point of contact sometimes.”

**Modelling mortgages**

Our research was undertaken with the telephone sales team in a company that sold a complex mortgage product, where all of a customer’s debts and savings could be combined in one “current account mortgage” (CAM). Unfortunately, the complexity was such that the CAM was difficult to sell. Engagement with atypical customers (where interaction was not scripted) required agents to communicate features of the mortgage relevant to that individual, by being able to work through a network of mathematical reasoning steps to link a customer characteristic to a feature of the product. However, all calculations for a mortgage quotation were performed by the company’s computer system. Only a summary of the costs and savings was made available to the sales agent.
Figure 7(a): Software tool for finance – a “visual calculator” to model compound interest. The model is based on number of periods rather than years so that situations of yearly and more frequent compounding can be investigated.

Figure 7(b): Software tool to model “present value” of investments; this calculates the reverse of compound interest: given a sum of money in the future, what is that money worth today? Employees can use the tool to model basic financial instruments that are used in products such as annuities, and for commission payments.
We observed a striking case of “pseudo-mathematics” in this company: sales employees frequently talk to customers about comparing the costs of maintaining a credit card debt against the lower costs of consolidating that debt within a CAM. The CAM is cheaper because its interest rate is lower, however this is obscured by the fact that mortgage interest is usually quoted as an annual rate (e.g., 5.9% APR) and credit card interest is usually quoted as a monthly rate (e.g., 1.8% per month). We expected that employees would be aware of the “mathematically obvious” relationship that an annual interest rate is approximately 12 times a monthly rate. In fact, this knowledge was absent among all but one or two of the employees we encountered. Thus, the interest rate numbers really were perceived as just labels attached to financial products: a “1.8% per month credit card” or a “5.9% APR mortgage”.

A second pseudo-mathematical object is the graph and savings table shown in Figure 8, where the dependence of the graph’s shape on interest rate was unknown to most employees, and the stated numbers for savings on interest and time were often unbelievable for both customers and employees.

![Figure 8: Pseudo-mathematical graphical and tabular artefacts used in communication with customers to sell the current account mortgage.](image)

<table>
<thead>
<tr>
<th><strong>This is what you will S-A-V-E</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortgage amount</td>
</tr>
<tr>
<td>Term</td>
</tr>
<tr>
<td>Monthly payment</td>
</tr>
<tr>
<td>Total payments</td>
</tr>
<tr>
<td>Interest SAVED</td>
</tr>
<tr>
<td>Term reduction</td>
</tr>
</tbody>
</table>

We identified the following TmL: understanding key variables and relationships in the financial product (e.g. interest rates, time of loan, administration fees and tax implications), modelling these relationships and communicating their structure; interpreting graphs and charts, and making estimates and predictions of costs based on customer requirements and personal details.

**TEBOs.** As in “Modelling Pensions and Investments”.

The evaluation conducted by our employer-partners was very positive, and it was also evident that working on our TEBOs had opened windows on the limited TmL even among the trainers. For example, sales agents admitted that they had never thought there was any relationship between monthly and annual equivalent interest rates, not even to the extent of approximately times 12! And even the trainer admitted he had not thought about this before:

"I knew they would be [unaware of any relationship between monthly and annual rate]. There is a complete misconception about this. And the only reason I picked it up is by having worked through your exercises myself, and realising that I had the same impression myself."
4.3 Major Concepts in the Research

Symbolic boundary objects and boundary crossing: this pair of concepts has come to underpin all aspects of our research, and in particular in our design of TEBOs as tools to mediate the learning of TmL and to promote communication between employees, managers and trainers. We also see the research process itself - of understanding TmL - as a form of boundary crossing between ourselves as researchers and the research subjects (companies and their employees).

Design research and the central importance of co-design: Design research was crucial at every phase as the basis for the development of our learning opportunities in collaboration with companies and industry sector experts. Design research is under-represented in workplace research, partly because it is so challenging. Co-design has received similarly scant attention in educational research in general. Yet it offers an important way to bring about sustainable change in practice, as well to as provide a window on employees’ TmL and how it can be developed.

Learning opportunities rather than training: Learning opportunities, particularly based around TEBOs, were designed to encourage exploration and discussion. We adopt this term in place of training to emphasise our position not as outside “trainers”, but as participants in boundary-crossing activity involving different communities.

TmL as a basis for communication and explanation: Our work has pointed to the importance of TmL in communicating about workplace systems and processes between different communities in the workplace and to the outside world of customers and suppliers.

Activities

We list here only a few highlights; detailed lists are given the project’s Annual Reports to the TLRP.

International Seminar on Learning and Technology at Work, March 2004. 39 participants from 12 countries. Funded by TLRP and the EU Kaleidoscope Network of Excellence. This led to a set of papers edited by the project team for a special issue of Mind, Culture and Activity.

The TmL project was a leading member in the establishment of the EU Kaleidoscope Special Interest Group on Learning and Technology at Work [www.lkl.ac.uk/kscope/ltw].


Outputs

The project outputs are presented on the project website, www.lkl.ac.uk/technomaths.

The major outputs are:

3Note regarding the ESRC Data Archive: The project’s submission of data was not considered suitable for inclusion in the Archive.
• journal articles, book chapters and other writing;
• the software TEBOs (on the website);
• the learning opportunities materials (see sample activities sheet given in Annexe 3).

Publications
We have 4 peer-reviewed journal articles published. A further four are being prepared for publication. In addition, we have 24 conference publications (4 of these being invited keynotes), 1 book chapter, and 4 media stories (in company magazines, professional journals and local press)

Project video
A professionally-produced video of the project’s results is in preparation (commissioned with a small additional grant from TLRP).

Impacts
Policy-makers: “Functional maths/skills” is at the heart of government policy developments. We presented our work to policy agents in several venues (e.g., QCA meeting on functional maths, March 2005; QCA 14-19 Advisory Group, September 2005; TmL Project dissemination, May 1, 2007 (see below)).

School and college educators: We are in contact with several organisations with whom we are exploring the potential of developing TmL ideas and approaches for school/college functional maths. Several consultancy-based connections with the education sector are developing through NCETM (National Centre for Excellence in the Teaching of Mathematics), and PFEG (Personal Finance Education Group, a charity which is working to develop financial literacy education in schools).

Employers & trainers: One of our key criteria for assessing learning was that participants used what they learned to change their practice. We have pertinent examples from companies in all sectors, as the quotations in Section 4 testify. We have also seen several companies adapt our learning tools for their own purposes (including assisting communication between trainers and managers). The most significant case of this is the tools developed for statistics in process improvement, which are being used in three automotive companies not only as part of their training but also to assist communication between managers. One company engineer was so impressed by them that he has demonstrated and disseminated them amongst international audiences of “master black belt” process improvement engineers, in Europe and the USA.

Project dissemination event: Techno-mathematics in the Workplace – Identifying and Addressing a Critical Skills Gap, 1st May 2007. This event involved 60 invited participants from industry, education and policy organisations, and we were privileged to be able to present our research in the form of joint presentations between us and our employer partners. The Chief of Operations for Europe of one company remarked at the end of this event:

“I have been very impressed today by what you have shown, and I am very pleased that our company has been involved in this project; the tools developed by the researchers have contributed significantly to our employees’ skills and employees’ sense of empowerment.”
Future Research Priorities

During 2006–2007 we worked on a 6-month TLRP (TEL)-funded development project: Workplace Personalised Learning Environments for the Development of Employees’ Technical Communicative Skills (www.workplace-ple.org). We scoped out the design of a workplace personalised learning environment that incorporated TEBOs relevant to career practitioners. We have submitted a follow-up proposal to the Second Call of the TLRP/TEL Programme, “Design of a technologically enhanced learning system to support the development of an innovation community for guidance practitioners”.

Dr Bakker returned to work at the Freudenthal Institute in the Netherlands, and has received funding to carry out a project that draws on the outcomes of the TmL project, “Boundary crossing between school and work for developing techno-mathematical competencies in vocational education” (Netherlands Organization for Scientific Research; €180k, 2007-2011).

Dr Kent is preparing a joint proposal (ESRC small grant, to be submitted October 07) with members of the newly-established, ESRC-funded LLAKES Centre at IOE to explore issues related to Techno-mathematical Literacies in lifelong learning in urban contexts.

We are looking for avenues of research funding to extend and generalise the set of TEBO software tools. There is willingness amongst our partner automotive companies, but funding has yet to be finalised.