Teaching and Learning RESEARCH BRIEFING

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Techno-mathematical Literacies in the Workplace: A Critical Skills Gap

There has been a radical shift in the mathematical skills required in modern workplaces. With the ubiquity of IT, employees now require Techno-mathematical Literacies, the mastery of new kinds of mathematical knowledge shaped by the systems that govern their work. The education system does not fully recognise these skills, employees often lack them, and companies struggle to improve them. This project has developed prototype learning resources to train a variety of employees in the mathematical awareness and knowledge that today's employment requires.

- Techno-mathematical Literacies are new skills needed in IT-rich workplaces that are striving for improvements in efficiency and customer communication.
  → Current theories of workplace learning, and training approaches that simply reiterate school mathematics, are inadequate to close the skills gap for Techno-mathematical Literacies.
- IT systems are based on models involving mathematics that is largely invisible
  → Techno-mathematical Literacies are rarely picked up on the job and need to be developed explicitly. It is difficult for managers and trainers responsible for skills development to recognise the nature and scope of the Techno-mathematical Literacies that impact on their business.
- Employees often understand symbolic information (in the form of numbers, tables and graphs) as "pseudo-mathematics", that is, as labels or pictures without appreciating the underlying mathematical relationships. Information often fails to fulfil its intended role in facilitating communication between communities.
  → Techno-mathematical Literacies are an effective challenge to the problem of pseudo-mathematics, and can help employees to have shared meanings for symbolic "boundary objects".
- Effective learning of Techno-mathematical Literacies can follow from activities that make work process models more visible and manipulable, through interactive software tools serving as technology-enhanced "boundary objects".
  → Determined efforts in iterative co-design, that authentically exploit the complementary expertise of employers and educators, are needed for effective and sustainable upskilling of Techno-mathematical Literacies.

T·L·R·P TEACHING & LEARNING RESEARCH PROGRAMME

E·S·R·C ECONOMIC & SOCIAL RESEARCH COUNCIL

The research

Most modern workplaces are highly automated, and are increasingly focused on flexible response to customer needs. This project set out to characterise and develop the Techno-mathematical Literacies needed for effective practice in such workplaces. We looked at how intermediate-level employees understand and communicate the mathematical aspects of workplace artefacts, such as computer input and output and paper-based documents that contain information expressed symbolically. Intermediate-level employees typically have post-16 qualifications or equivalent work-based experience but are not graduates. Our aim was to elaborate the the nature of the Techno-mathematical Literacies required by such employees, and to understand how these mathematical skills are needed to reason with symbolic data, and to integrate data into decision-making and communication.

Boundary objects and Technology-enhanced boundary objects (TEBOs)

We identified artefacts used in workplaces which symbolically represent mathematical relationships inherent in workplace processes, and which are expected to convey meanings to different communities. This focus led us to take the notions of "boundary object" and "boundary crossing" as orienting frameworks for our research. Boundary objects exist in several communities of practice and satisfy the information requirements of each. Boundary crossing happens if boundary objects serve to facilitate communication between and within communities: in our case, managers, trainers, customer-facing employees and customers. We built on this idea to develop technology-enhanced boundary objects (TEBOs), software tools which adapt symbolic boundary objects from existing practice to the learning of Techno-mathematical Literacies.

Research methods

Our research was in two phases, and took place in collaboration with companies, employer federations and sector skills organisations in the following manufacturing and service sectors in the UK: Financial Services, Packaging and Automotive Manufacturing. In Phase 1, we carried out ethnographic case studies in ten companies to identify and characterise the Techno-mathematical Literacies needed to function effectively in each workplace. We probed the meanings attached by different groups to the symbolic inputs and outputs of IT systems that were supposed to convey information between groups, and looked for problems of communication and how employees reacted to them.

In Phase 2, we carried out design-based research with our employer partners, to develop learning opportunities aimed at fostering the Techno-mathematical Literacies identified in the first phase, incorporating TEBOs that modelled elements of the work process. These learning opportunities were embedded in activity sequences largely derived from authentic episodes recorded in Phase 1.

Collaborative design involving researchers and employer partners has received little attention in research on the workplace. Our research points to its considerable potential in bringing together the range of expertise essential to address the Techno-mathematical Literacies skills gap, especially as it encourages employers to take control of what begins as a researcher-led intervention.

Results in manufacturing industry

(1) Modelling the manufacturing process

In a packaging factory making plastic film, we investigated how the computer control system served as a boundary object between managers, engineers and shopfloor machine operators. The process is complex: the plastic starts as raw granules and is melted to form a thick tube, which is then stretched at different temperatures and tensions that need to be very precisely controlled, becoming thinner at each stage until the desired thickness, perhaps only 15 micrometres, is reached.

The production computer system monitors and records numerous process parameters such as temperatures and pressures at different points in the line, and stores these as historical data. Although these records are accessible to all, shopfloor operators and line managers rarely look at them. The engineer in charge of this process was convinced that if operators were able to engage with this 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 for the company.

TEBO and Learning activities: Simulating and "opening up" a model of the process. We developed a simplified software simulation of the production process, in which just the start and end parts of the process are modelled, but the format of the real computer systems is imitated. Learners can control the process to achieve stability and produce film "on target" by manipulating control parameters and observing graphical outputs about the process. We designed activities concerned with real events to challenge the process operators. For example, if one part of the process machinery is broken, how can the parameters be adjusted to keep the process running? Employees were invited to predict and test outcomes and thus come to appreciate aspects of the mathematical relationships embedded in the process.

A process engineer commented: "If every operator and shift leader went through training using this tool there would be a base-line level of understanding that we risk not getting with the observational style of 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. After going through the training activities with him, I now know far more about William and the way he thinks about things than I knew before. As someone who hates open-ended tasks, I'm pleased I can now give them all to William!"

(2) Statistical Process Control (SPC)

SPC is a set of techniques widely used in workplaces as part of process improvement activities, such as "Six Sigma". Using such techniques requires many employees to interpret and communicate one-number process measures, which we have observed to be mathematically and contextually challenging. In several car factories we investigated how "process capability indices" were used and trained. We found that the introduction of such measures usually involved statistical and algebraic symbolism as well as laborious manual calculations that hindered employees' understanding of the underlying mathematical relationships. The indices were mainly understood as "pseudo-mathematics," labels for "good" or "bad" processes without meaningful connection to their basis in the manufacturing process. The company wanted the indices to be meaningful prompts for action; working in partnership with the company trainers, we developed tools and activities to enhance existing training and shopfloor practice.

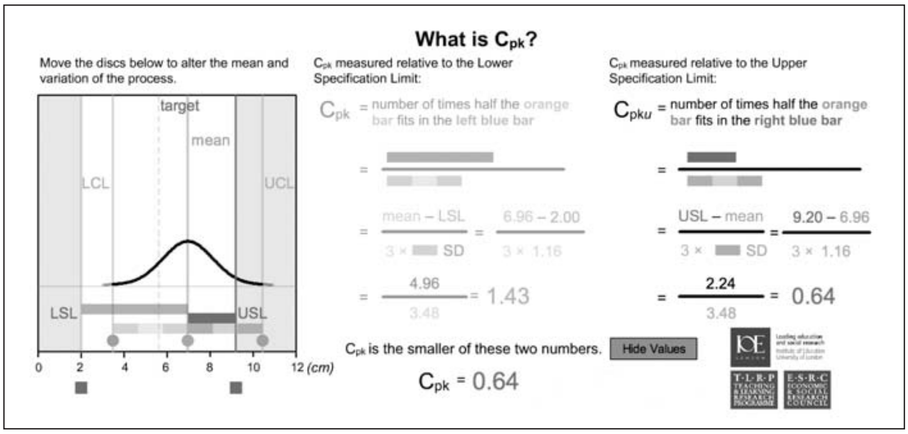

Figure 1: Software tool which models Cpk, a "capability measure" for how well a process is under control and meeting required targets. This is a visual and interactive representation to help employees understand how these measures depend on the statistical behaviour of physical data and the imposed human specification of targets

We developed TEBOs (Figure 1) to make the statistical concepts used in SPC training courses more understandable to intermediate-level employees, by allowing direct manipulation of capability measures with visual feedback alongside algebraic formulae that are quoted to trainees but hardly understood.

An SPC specialist commented: "One of the hardest things we have to get across is what the Cpk means. The tool enables you to show in a dynamic way… 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."

Process manager comment: "Before, data was just a load of numbers, and what does Cpk matter anyway? Now they can see it moving out of spec, they can see now what they need to do to bring it back in. With numbers, they don't understand what's going on. The graphical representation shows them, and now they understand what needs to be done."

Results in financial services

Our focus was on employees with intermediate-level skills working in the customer-focused areas of pensions, investments and mortgages. They used data mediated by computer systems. A dominant theme that emerged was employees' appreciation of computer models of financial products. Employees who were unable to understand where the numbers that formed the output of the computer system came from were often unable to communicate the detailed features of products to customers. While "pseudo-mathematical" numbers such as interest rates were often attached to a financial product ('a 5.9% APR mortgage') the employees applying these labels did not appreciate the underlying models of how the products work. This mattered because customers have particular needs and backgrounds. Successful communication involves being able to adapt standardised responses emerging from an IT system to the individual customer needs, or to know when a particular customer query requires expert intervention.

TEBOs and Learning activities:

- spreadsheets that allowed users to construct formulae and generalise relationships;
- specially developed graphical software (Figure 2) that allowed manipulation of the key variables underlying two major financial concepts, compound interest and its reverse, present value, and provided visual representations of how the variables interconnected and changed over time.

After engaging with these activities, customer enquiry teams were more 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.

An employee commented: "When I'm talking to people on the phone now, it makes more sense in my 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 was also evident that enhanced mathematical understanding could help employees with their studies for the work-based vocational qualifications that are required by all employees in financial services.

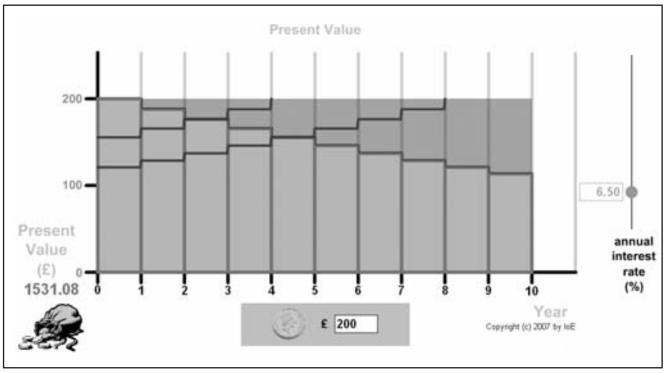

Figure 2: A visual calculator to model "present value" of investments. This calculates the reverse of compound interest: given a sum of money in the future, what is that money worth today? Employees can use the tool to model basic financial instruments that are used in products such as annuities and bonds.

Major implications

The central implication of our research is that the major skills deficit for mathematics in workplaces is the understanding of systems, not the ability to calculate. Calculation and basic arithmetic are less important than a conceptual grasp of how, for example, process improvement works, how graphs and spreadsheets may highlight relationships, and how systematic data may be used with powerful, predictive tools to control and improve processes.

We have reported instances of the problem of "pseudo-mathematical" understanding where numbers become labels that are attached to workplace artefacts, and are disconnected from the underlying mathematical models and relationships which make them meaningful. Pseudo-maths is very common. It arises in part from the ubiquity of IT systems and how they are designed by mathematical experts, with the workplace routines organised around them. The effect is that "ordinary" employees are disconnected from the mathematical models which drive the IT systems. Engaging employees in the development of Techno-mathematical Literacies, through authentic modelling activities, can be an effective challenge to the growing problem of pseudo-maths.

The skills gap in Techno-mathematical Literacies needs to be systematically addressed by employers, working together with educators. It needs a commitment of time and resources on the part of employers to come to terms with the need for this new kind of mathematical understanding and to develop new pedagogical approaches for training, so as to make Techno-mathematical Literacies more visible and available for exploration and development.

Techno-mathematical Literacies are most evident in workplaces that are involved in changes in working practices. However, even in sites where the need for change is recognised and supported, we did not find that the need for Techno-mathematical Literacies is sufficiently recognised. Long-established preconceptions about mathematics, in terms of arithmetic and algebra, are deeply ingrained, both in the world of work and in the world of education. Employers complain about "poor numeracy skills" in businesses such as financial services, where employees have little need to do arithmetic because of the computerisation of work processes. A central challenge for skills development is to educate employees and managers about important mathematical models and relationships that are rendered invisible by IT within workplaces.

The project has developed a framework for the effective workplace learning and use of Techno-mathematical Literacies, which draws on the concepts of boundary object and boundary crossing. We have shared expertise with companies in the joint development of prototype boundary-crossing learning interventions for Techno-mathematical Literacies. Some rely on adapting existing symbolic artefacts, while in others we have seen a need to develop and introduce Technology-Enhanced Boundary Objects (TEBOs), which are software tools designed to facilitate learning and communication around techno-mathematical concepts.

We have identified three key principles for learning design:

- *authenticity*, in which situations derived from actual workplace events can be the subject of discussion and reflection;
- *visibility*, in which hitherto invisible relationships become visible and manipulable;
- *complexity*, in which relationships are represented in ways that reflect real situations, but alternative representations are used which avoid conventional algebraic symbolism.

The sustainability of the type of learning intervention we have developed requires an emphasis on co-design with workplace trainers and managers, and where possible, on co-teaching. Companies must be engaged to transform learning opportunities so that they will remain useful as part of the company's internal activity. This was difficult to achieve, not because of the participation of trainers (which has often been excellent) but because of the lack of priority accorded to upskilling their workforce by many senior managers. We have become increasingly aware of a gap between rhetorical commitment to process improvement or improved customer engagement and the reality of employee development in practice.

Further information

The project's website presents a detailed project overview, illustrations of our approach to the training of Techno-mathematical Literacies (images and videos), software downloads, and publications information.

A book presenting a broad account of the research and the methods used, is being prepared for the TLRP *Improving Learning* series, published by Routledge Falmer.

To find out more about the different aspects of the research, we suggest the following of our publications:

Manufacturing sectors:

Bakker, A., Hoyles, C., Kent, P., & Noss, R. (2006). "Improving work processes by making the invisible visible". *Journal of Education and Work*, 19, 4, 343–361.

Noss, R., Bakker, A., Hoyles, C., & Kent, P. (2007). "Situating graphs as workplace knowledge". *Educational Studies in Mathematics*, 65, 3, 367–384.

Hoyles, C., Bakker, A., Kent, P., & Noss, R. (in press). "Attributing meanings to representations of data: The case of statistical process control". To appear in *Mathematical Thinking and Learning*.

Financial Services sector:

Kent , P., Noss, R., Guile, D., Hoyles, C., & Bakker, A (2007). "Characterizing the use of mathematical knowledge in boundary-crossing situations at work". *Mind, Culture, and Activity* 14, 1–2, 64–82.

Bakker, A., Kent, P., Hoyles, C., Noss, R. and Bhinder, C. (2006). "'It's not just magic!' Learning opportunities with spreadsheets in the financial sector". In D. Hewitt (Ed.), Proceedings of the British Society for Research into Learning Mathematics, 26, 1, 17–22.

Design-based research for the development of learning opportunities:

Kent, P. et al (submitted). "Learning through boundary crossing with computational artefacts".

(in preparation) "Co-designing computer tools for alternative representations of statistical measures in industry".

(in preparation) "Mathematics as a tool for explanation across boundaries: Recontextualising mathematics in IT-mediated articulation work in financial services workplaces".

(in preparation) "Workplace modelling: A step towards appreciating Techno-mathematical Literacies in practice".

The warrant

Our research is based on detailed engagement with companies, so the number of sectors and companies involved in the project had to be small, but also representative of industry trends. The manufacturing sectors, Packaging and Automotive, present a useful contrast in that the former is a mostly limited user of information technology, while in the latter processes are often highly automated and computer-controlled.

In each sector, we visited three to four companies for ethnographic investigation, comprising typically five to ten person-days of site visits. Our subsequent design-based research on learning opportunities involved two or three companies in each sector, comprising typically 10-15 person-days of site visits.

We collected data from many sources. These include: workplace artefacts such as graphs and charts and financial statements sent to customers; audio and occasionally video recordings of workplace observations and interviews; email trails with co-designers; evaluation forms; and questionnaires. We sought to triangulate different views of the same workplace activity through the perspectives of employees at different levels of a company. We made extensive use of the expertise of the project's Advisory Group, and of expert consultants in the different sectors and research sites.

One of our key criteria is that participants use what they have learned to change their practice. We have pertinent examples from companies in all sectors, as the quotes above testify. We have also seen several companies adapt our learning tools for their own purposes. The most significant case is the tools developed for statistics in process improvement, which are being actively used in three automotive companies. One company engineer was so impressed that he has demonstrated and disseminated them amongst international audiences of process improvement engineers, in Europe and the USA.

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Teaching and Learning
Research Programme

TLRP involves over 60 research teams with contributions from England, Northern Ireland, Scotland and Wales. Work began in 2000 and will continue to 2011.

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Expertise: TLRP works to enhance capacity for all forms of research on teaching and learning, and for research informed policy and practice.

Improvement: TLRP develops the knowledge base on teaching and learning and policy and practice in the UK.

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