Mathematical Components of Engineering Expertise

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For more info visit the project website at:

www.ioe.ac.uk/rnoss/MCEE

In the midst of all the debate in the United Kingdom about the study of mathematics by engineering students, it is remarkable that very little systematic research has been done on the way that mathematics is being *used* by professional engineers in their working lives. (Although, this is not to say that there are not many "feedback loops" by which professional engineers monitor and inform engineering education, via the various professional Institutions, the Engineering Council, visiting professorships in university departments, etc.)

Last year, in collaboration with Professor Richard Noss, I carried out a research project with precisely that aim. "The Mathematical Components of Engineering Expertise" (MCEE) project, funded by the Economic and Social Research Council, investigated the mathematical ideas and techniques used by civil engineers in professional practice, by means of interviews and observations carried out in a large, multidisciplinary engineering consulting firm. Although we do not claim any terribly novel insights, perhaps as outside observers of both engineering practice (and engineering academia) we have been able to identify some key ideas which may be regarded as "obvious" by engineers themselves. Our findings are just very briefly introduced here — see the project website for detailed results.

Over a period of years, the mathematics group at the Institute of Education has undertaken a number of projects concerned with the use of mathematics in various professional workplaces, including nursing, banking and commercial aviation. Whilst all of those jobs depend crucially on doing mathematics, the mathematics involved tends to be rather limited: that is, mathematics is essential but marginal to the job. Our aim in MCEE was to apply the ethnographic-style research methodology developed in the previous projects to the domain of professional engineering, where the mathematics involved is much richer and much more central to the work.

Or so we thought. Given what we knew about how much mathematics is taught to (civil) engineers in undergraduate courses, it was a little surprising in our first interviews at the company to hear comments like:

> *Once you've left university you don't use the maths you learnt there, 'squared' or 'cubed' is the most complex thing you do. For the vast majority of the engineers in this firm, an awful lot of the mathematics they were taught, I won't say learnt, doesn't surface again.*
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> *There is a whole lot of maths in what we do that we don't need to think about really, because other people have done it for us — getting to the simple maths that we do actually use, based on a much more complicated level of maths. The engineering discipline in the UK has certainly been set up so that we can avoid doing the complicated maths 95% of the time.*

So, although complicated mathematics exists in civil engineering, it seems to be the case that it isn't *done* by the majority of engineers, but it is *used* by them. Mathematical tasks and expertise are distributed across people and machines: analytical work is done largely by computer software, and there are a relatively small number of analytical specialists (just 2% of the engineers in the company we visited!) who are able to deal with any non-standard or ambiguous problems. For example, we were told about one particular design project where:

> *the specialist took on the task of carrying out whatever [advanced] statistics was needed in order to give us some figures for design.… although the complicated maths, was, realistically, out of the range of my boss or me, once the specialist had worked it out then it was within the range of us to understand what he had done at some level, to be able to use the results of it.*

The picture that emerges is that what most design engineers need is an "appreciation" for advanced mathematics, an understanding of the "interfaces" between engineering design and its analytical aspects. This is striking from an educational point of view, because this form of understanding seems to be very different from the way mathematics is taught to engineers as "service mathematics": that is, the student first learns the mathematics and then learns how to apply it to engineering. This way conveys much about the details on the analytical side of the interface (which few civil engineers nowadays will be practically involved with), but very little about the appreciation required on the design side. Of course, service mathematics is a tried and tested approach that has operated successfully for many decades, but our impression is that it now looks highly mis-matched with modern engineering practice, and we are wondering (see Future Work below) what new "design side" approaches may be desirable and possible.

We have been able to recognise a few of the "mathematical interfaces" between the design engineer and the forms of mathematical expertise that are accessible to him/her through computer software and analytical specialists. Crucial to these is the kind of understanding that allows design engineers to make use of mathematical work that is done by others. A paradigmatic example for structural engineers is the expert engineer's repertoire of qualitative and quantitative ways of thinking about structures. There seems to be a crucial mode of thinking in which engineers use the geometrical and algebraic language of mathematics as part of a "structural geometry" grounded in a knowledge of physical materials and structures:

> *Geometry is enormously important. For example, its relation to structural behaviour: the bending moment in a beam being a significant shape — it's a parabola, and not just any old parabola, but one that represents the structural behaviour. Similarly for the catenary, a curve that corresponds to the structural behaviour of a chain. Historically, this began with things like Hooke's analysis of the hanging chain as an inverted stable arch, and it goes on through the development of the I-beam as the most efficient way of using material, the largest second moment of area per weight of material. The geometry of an I-beam is something fundamentally structural, embodied within it is the structural concept called second moment of area. Or, in a complex three-dimensional tent, there's the equilibrium of forces in three dimensions. And that's not Platonic geometry, it is structural geometry.*

Our interpretation of this is that understanding is "situated" in the sense that structural engineers think about geometrical and algebraic forms for what they mean in structural terms. In one sense, this is not so surprising: in any situation where mathematics is used, it is natural for specialised languages and methods to develop. The question that we want to pose about this, and it is a vital one for education, is what happens to mathematics as structural expertise develops? Does the engineer's mathematical knowledge simply disappear to be replaced by an alternative, engineering-based expertise? We think it needs to be described rather as an "embedding" of mathematics into engineering expertise, though of course much remains to be said about what embedding means in detail. We know that in the past, thirty or forty years ago, engineers emerged from university armed with a body of mathematics-based analytical methods, intensively practiced those methods for a period of years as junior engineers doing practical design calculations, and out of that somehow emerged engineering expertise. In the modern state of civil engineering practice, another model is needed for how mathematics fits into the development of engineering expertise, which recognises the ubiquitous presence of IT tools.

Future work

We will be commencing shortly a new project that will aim to make some reassessment of the roles of mathematics and IT in the education of engineers, drawing in part on our findings from MCEE. We will be consulting widely with engineering and mathematics academics, and engineering practitioners. Please contact myself and Richard Noss (p.kent@ioe.ac.uk, r.noss@ioe.ac.uk) if you are interested to know more about this.

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