ROYAL ACADEMY OF ENGINEERING

Centre for Real-World Learning at the University of Winchester

Thinking like an engineer

Implications for the education system

May 2014

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A report for the Royal Academy of Engineering Standing Committee for Education and Training
Full report, May 2014

ISBN: 978-1-909327-08-5

Available to download from:
www.raeng.org.uk/thinkinglikeanengineer

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About the Centre for Real-World Learning (CRL) at the University of Winchester

CRL is an innovative research centre working closely with practitioners in education and in a range of vocational contexts. It is especially interested in new thinking and innovative practices in two areas:

- The science of learnable intelligence and the implementation of expansive approaches to education
- The field of embodied cognition and its implications for practical learning and for vocational education.

Visit **www.winchester.ac.uk/realworldlearning** and **www.expansiveeducation.net**

Acknowledgements

We have been greatly helped by a number of people who gave their time and thinking extremely generously. In particular we would like to thank:

The education team at the Royal Academy of Engineering

Dr Rhys Morgan, Stylli Charalampous, Claire Donovan, Bola Fatimilehin, Professor Kel Fidler and Dominic Nolan

A group of experts who offered helpful advice on all aspects of the research and attended two workshops

Heather Aspinwall, David Barlex, Jayne Bryant, Professor José Chambers, Andrew Chater, Linda Chesworth, Dr Robin Clark, Dr Ruth Deakin Crick, Claire Dillon, Professor Neil Downie, Joanna Evans, Professor Patrick Godfrey, Professor Peter Goodhew, Dr David Grant, Professor Kamel Hawwash, Mark Henshaw, Dr Ivor Hickey, Marina Higab, Martin Houghton, Chris Kirby, Frank Kirkland, David Knott, Ed McCann, Professor Iain MacLeod, Tony Moloney, Professor David Nethercot, Linda O'Donnell, Professor David Oxenham, David Perry, Paul Pritchard, Tony Rooke, Susan Scurlock, Professor Jonathan Seville, Steve Smyth, Professor Sarah Spurgeon, Neil Wooliscroft, Helen Wright.

Special thanks to Professor Matthew Harrison who commissioned this research while he was Director of Engineering and Education at the Royal Academy of Engineering.

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A Level	General Certificate of Education Advanced Level
BTEC	Business and Technology Education Council
BLP	Building learning power
BIS	Department for Business, Innovation & Skills
CAVTL	Commission on Adult Vocational Teaching and Learning
C&G	City & Guilds
CDIO	Conceive – Design – Implement – Operate
CHoM	Creative habits of mind
CRL	Centre for Real-World Learning
DfE	Department for Education
D&T	Design & technology
Diploma	Qualification for students aged 14 to 19 that combines academic and vocational learning
EHoM	Engineering habits of mind
EHEA	European Higher Education Area
ETF	The Education and Training Foundation
EUR-ACE®	Framework for accrediting engineering degree programmes in the EHEA
FE	Further education
Gazelle	A group of colleges focusing on developing entrepreneurs and in STEM
GCSE	General Certificate of Secondary Education
HE	Higher education
HEA	Higher education academy
HEFCE	Higher Education Funding Council for England
HEFCW	Higher Education Funding Council for Wales
HND/C	Higher National Diploma or Certificate
HoM	Habits of mind
MHoM	Mathematical habits of mind
NVQ	National Vocational Qualification
Ofsted	Office for Standards in Education, Children's Services and Skills
PBL	Problem-based learning
PEI	Professional engineering institution
PEST	Political economic scientific technical
PjBL	Project-based learning
QAA	Quality Assurance Agency for Higher Education
RSA	Royal Society for the encouragement of Arts, Manufactures and Commerce
STEM	Science, Technology, Engineering and Mathematics
STEMNET	Science, Technology, Engineering and Mathematics Network
SHoM	Scientific Habits of Mind
SIM	See Inside Manufacturing
SWOT	Strengths, weaknesses, opportunities, threats
TechBac®	Vocational programme of study being developed by City & Guilds
UCAS	Universities and Colleges Admissions Service
UK	United Kingdom
UKCES	UK Commission for Employment and Skills
US	United States of America
UTC	University Technical College

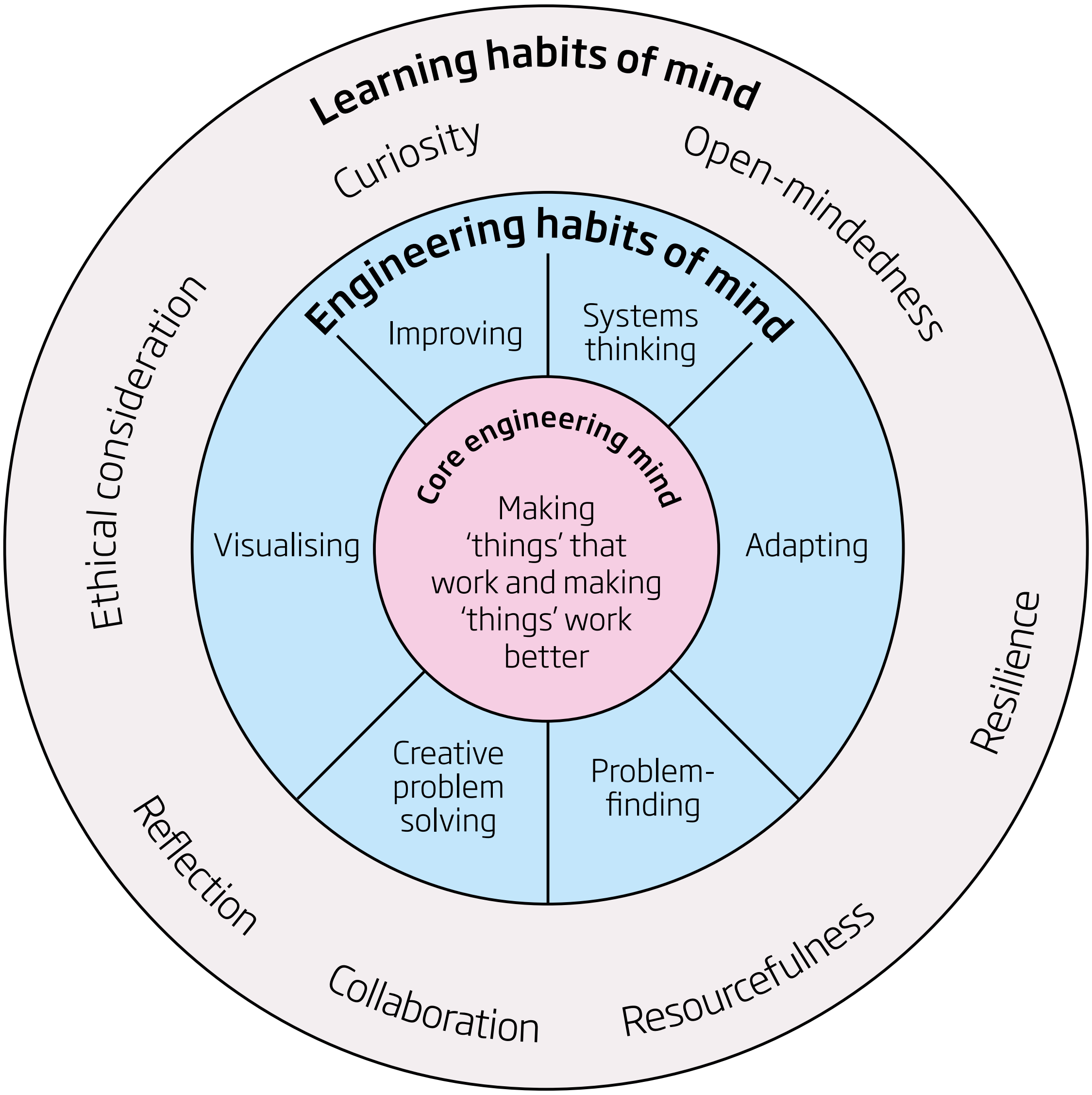
Foreword

The Academy welcomes this important new report by the Centre for Real-World Learning on the characteristics or *habits of mind* of engineers. As has been reported by the Academy in recent studies, there is continuing and increasing demand in the UK for the skills and attributes that engineers develop through their education and training. These skills are in demand not just in engineering industries but across the whole economy, in sectors as diverse as healthcare, media, entertainment and sport. This has highlighted a shortage of young people choosing to study engineering to meet this future demand.

There is increasing consensus among the engineering community for a concerted effort to change public understanding and attitudes towards engineering, to reflect the diverse range of activity and career opportunities open to young people through the profession.

This insightful work by Professor Bill Lucas, Dr Janet Hanson and Professor Guy Claxton, who worked with engineers and engineering educators to develop an agreed set of thinking characteristics, skills and attributes of engineers, suggests that even with an improved public understanding of engineering, our current education system in the UK does not sufficiently develop the habits of mind of young people to encourage them to pursue further study towards engineering careers. The Academy is grateful to the authors for bringing a new perspective on an important issue for educating future generations of engineers in the UK.

Professor Helen Atkinson CBE FREng
Chair of the Standing Committee for Education and Training


Learning habits of mind
Curiosity
Open-mindedness
Resilience
Resourcefulness
Collaboration
Reflection
Ethical consideration
Engineering habits of mind
Improving
Systems thinking
Adapting
Problem-finding
Creative problem solving
Visualising
Core engineering mind
Making 'things' that work and making 'things' work better

Executive summary

This report, commissioned by the Royal Academy of Engineering, offers fresh insights into the ways engineers think. It goes on to suggest ways in which the education system might be redesigned to develop engineers more effectively. The report also makes suggestions as to how the wider public might become engaged with these issues.

Engineers make 'things' that work or make 'things' work better. But they do this in quite particular ways. The report identifies six engineering habits of mind (EHoM) which, taken together, describe the ways engineers think and act:

1. **Systems thinking**
2. **Adapting**
3. **Problem-finding**
4. **Creative problem-solving**
5. **Visualising**
6. **Improving.**

In selecting these six aspects of the engineering mind, the research team found strong consensus among a wider variety of engineers and engineer educators.

Thinking like an engineer makes a strong case to suggest that, if the UK wants to produce more engineers, it needs to redesign the education system so that these EHoM become the desired outcomes of engineering education. It also needs to work closely with the teachers of, for example, science, design and technology, mathematics and computing.

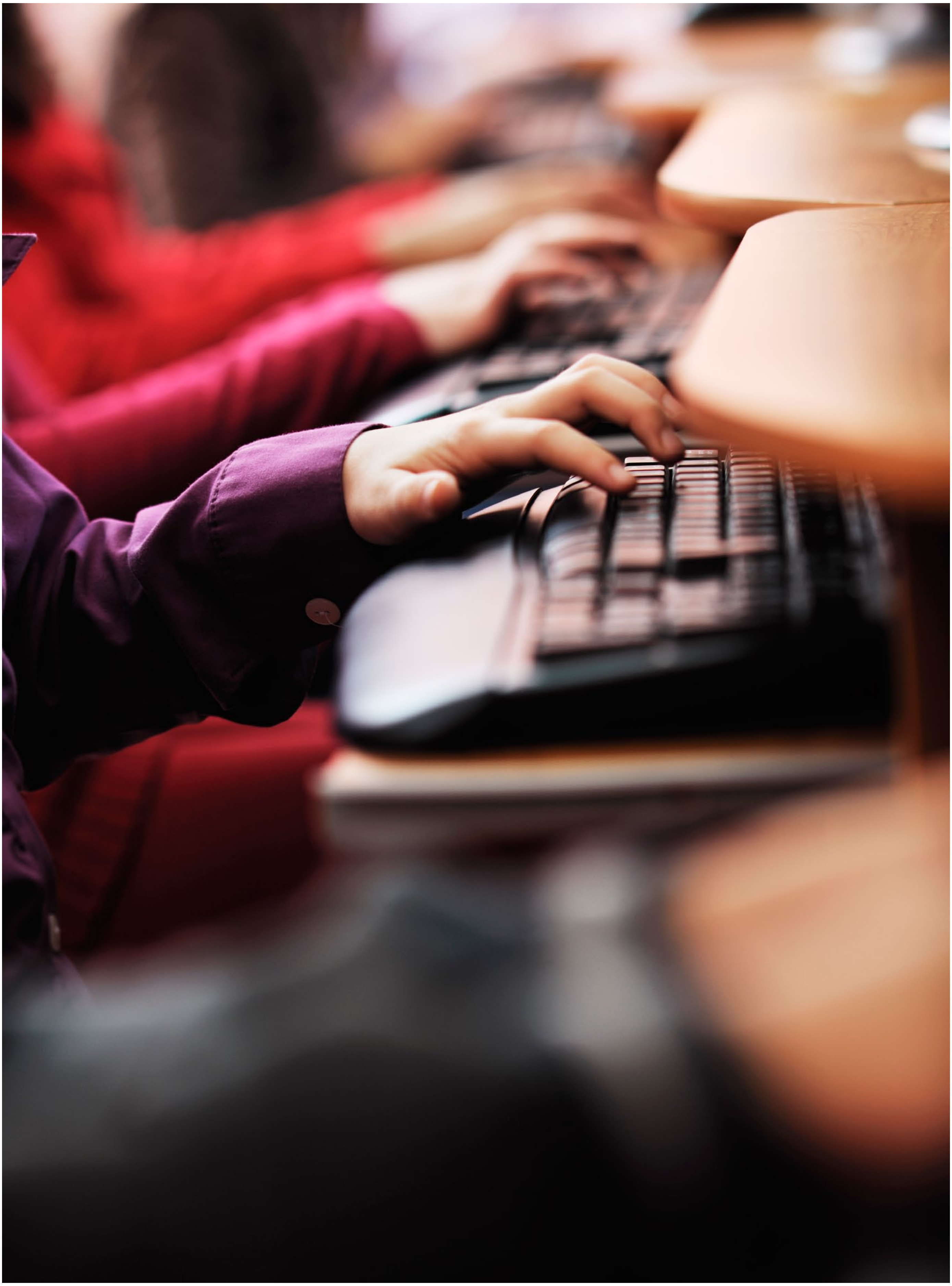
Young children are little engineers. Yet the primary school system almost extinguishes any opportunities for them to flourish as engineers and the teaching of engineering at secondary school is highly variable.

The report identifies those learning methods – problem-based and project-based learning, for example – which when rigorously introduced are highly effective at teaching learners to think like engineers.

Thinking like an engineer makes three broad recommendations:

1. The Royal Academy of Engineering to disseminate its findings to ensure wide engagement in the conversation about how engineering is taught.
2. The engineering teaching and learning community to seize the opportunity of the National Curriculum and the report's new thinking to bring about a mind-set shift in schools and redesign engineering education, especially at Primary level.
3. For employers, politicians and others to engage in a dialogue with schools and colleges about the EHoM they think are most important, suggesting practical ways in which they can help.

Given the continuing concerns about lack of STEM expertise in the UK and the recent publication of Review of Engineering Skills by Professor John Perkins, this report makes a timely addition to the debate with clear suggestions on the kinds of pedagogies which are likely to develop more and better engineers.



1. Introduction

1.1 The engineering context and two engineering challenges

'Shortage of engineers is hurting Britain' has been both an actual newspaper headline[2] and a more general national lament for too many years. Britain, we are told, does not have enough graduate and non-graduate engineers[3]. Furthermore, lamentably low numbers of women choose to study or practice engineering.

At first sight, this lack of engineers would seem to be a classic supply and demand problem as most recently described in the *Perkins Review of Engineering Skills*.[4]

Certainly demand appears to outstrip supply in many areas and for many kinds of engineers. So, we could use economics or marketing to fix the problem. Pay engineers more? Offer funding to more people to take courses at college and university? Create a campaign to improve the image of engineering as a profession? One of these will surely ensure that the supply of engineers increases. Or will it? In different ways each has been tried, as illustrated by the following government initiatives, reviews and funding opportunities, and yet we *still* have a mismatch between supply and demand.

The *Science and Innovation Investment Framework 2004–2014*, and subsequent *Next Steps* document[5], set out the government's ambitions to build a science, technology, engineering and mathematics (STEM) education and training environment capable of delivering a strong supply of scientists, technologists, engineers and mathematicians.

In 2005, the Higher Education Funding Council for England (HEFCE) identified STEM subjects as 'strategically important and vulnerable subjects' in terms of the mismatch between the supply and demand in these areas[6] and together with the Higher Education Funding Council for Wales (HECW) funded the National HE STEM Programme to encourage innovative STEM curriculum projects in universities between 2009–2012[7].

The Sainsbury Review of Science and Innovation by HM Treasury in 2007[8] identified a wide range of further developments to educate a new generation of young scientists and engineers, including offering financial incentives to STEM teachers to remain in teaching.

What if at least part of the reason that we do not have enough engineers is because we just don't know enough about how great engineers actually think? Or at least if we do know this we do not make enough use of what we know. And what if schools, colleges and universities are actually teaching engineering in ways which do *not* cultivate the kinds of engineering minds we need?

Re-present the issue like this and it moves away from economics and market forces towards psychology and pedagogy.

This is precisely the approach the Centre for Real-World Learning (CRL) has chosen to adopt in its research for the Royal Academy of Engineering (the Academy). In response to a more general invitation to consider engineering education, we suggested that the Academy might like to approach the apparent supply-demand issue by asking two fundamental questions:

1. **How do engineers think and act?**
2. **How best can the education system develop learners who think and act like engineers?**

Our first challenge was whether we could we reach consensus as to how engineers think, considering the huge breadth of the engineering sector. This question has a psychological edge as we are seeking to get into the mind of an engineer. Our second question

> The real 'problem' of engineering education is the implicit acceptance of the notion that high-status analytic courses are superior to those that encourage the student to develop an intuitive 'feel' for the incalculable complexity of engineering practice in the real world.
>
> **Eugene Ferguson[1]**

is dependent on a successful result with the first. It is, in a sense a true engineering challenge. Can we redesign the education system in terms of its pedagogy so that it is more likely to produce more people who think and act like engineers?

AT CRL, we assume that you cannot answer questions to do with educational methods unless you are prepared to ask and answer more challenging questions to do with desired educational outcomes.

So, for example, if you want 19-year-olds who can think for themselves, solve problems with others and persist in the face of difficulty, then you will not give them pre-packaged topics, individual tasks and problems which are well within their comfort zone. Instead you will invite them to take a role in designing their own learning, train them in the different roles and methods needed in successful group work and reward them for pushing themselves hard, making mistakes and bouncing back to do even better as a consequence.

With regard to engineering education, our working hypothesis is that the current system, at a fundamental level, uses teaching and learning methods which tend only accidentally to develop engineers. Our hunch is that, in far too many cases, teachers unintentionally put off potential engineers, especially girls, by the way they choose to teach science, mathematics, and design and technology. Schools in the UK also hugely disadvantage potential engineers by making the important discipline of engineering at best only available in one-off projects and at worst invisible in the school curriculum.

1.2 Why the minds of engineers matter

What do engineers do? What, if you like, is the point of an engineer? How do they think? How do they approach problems? How is what they do similar to but different from how a scientist or a mathematician sees the world? What does an engineer have in common with an artist or a designer or a technologist or a politician or a team sports player? What, in short, goes on in the mind of an engineer when he or she is in full flow doing engineering? What does an engineer think and do when encountering novel situations and challenging assignments?

Engineering is a broad field, typically being described as including four main traditions or disciplines – civil engineering, chemical engineering, electrical engineering and mechanical engineering and in recent years, the introduction of a fifth distinct but important discipline of digital or software engineering. There are also numerous subdivisions, many of which are represented by the professional engineering institutions (PEI). These PEIs are licensed by the Engineering Council to act as the awarding bodies for engineers' registration in their disciplines. There are currently 36 PEIs[9] offering accreditation for engineering qualifications.

There are a number of widely accepted definitions of engineering on which we have drawn as we have undertaken our research including:

The Engineering Council:

'Engineers use their judgement and experience to solve problems when the limits of scientific knowledge or mathematics are evident. Their constant intent is to limit or eliminate risk. Their most successful creations recognise human fallibility. Complexity is a constant companion.'[10]

The International Engineering Alliance:

'Engineering is an activity that is essential to meeting the needs of people, economic development and the provision of services to society. Engineering involves the purposeful application of mathematical and natural sciences and a body of engineering knowledge, technology and techniques. Engineering seeks to produce solutions whose effects are predicted to the greatest degree possible in often uncertain contexts. While bringing benefits, engineering activity has potential adverse consequences. Engineering therefore must be carried out responsibly and ethically, use available resources efficiently, be economic, safeguard health and safety, be environmentally

sound and sustainable and generally manage risks throughout the entire lifecycle of a system.'[11]

Sir James Dyson:

'Engineering is about looking at the world, its systems and objects, with a critical eye and having an inkling of an idea. And then testing that idea out, failing, and then experimenting again. That's how it was with my first vacuum cleaner and the thousands of prototypes I made; and that is how it is for the hundreds of engineers who work with me at Dyson today though I try and encourage them to be a bit quicker!'.[12]

What is Engineering, a website in the US aimed at young people considering engineering as a course of study:

'Engineering combines the fields of science and maths to solve real world problems that improve the world around us. What really distinguishes an engineer is his [sic] ability to implement ideas in a cost effective and practical approach. This ability to take a thought, or abstract idea, and translate it into reality is what separates an engineer from other fields of science and mathematics'.[13]

Tomorrow's Engineers, a website in the UK providing advice for young people and teachers, supported by the Academy and EngineeringUK:

'Engineering's about finding out what people need, developing an idea and seeing how it can be made at a good price, developing the 'product' on time and running tests to make sure it's safe and reliable, producing something that makes our lives better, whether that's a new games console, high-tech sports equipment or quicker, greener and safer travel'[14]

In Figure 1 we present these definitions as two word clouds as a means of seeing at a glance some of the frequently recurring words associated with engineering. The first version simply shows frequency of words used by making the most used words larger[15], while the second seeks to highlight the underlying concepts of the words and show these in similar mode:[16]

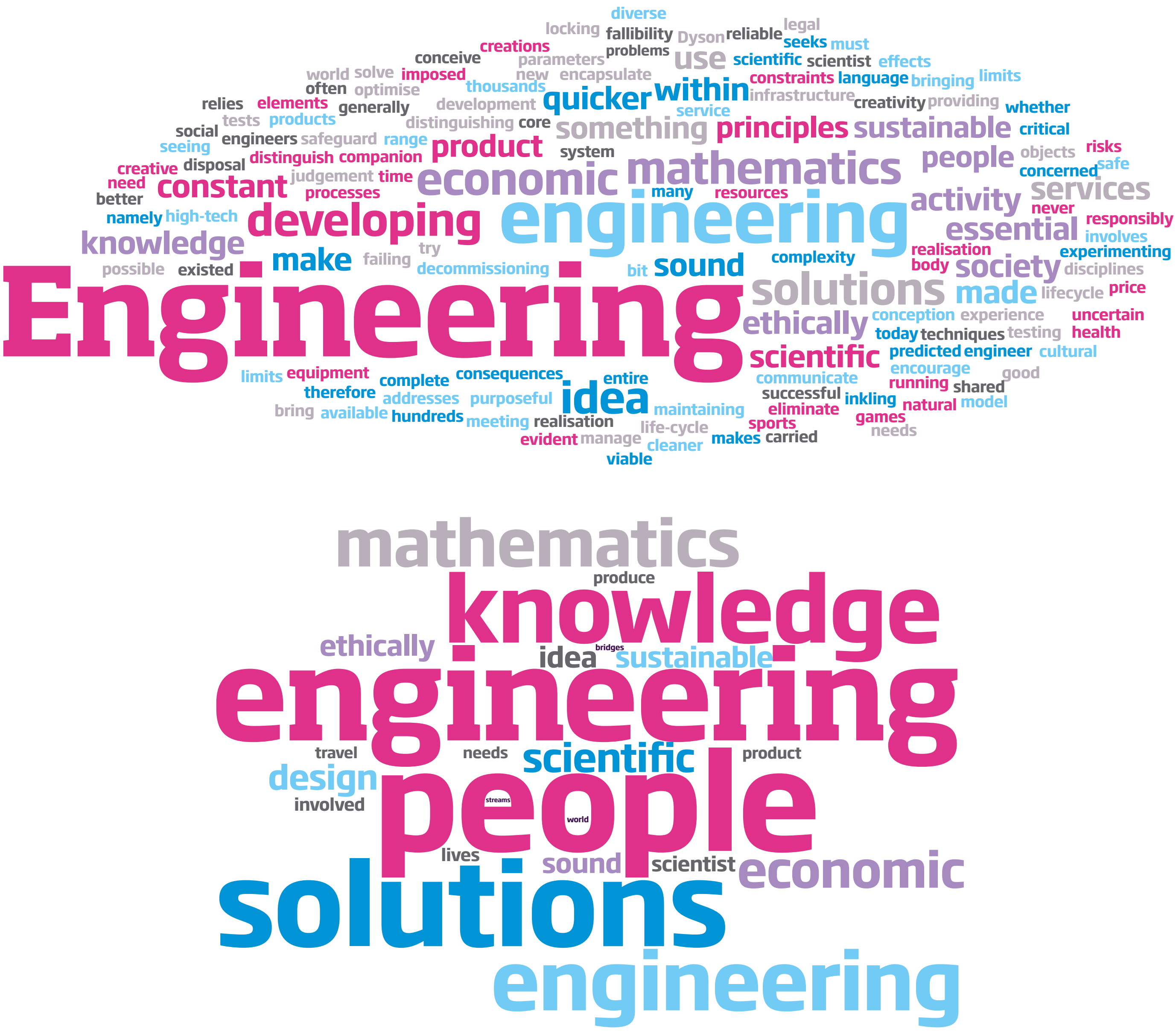


Figure 1 – Words most associated with engineering

We are struck by the way that the word 'people' emerges in the second word cloud, suggesting that many of the more fragmented concepts of the first relate to human activity. We were interested that the concept that has been most powerful in all of our conversations with engineers and engineer educators – making – is absent from both of them. Sharon Beder makes this point strongly when she draws on similar sentiments from Australian educator John Webster:

'Engineering in the real world also involves many social skills. These include the ability to understand and realize community goals; to persuade relevant authorities of the benefits of investing money in engineering projects; to mobilize, organize, and coordinate human, financial and physical resources; to communicate...'[17]

Reed Stevens says something similar:

'Something I learned from five years of studying the experiences of undergraduate engineering students is that engineering education has a funny, maybe even neglectful relationship to... people.'[18]

As we have sought to understand the minds of the engineers with whom we have been working and learning, we have gained many insights from some widely known, almost iconic quotations we were shown. We have distributed some of these throughout the report to ensure that the voices of engineers past and present are constantly heard.

We also learned much about the engineering mind from engineering humour. Here are just two examples:

'**Question:** How do you drive an engineer completely insane?

Answer: Tie her/him to a chair, stand close, and fold up a road map the wrong way.'[19]

'To the engineer, all matter in the universe can be placed into one of two categories: (1) things that need to be fixed, and (2) things that will need to be fixed after you've had a few minutes to play with them. Engineers like to solve problems. If there are no problems handily available, they will create their own problems. Normal people don't understand this concept; they believe that if it ain't broke, don't fix it. Engineers believe that if it ain't broke, it doesn't have enough features yet.'

Scott Adams, The Dilbert Principle[20]

1.3 A challenge to the education system

With a few exceptions, engineering does not appear on the timetables of pupils of primary or lower secondary age in the UK, unless engineering projects are used to teach aspects of design and technology (D&T) or to demonstrate the real-world application of mathematics and science. After age 14, engineering starts to be visible as, for example, in some academies, university technical colleges (UTC)[21] and studio schools[22]. Students might encounter engineering at GCSE, A Level or Diploma (14–19) programmes in engineering.

Further education (FE) colleges offer a wide range of engineering qualifications from level 2–5. Colleges and training providers also support employers in providing apprenticeships and other accredited work-based learning routes.

Once at university there is a rich tradition of higher level study with more than 5% of the higher education (HE) sector involved in engineering. It has been estimated that a total of 182 independent institutions offer a wide variety of engineering programmes. Undergraduate engineering is taught in 109 universities in the UK, with 73 FE colleges also recruiting engineering students through UCAS and directly to Level 4+ programmes[23].

There are 670 engineering entries in the 2012 UCAS database, 115 subclassifications and thousands of separate programmes[24]. In 2012, just within this single classification, 24,900 students gained places on engineering courses. There are also programmes spread across other classifications, in technology, architecture and mathematics and computing, that could be considered within the wider definition of engineering.

Engineering, like law or medicine or teaching, is something that the education system has decided that you do not need to study when you are younger; it is something that you choose later on at college or university.

But while society needs more engineers, as we saw on page 5, there are plenty of people wishing to be doctors or lawyers or teachers at least in most subjects. The supply and demand for other vocational options is more balanced. One possible reason for this is that doctors, lawyers and teachers are more visible to the public through everyday interaction with the public than engineers. They also have more 'heroes', including in soap operas on television!

Engineering, then, presents a specific challenge to the education system.

Our response to this is to seek to understand this challenge and reframe it in ways which may help to move our thinking beyond the perspective of supply and demand.

The argument goes like this.

Engineers think and act in certain distinctive ways. If we had a better understanding of this we could better specify the kinds of teaching and learning experiences which might develop engineer-learners. We refer to these specific ways of thinking and acting as 'habits of mind' and in 3.3 we explore the engineering habits of mind (EHoM) which have emerged in this research through an iterative process involving an academic study of

the literature and conversations with engineering educators and practising engineers.

The knowledge and skills required by certain engineering disciplines are already widely discussed and there are a number of well-regarded specifications of these that form the basis for the accreditation of engineering education programmes. The following are good examples:

UK – Engineering Council UK Standard For Professional Engineering Competence UK-SPEC[25]

Australia – Engineers Australia[26]

Canada – Engineers Canada Core Engineering Competencies 2012[27]

European Higher Education Area (EHEA) – EUR-ACE[28] the framework for the accreditation of engineering degree programmes in the EHEA

But we do not present our EHoM simply as a different way of describing or packaging the engineering curriculum. At the very least we think that how people think and act as they learn is more likely to give us insights into their minds than what they know – their knowledge – or what they can do – their skills. We suggest that, without a good understanding of EHoM on which to ground choices about teaching and learning methods, we should not be surprised that too few pupils choose to study engineering.

There are two other aspects of education which are relevant to engineering here. For engineering is part of a larger cultural problem we face. There is a general perception that as we grow up we should move away from practical learning and become more theoretical and abstract. Schools, like society in a post-Enlightenment world, choose to persist in believing that people who design, make and fix things must be less intelligent than those who can write essays or deliver speeches or understand quadratic equations. The trend in schools is away from practical experimentation towards theoretical abstraction.

While this undervaluing of the practical is a cultural problem, it is also a psychological one. Ever since Jean Piaget's popular theory of child development, it has been assumed that growing out of an interest in the world about us and growing into a world of abstractions is part of a desirable development trajectory in all children as they reach what Piaget described as the 'formal operations' stage[29]. It is a sign of progress in Piagetian thinking to learn in ways which are increasingly more abstract, less applied, less practical, less engineering.

Yet young children are natural born engineers. As they engage with the world around them they are constantly seeking to understand the property of materials. A tower of bricks stands up for a few moments before toppling over and causes a surge of pleasure in the young mind. When the cardboard structure they have made is strong enough to bear the weight of other toys and become a medieval castle, there is the thrill of persistent and successful experimentation. Young children exhibit EHoM in the raw. They are prototype engineers or, if you like, 'homo practicus'.

Importantly, EHoM clearly emerge in young people *prior* to skills and knowledge. They are a more potent guide to the essential characteristics of an engineer than any specification of what engineers need to know or be able to do. Far from educating children out of the very ways of thinking and acting which we want to see much later in their lives, we could decide to ensure that such EHoM are cultivated *throughout* school life, wherever they may occur. Designing, making and tinkering are what children do instinctively. They are also desired outcomes for trained engineers! Turn Piaget's thinking on its head and the system could respond quite differently.

Indeed, proof of the value of EHoM to all learners is provided by the employability record of engineering graduates. Engineers are much in demand in the economy and not just in sectors that have 'engineering' in the title. Because of that pervasiveness, engineers remain in demand even when the economy drifts away from the productive sectors towards the service sectors[30]. Engineers are also in demand with employers in sectors other than engineering, such as finance and banking, including KPMG, who value their systematic problem solving skills[31].

Notwithstanding these challenges there are a few outstanding examples of innovative practices in schools and we have included mini case studies throughout this report as well as providing an overview of the range of approaches to engineering education at primary, secondary, college and university in section 4.

2. Our approach

A person filled with gumption doesn't sit about stewing about things.

He's at the front of the train of his own awareness, watching to see what's up the track and meeting it when it comes.

That's gumption.

Robert Pirsig[32]

2.1 Research methods

We adopted a mixed methods approach for our analysis and its subsequent synthesis of opinions, experiences and theoretical approaches to teaching and learning to produce our model of engineering habits of mind (EHoM). The pragmatic philosophy underpinning mixed methods and its recognition of the value of using data gained from contrasting methods aligned well with the Academy's wish to incorporate multiple perspectives and explore real-world approaches to learning[33]. You might say that a mixed methods approach is the researcher's equivalent of Pirsig's gumption.

Following a literature review through which we developed our initial list of potential EHoM, we carried out semi-structured interviews with ten engineering educators. In order to validate our findings from these interviews and gain further insight into EHoM and effective pedagogies, we established an expert group of individuals whom we brought together on two occasions for seminars held at the London offices of the Academy. We also developed a questionnaire survey that was circulated to a wider group of engineers and engineer educators and completed online.

Our starting point was to undertake a review of the literature relating to habits of mind in engineering, mathematics and science. Our search for examples of case studies in which innovative pedagogies had been used to develop these habits of mind produced limited results so we relied on citation indexing of a few seminal sources to generate further similar references. We also searched key journals including *Engineering Education, International Journal of Engineering Education and European Journal of Engineering Education*.

Much of the literature at primary and secondary education levels that we found originated from the US, and in recognition of the differing nature of schooling between the US and the UK, or even just England, this has been used sparingly throughout our report, mainly to illustrate how things might be.

There is also a very active international community of academics who are publishing articles and conference papers that report innovations in teaching engineering and developing students' skills and competences in higher education. Despite the volume of literature for the HE sector, again, we found limited reference to habits of mind.

The publications section of engineering organisations' websites such as the Academy, EngineeringUK, the Engineering Council and the National Academy of Engineering provided other research and policy papers.

Internet searching and social networking sites such as Quora[34] provided examples of engineering jokes and definitions and led us to many of the websites we cite as examples of interesting practice. Members of our expert panel also provided us with some of their own publications.

We asked the Academy to supply us with a range of engineering educators from whom we selected individuals to be invited to be interviewed. From this list of 28 names we invited 16 individuals to participate in a telephone interview lasting around 35–40 minutes. Eight agreed to be interviewed and a further four provided responses by email. The interviews were recorded and transcribed. Three respondents were familiar with the primary education sector, four with secondary, three with FE and four with HE. Some had knowledge of more than one sector. Eight were male; four were female. The disciplines with which they were familiar included chemical, mechanical and automotive engineering, physics and design and technology. We realise that there are many engineering disciplines, but the scope of this research did not enable us to include the wide range[35].

The aim of the interviews was to explore with respondents the validity of each EHoM with reference to different education sectors and engineering disciplines and also to explore their perceptions of the characteristic ways of thinking used by engineers. Broad, open-ended questions encouraged our respondents to tell their own stories about their path to becoming an engineer or engineer educator and the role of their own education in that process.

We wanted to learn:

1. What encouraged them to become an engineer and what was specific, if anything, about their schooling or background that contributed to them embarking on a career in engineering.
2. What motivated them to become involved in engineering education?
3. What they thought great engineers do and what distinctive habits of mind they characteristically display, especially when confronted with challenging problems.
4. Which three of our six EHoM they thought were most important and which EHoM, if any, they thought were potentially valuable but underdeveloped in our list.
5. Whether they could identify any EHoM that come into play at different stages of an engineering project, or at different stages of an engineer's career.
6. Whether there were other HoM in our mathematics or science lists that they thought should be included in the EHoM list.
7. Whether they agreed with our list of EHoM.
8. Whether they thought that their education sector actually used teaching and learning approaches that cultivated engineering habits of mind.
9. Finally, we wanted to find out if there was anything we had missed that they thought might be useful in our inquiry.

With further advice from the Academy we brought together an expert reference group composed of the individuals who had agreed to be interviewed and a wider group of engineers and engineer educators who expressed interest in contributing to the research. A total of 23 individuals participated in the first session and 12 in the second. In the first session we discussed our EHoM model and invited participants to share examples of effective pedagogies. Since our aim was to value what is already working well in engineering education and build relationships with experienced professionals, we adopted an appreciative inquiry[36] approach to the discussions. In the second session we invited participants to discuss our draft report and help us formulate recommendations based on our findings.

In order to reach a wider audience of engineers we developed a 22-question survey (Appendix 1). The questions were designed to further validate the overall relevance of our six EHoM but also to explore the possibility that different EHoM are more important at different stages of education, at different stages of an engineering project, or at different times in an engineer's career. The questions were piloted by colleagues at the Academy and the final online version was circulated by the Academy to its relevant groups including Visiting Professors, the A Level engineering curriculum review group, the Engineering Professors' Council and members of the E4E initiative, with an open invitation to respond. 43 individual responses were received, which provided us with some additional contacts and further comments used to triangulate with views expressed by interview respondents.

Anonymised quotes from the interviews and the survey are used to illustrate points throughout the report. Quotes from interviews are referred to as Respondent [number] and quotes from the survey are referred to as Survey respondent [number].

The final part of the research involved a matching of known learning and teaching methods used in a wide range of disciplines to our validated EHoM, allied to conceptual development by the research team of a broader pedagogical framework within which these might fit.

2.2. Scope of the research

In terms of time and budget, this was very much a scoping study which, if found to be a helpful contribution to thinking about engineering and engineering education would require more lengthy and in-depth research and development work.

3. Engineering habits of mind

In this report we are exploring the idea that a better understanding of engineering habits of mind or EHoM as we are calling them could lead in turn to more precise specification of the kinds of learning cultures and learning methods which might best cultivate the desired EHoM. So the pedagogies used by teachers in schools, colleges and universities might change to produce more and better engineers and we no longer have to talk of 'shortages'.

Engineering is often described in terms of its close relationship with the disciplines of mathematics and science. It may be particularly helpful, therefore, to learn from experiences in these subjects.

3.1 Mathematical and scientific habits of mind

In the 1980s and 1990s, concerns about the role of science and mathematics in society began to surface. Scientists, mathematicians and educationalists began openly to discuss issues such as:

- the contribution of their subjects to solving important real world problems
- which aspects of their subjects should be taught to which students in schools
- what mathematical or scientific 'literacy' really encompassed
- how much mathematics or science an educated person needed to know
- a mismatch between what scientists and mathematicians actually do and what gets taught in school.

In the case of science, there was also a concern about the negative impact of some scientific inventions. With mathematics the lack of career opportunities for mathematicians and a lack of understanding of mathematical concepts were additional issues.

In many of these topics it is possible to hear echoes of the kinds of concerns aired about engineering and engineering education today. One way of resolving such complex issues was suggested by Al Cuoco and colleagues in a seminal article, *Habits of Mind: An Organising Principle for Mathematics Curricula*[39]. It's worth exploring Cuoco's arguments in some detail as they provide clear lines of thought for our later exploration of EHoM. He starts by distinguishing between real world mathematics and what happens in schools:

> 'For generations, high school students have studied something in school that has been called mathematics, but has very little to do with the way mathematics is created or applied outside of school.' **[page 375]**

This is followed by an explicit refocusing of the desired outcomes of teaching mathematics, that it should be the cultivation of mathematical habits of mind – let's call them MHoM – rather than on precisely which mathematical content is taught.

> 'The goal is not to train large numbers of high school students to be university mathematicians. Rather it is to help high school students learn and adopt the ways that mathematicians think about problems.' **[page 376]**

From here it is an entirely plausible next step to want to identify what the MHoM are as a means of ensuring that more students emerge thinking and acting like real mathematicians. The rapid increase in mathematical knowledge, Cuoco argues, rendered curricula quickly out of date. Teaching mathematics was traditionally more about demonstrating the solution of a problem to students and expecting them to solve problems by substituting one set of numbers for another.

Instead, Cuoco suggests that it would be more useful if the curriculum was built around the habits of mind used by mathematicians when they think about problems and how they set about solving them. While up-to-date content is useful, the tools to use such

> Engineers make stuff and fix stuff.
>
> **Erik Nelson[37]**

> If engineering students are to be prepared to meet the challenges of today and tomorrow, the centre of their education should be professional practice, integrating technical knowledge and skills of practice through a consistent focus on developing the identity and commitment of the professional engineer.
>
> **The Carnegie Foundation for the Advancement of Teaching[38]**

knowledge immediately and in the future are more important.

'A curriculum organized around habits of mind tries to close the gap between what the users and makers of mathematics do and what they say. Such a curriculum lets students in on the process of creating, inventing, conjecturing, and experimenting…' **[page 376]**.

Cuoco identifies a generic set of MHoM, see Figure 2, along with more specific subsets for geometry and algebra.

Cuoco concludes that is possible to design courses that:

'meet the needs of students who will pursue advanced mathematical study, at the same time as serving those who will not go on to advanced mathematical study but who will nevertheless use these ways of thinking in other researchlike domains such as investigative journalism, diagnosis of the ills of a car or a person, and so on.' **[page 401]**

Marshall Gordon, a mathematics teacher at the Park School of Baltimore, draws on Cuoco's thinking today to illustrate how it is possible to design learning experiences that enable students not only to become successful problem solvers, but to think of themselves positively as such, thereby developing greater resilience for mathematics learning. He also demonstrates how students can have the opportunity of constructing, testing and discussing their own conjectures, and so develop their self-confidence as 'doers' of mathematics. By adopting a MHoM approach, Gordon argues that:

'We have to make the inquiry process an integral element of the curriculum content so that the productive practices of a mathematically-inclined mind are made explicit, and promoted as worthy of study.'[40]

In the hands of a skilled teacher, MHoM are not simply an alternative way of presenting the mathematics curriculum. The MHoM are the curriculum. See Example 1.

Over a similar timeframe to our discussions about mathematics there has been parallel thinking about scientific habits of mind or SHoM. In 2007 the Linnaeus Tercentenary Symposium lamented the fact that science education was not contributing to our understanding and solving of

Figure 2 – Mathematical habits of mind

Students who think like mathematicians should be:

Pattern sniffers	Always on the lookout for patterns and the delight to be derived from finding hidden patterns and then using shortcuts arising from them in their daily lives
Experimenters	Performing experiments, playing with problems, performing thought experiments allied to a healthy scepticism for experimental results
Describers	Able to play the maths language game, for example, giving precise descriptions of the steps in a process, inventing notation, convincing others and writing out proofs, questions, opinions and more polished presentations
Tinkerers	Taking ideas apart and putting them back together again
Inventors	Always inventing things – rules for a game, algorithms for doing things, explanations of how things work, or axioms for a mathematical structure
Visualizers	Being able to visualize things that are inherently visual such as working out how many windows there are on the front of a house by imagining them, or using visualization to solve more theoretical tasks
Conjecturers	Making plausible conjectures, initially using data and increasingly using more experimental evidence
Guessers	Using guessing as a research strategy, starting with a possible solution to a problem and working backward to achieve the answer.

Adapted from Cuoco et al 1996

world problems such as how we feed the world's population, ensuring water resources for everyone on the planet, mitigating climate change and the eradicating of disease[42].

And when you look back over thirty years, similar concerns are expressed. Individuals find it difficult to engage in informed discussion about the scientific and technological innovations that are affecting their daily lives – from vaccination programmes, food radiation or nuclear power. They lack the ability to judge whether their lives maybe enriched or harmed by these socio-scientific innovations and are therefore apprehensive about them. Even teachers who might be expected to introduce discussion in their classes about these innovations in order to link science teaching to real-world issues appear reluctant to do so, contributing to a climate of fear about the pace of scientific advances. These issues prompted Muammer Çalik and Richard Coll to explore whether it was possible to teach science in a different way, with an explicit focus on SHoM. As part of their research they evaluated various approaches to the selection and definition of key SHoM, drawing extensively on the work of Colin Gauld[43]. Their selection of SHoM after due examination of the literature, see Figure 3, proved to be reliable and useful as a predictive tool in various areas.

Studies of children's perceptions of science and mathematics education reveal that they find it difficult to engage with these subjects because they seem remote from the world outside school, so researchers at the University of Durham[44] investigated how scientists used their scientific knowledge, see Example 2. By gaining a greater understanding of how scientists set about solving problems in the real world and what knowledge they used, the researchers hoped to identify ways in which science education might be made more interesting for children and also more likely to develop appropriate skills and competencies for the workplace.

A powerful example of what SHoM look like in a young person is given by Craig Leager. Describing the beginning of a science lesson on a Monday morning he writes:

'Alondra bursts into her classroom with an exuberance and energy more typical of a toddler than for a fourth grader returning to school after a long weekend. Without hesitation she scurries over to her teacher and, in her limited English, begins a rapid-fire succession of questioning on every aspect of wetlands. For what seems like ten straight minutes Alondra peppers the teacher with her questions while barely taking time to take breaths between thoughts.'[45]

Example 1: Mathematics at The Park School of Baltimore, Brooklandville, Maryland, US[41]

The Park School of Baltimore is an independent K-12 Grade school providing education for 835 children. Mathematics teachers have written a curriculum for 9th-11th grade secondary level based on mathematical habits of mind.

In a lesson designed to develop the ability to tinker and to play around with numbers and figures, students are presented with problems and encouraged to try possibilities. One such problem is adapted from the puzzle in the film 'Die Hard With A Vengeance' where the characters John McClane and Zeus Carver open a briefcase only to discover that in doing so they have armed a powerful bomb. It will explode in a matter of minutes unless they can disarm it. Inside the briefcase there is a scale. They have at their disposal two jugs – one holds exactly 5 litres and the other holds exactly 3 litres. To disarm the bomb, they have to fill the 5 litre jug with exactly four litres of water and place it on the scale. A few grams too much or too little will detonate the bomb. The water can be obtained from a nearby fountain. How can they disarm the bomb?

This example demonstrates the teachers' belief that learning how to think in mathematics is at least as important as the content.

Figure 3 – Scientific habits of mind

Open-mindedness	Being receptive to new ideas, prepared to consider the possibility that something is true and willing to change ideas in the light of evidence
Scepticism	Using critical questioning, adopting a critical appraisal approach, only according provisional status to claims until proved otherwise
Rationality	Appealing to good reason and logical arguments as well as a need to revise arguments in the light of evidence and argument
Objectivity	Adhering to accepted modes of inquiry in different disciplines and recognising the need to reduce the idiosyncratic contributions of the investigator to a minimum and always looking for peer scrutiny and replication of findings
Mistrust of arguments from authority	Treating arguments sceptically irrespective of the status of the originator
Suspension of belief	Not making immediate judgements if evidence is insufficient
Curiosity	Demonstrating a desire to learn, inquisitiveness and a passion for discovery

Adapted from Çalik and Coll, 2012

Example 2: Developing scientific habits of mind for the real world

Employees within science and engineering companies were interviewed to identify the knowledge and skills they needed to fulfil the requirements of their job. Analysis of descriptions of what they did at work revealed that they used both conceptual understanding, ie knowledge of the science and also procedural understanding, ie knowledge of the processes they used in their work when they applied their scientific knowledge. The employees made extensive use of procedures that required problem-solving, accuracy, selecting the right instrument for the task, observation and noting control variables. However, the employees did not regard these procedures as 'science' but referred to them as 'common sense', and suggested that they were habits they had learnt on the job rather than during their formal science education.

This illustrates the need for science education to more overtly address 'the thinking behind the doing of science' which the researchers identified as a disposition towards collecting valid and reliable evidence. Presenting children with problems and encouraging them to carry out investigations, collect, analyse and interpret their own evidence is an effective way of developing this disposition.

These 'thinking like a scientist' habits of mind are valuable not only for those who leave education and continue into science careers, but also for all adults in enabling them to engage more effectively with scientific innovations affecting their lives.

Alondra is, it would appear, a prototypical scientist demonstrating the SHoM of curiosity in huge measure. Leager writes thoughtfully about how a teacher can respond to her, how he can model scientific behaviours himself in the way he conducts his lessons and, specifically, how he can encourage authentic questioning in an atmosphere of risk-taking. As he puts it: '*a judgment free classroom encourages students to pursue questions open-throttled.*'

What might a young engineer want to tell their teacher about as they rush into a classroom after a holiday weekend? And how might a Year 4 teacher respond in such a way to encourage that student's engineering habits of mind to grow and for others in that classroom to see engineering activity as engaging and worthwhile?

Antonio Dias de Figueiredo has helpfully tried to show the influence of basic sciences, human sciences, design and the crafts.[46]

Each of these four dimensions can be explored in several ways, for example, 'engineer as designer'.[47]

3.2 A broader idea of habits of mind

At the same time as the idea of habits of mind (HoM) were being explored in science and mathematics, the expression was also being used to describe aspects of intelligence more generally. Psychologist Lauren Resnick memorably argued that:

'Intelligence is the habit of persistently trying to understand things and make them function better. Intelligence is working to figure things out, varying strategies until a workable solution is found... One's intelligence is the sum of one's habits of mind.'[48]

In other words not only can individual subject disciplines be viewed through the lens of HoM, but so, too, can intelligence more generally.

Also working in the US, Art Costa and Bena Kallick began to think about how the role of the teacher might change if they were deliberately trying to encourage the kinds of HoM mentioned by Resnick. To do this, they needed to be more precise about what such habits might be. They came up with sixteen HoM[49] see Figure 5 below. Costa and Kallick wanted first of all to describe what human beings do when they behave intelligently in the real world, and then explore the kinds of actions which teachers might take in the classroom as they went about teaching subjects such as the mathematics and science which we have been exploring, but extending this to every subject on the school curriculum. The sixteen HoM are a set of dispositions which, taken together, describe what smart people do as they go about their lives successfully dealing with whatever unexpected problems are thrown at them. These HoM or dispositions provide a map of intelligent behaviour, just as the science curriculum maps the areas of knowledge which a scientist might need to know along with the

Figure 4 – Figueiredo's four dimensions of engineering

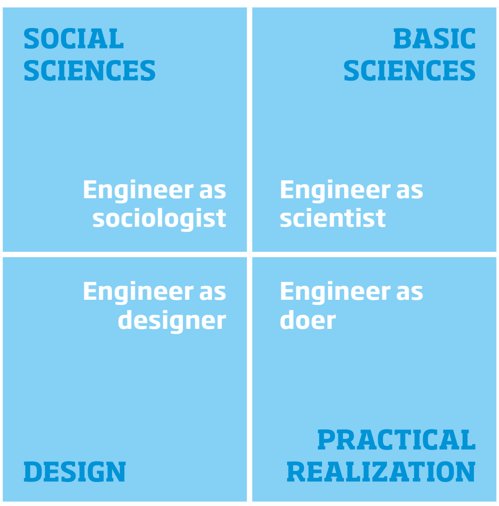


Figure 5 - Sixteen habits of mind

1	Persisting	9	Thinking about thinking meta-cognition
2	Thinking and communicating with clarity and precision	10	Taking responsible risks
3	Managing impulsivity	11	Striving for accuracy
4	Gathering data through all senses	12	Finding humour
5	Listening with understanding and empathy	13	Questioning and posing problems
6	Creating, imagining, innovating	14	Thinking interdependently
7	Thinking flexibly	15	Applying past knowledge to new situations
8	Responding with wonderment and awe	16	Remaining open to continuous learning

Costa and Kallick 2002

understanding and skill which he or she might need to demonstrate.

Costa and Kallick's intention was to encourage schools to see that such dispositions are as valuable as the subject or discipline which provides their context. So, to continue the example of science, it is possible to teach acids and bases while at the same time actively encouraging a learner to persist with the tricky parts of this learning.

Costa and Kallick's HoM are now widely used in the US and in countries across the world[50]. Indeed, in the US, they have specifically been drawn on to consider which HoM might be at the core of engineering, as we will see on see page 23.

At almost exactly the same time, in the UK, Guy Claxton created an approach to teaching and learning called 'Building learning power' (BLP). BLP has seventeen HoM. Claxton terms them 'learning muscles'[51] or, more formally, 'learning dispositions'. The BLP dispositions are listed below in Figure 6. There are four main 'muscle groups', each beginning with the letter 'R' in an acknowledgement of the pervasive influence of the 3Rs of wRiting, Reading and aRithmetic.

Claxton, like Costa and Kallick, is also trying to describe intelligent thought and action but has specifically introduced a related concept, 'learning power'. Learning power is the degree to which any learner can summon up the best learning strategies when learning, especially when meeting situations which are novel. BLP imagines that intelligence is closely related to learning and that the more powerful you become as a learner, the more intelligent you are in whatever context you exercise your learning power.

The BLP approach then considers how a school might go about encouraging children to ask better questions at the same time as studying history. Or they might be helped to make links between, for example, the drafting that they do when writing a poem in English and the development of a series of connected mathematical formulae.

In general education HoM and associated phrases such as 'dispositions for learning' and 'learning attributes' have also been associated strongly with the work of Project Zero at Harvard University[52].

More recently, at the Centre for Real-World Learning (CRL) we have drawn from these three traditions to create and validate an extended model of practical learning which blends habits and frames of mind[53], see Figure 7. Our 4-6-1 model tries to draw a distinction between more general frames of mind such as curiosity, wisdom, reflection, sociability, resourcefulness and determination and what we see as four main 'compartments' of the learner's 'toolkit' – investigation, experimentation, imagination and reasoning. In the middle is what we have called 'presence of mind': the ability and confidence to be able to use any of the ten habits and frames of mind when the occasion demands or suggests it.

Figure 6 – Building learning power – learning dispositions	
Resilience	**Being ready, willing and able to lock on to learning**
Absorption	Flow, the pleasure of being rapt in learning
Managing distractions	Recognising and reducing distractions
Noticing	Really sensing what's out there
Perseverance	Stickability; tolerating the feelings of learning
Resourcefulness	**Being ready, willing and able to learn in different ways**
Questioning	Getting below the surface; playing with situations
Making links	Seeking coherence, relevance and meaning
Imagining	Using the mind's eye as a learning theatre
Reasoning	Thinking rigorously and methodically
Capitalising	Making good use of resources
Reflectiveness	**Being ready, willing and able to become more strategic about learning**
Planning	Working learning out in advance
Revising	Monitoring and adapting along the way
Distilling	Drawing out the lessons from experience
Meta-learning	Understanding learning, and yourself as a learner
Reciprocity	**Being ready, willing and able to learn alone and with others**
Interdependence	Balancing self-reliance and sociability
Collaboration	The skills of learning with others
Empathy and listening	Getting inside others' minds
Imitation	Picking up others' habits and values
Claxton 2002	

Many of the HoM in the outer ring of our model have, in discussions with engineers, proved to be hugely relevant. Members of our expert reference group have told us how they are both important and, in some cases, as in communication and people skills, have been highlighted as significantly absent in too many engineers when they are very much required.

CRL has also focused specifically on the development of creative habits of mind in a piece of research for Creativity, Culture and Education subsequently commissioned as a Working Paper by the OECD[54]. It is included as Figure 8 as it is, in a sense, a proof of concept for taking a broader concept such as engineering and seeking to identify its characteristic HOM.

Within creativity we focused on five broad habits and then broke each down into three 'sub-habits'. So 'imaginative' incorporates 'playing with possibilities', 'making connections and 'using intuition'.

It is no accident that there are considerable areas of overlap between Figures 2, 3, 5, 6, 7 and 8. For there are clearly some important learning 'skills' which are applicable to many areas of life, just as there are some contextual, cultural and epistemological ones which apply particularly to certain disciplines.

Figure 8 illustrates another feature of our own HoM research. It was something which struck the research team as we took the model through field trials with creative 'artists' of all kinds and with teachers who were originally trained in some aspect of creativity. For what they said to us in various different versions was that our 'wheel' somehow captured the heart of what it is to be a creative person. Our creative habits of mind or CHoM encapsulated for teachers more of what it was to be creative than the current art or music or mathematics or design and technology syllabuses were somehow doing. CHoM took them to the essence of an important concept – creativity.

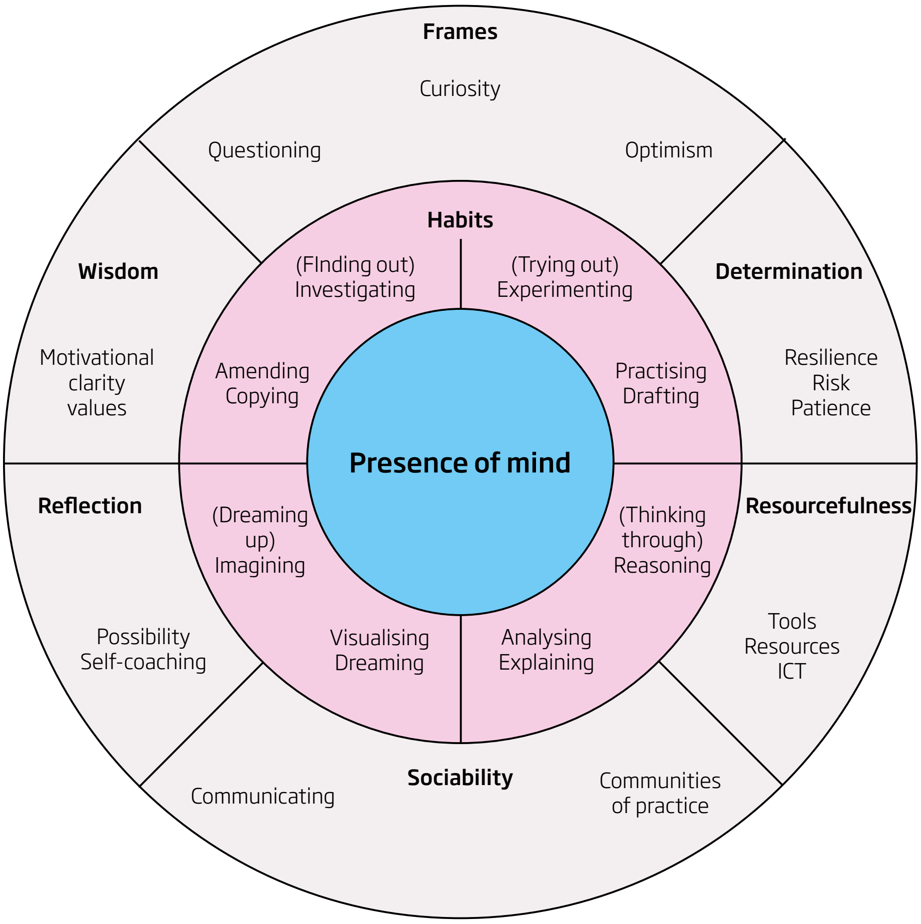


Figure 7 - The Centre for Real-World Learning 4-6-1 model of practical learning

In the interests of 'scientific' objectivity we must report that not everyone agreed with the model! So, for example, some cavilled at the notion of putting 'disciplined' as one of our five habits, arguing that it suggested a mechanistic idea of creativity. Others counter-argued that discipline and pride in craftsmanship were exactly what was required in the development of creative artefacts. But even those who took different views were keen to stress that a HoM-type of approach provoked a much richer conversation than scrutiny of a proposed syllabus which would almost always lead to tedious disagreement.

Could EHoM also similarly reveal the essence of engineering? And even if it were not possible to reach a consensus model of EHoM, would the conversations themselves be a good way of promoting better understanding about engineering, one that could itself also be used at all phases of engineering education?

3.3 Engineering habits of mind

We have already seen that there have been well-researched attempts at developing HoM which can operate at the subject level, at the general level of intelligence or learning and in terms of a broader concepts like 'practical learning' or 'creativity'.

What of the possibility of developing engineering habits of mind EHoM, our first research challenge?

In this section we:

a) describe earlier attempts at articulating EHoM;

b) present the two iterations of a model we have derived from the literature and from conversations with engineers/engineer educators and which has been validated to a considerable extent by an online survey circulated by the Royal Academy of Engineering, and

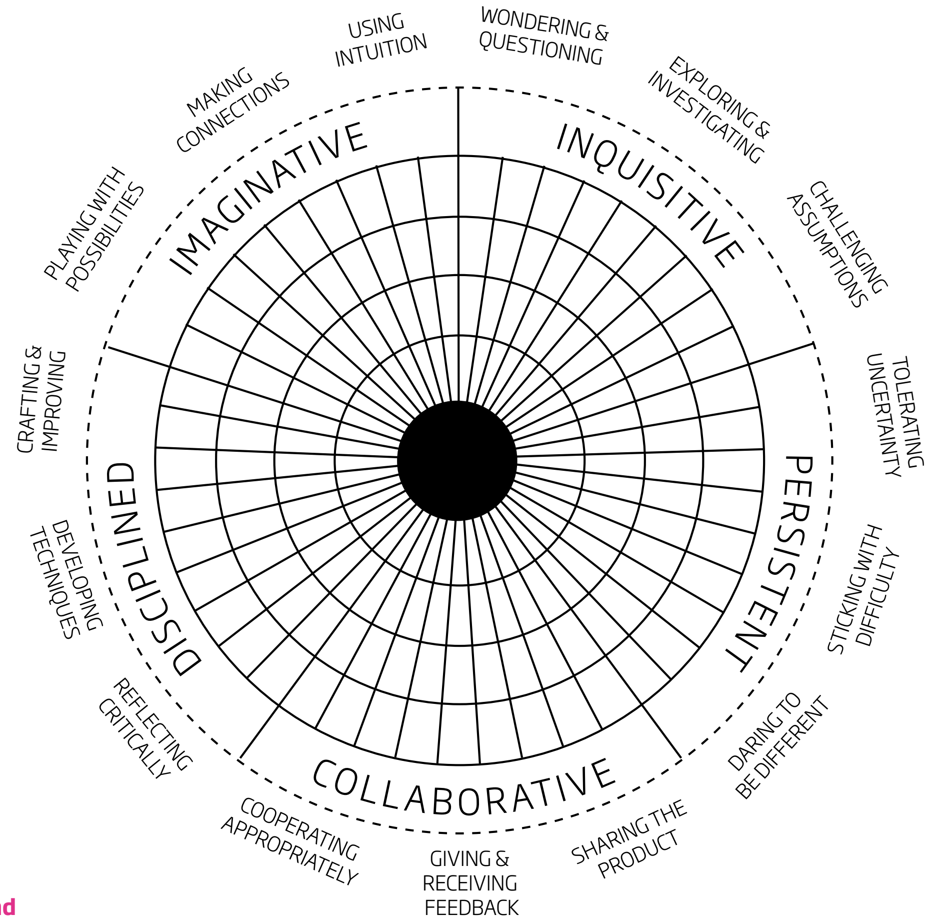


Figure 8 - The Centre for Real-World Learning model of creative habits of mind

c) report on what we have learned from interviews, from an appreciative inquiry session and from ongoing discussions with our reference group.

In the UK, engineering, like creativity, only very rarely appears on the school curriculum. See section 4 for a more in depth description of how it is experienced at primary, secondary, further and higher education.

But in the US this is not the case. Here engineering is now included as a specific subject within the school curriculum at primary and secondary levels. But, just as in the UK, there are many voices airing their dissatisfaction. These are well summarised by the National Academy of Engineering:

In contrast to science, mathematics, and even technology education, all of which have established learning standards and a long history in the K–12 curriculum, the teaching of engineering in elementary and secondary schools is still very much a work in progress, and a number of basic questions remain unanswered. How should engineering be taught in grades K–12? What types of instructional materials and curricula are being used? How does engineering education "interact" with other STEM subjects? In particular, how does K–12 engineering instruction incorporate science, technology, and mathematics concepts, and how are these subjects used to provide a context for exploring engineering concepts? Conversely, how has engineering been used as a context for exploring science, technology, and mathematics concepts? And what impact have various initiatives had? Have they, for instance, improved student achievement in science or mathematics? Have they generated interest among students in pursuing careers in engineering?[55]

A major review of engineering education within K-12 primary and secondary education[56] recently established three principles that should underpin curriculum development in the future. These three principles included:

1) an emphasis on engineering design

2) the incorporation of appropriate mathematics, science, and technology knowledge and skills, and

3) the promotion of six engineering habits of mind.

These six HoM are described in Figure 9 below, along with the brief description that appears with them.

Based on our review of the literature of EHoM, and drawing on others' work in the field of engineering[57] and the contributory disciplines of mathematics and science, we developed the first version of our proposal for discussion with engineers and engineer educators, see Figure 10.

We have also been clear in our discussions with engineers and engineer educators that, as well as the specific EHoM, there are other powerful learning dispositions such as curiosity, optimism, resourcefulness, resilience and reflection, which engineers, like mathematicians and scientists, also need.

But at the heart of our model is the idea that we believe drives engineers of whatever kind – making things that work. Engineers, as the quotation with which we began this section says, like to make stuff and fix stuff. We recognise that here we are referring principally to the traditional engineering disciplines. But as the *Universe of Engineering*[59] recognises, engineers engage in all sorts of activity which may not involve making things. However, even engineers such as chemical engineers or software engineers who do not 'make' physical products as such, are involved in the sub-elements of making such as designing and implementing. It is this extended and inclusive definition of making to which we attach central importance.

Given that, at first sight, an electrical engineer is very different from one who works in agriculture, a civil engineer building a bridge is using very different materials from one exploring the properties of a new chemical compound and that, for example, a term such as sustainability is a very different concept when used by a software engineer or by a civil engineer, we imagined that it would be difficult to reach a consensus on a set of EHoM.

But in fact, the first finding to report from this research is that there was considerable consensus, both in the literature, among all our respondents and from our expert reference group that the six EHoM we had identified were appropriate descriptors for the characteristic ways in which engineers think and act when faced with challenging problems.

Figure 9 – National Academy of Engineering 6 habits of mind

1. Systems thinking	Equipping students to recognize essential interconnections in the technological world and to appreciate that systems may have unexpected effects that cannot be predicted from the behaviour of individual subsystems
2. Creativity	Inherent in the engineering design process
3. Optimism	Offering a world view in which possibilities and opportunities can be found in every challenge and every technology can be improved
4. Collaboration	Reflecting a view of engineering as a team sport, leveraging the perspectives, knowledge, and capabilities of team members to address design challenges
5. Communication	Essential to effective collaboration, to understanding the particular wants and needs of a customer, and to explaining and justifying the final design solution
6. Attention to ethical considerations	Drawing attention to the impacts of engineering on people and the environment, including possible unintended consequences of a technology, the potential disproportionate advantages or disadvantages for certain groups or individuals, and other issues

Adapted from the National Academy of Engineering

Figure 10 – Centre for Real-World Learning engineering habits of mind, version 1	
Systems thinking	Seeing whole systems and parts and how they connect, pattern-sniffing, recognising interdependencies, synthesising
Problem-finding	Clarifying needs, checking existing solutions, investigating contexts, verifying
Visualising	Being able to move from abstract to concrete, manipulating materials, mental rehearsal of physical space and of practical design solutions
Improving	Restlessly trying to make things better by experimenting, designing, sketching, guessing, conjecturing, thought-experimenting, prototyping
Creative problem-solving	Applying techniques from different traditions, generating ideas and solutions with others, generous but rigorous critiquing, seeing engineering as a 'team sport'
Adaptability[58]	Testing, analysing, reflecting, rethinking, changing both in a physical sense and mentally

The three EHoM ranked the most important by our respondents were:

- Creative problem solving
- Visualising, and
- Improving.

Creative problem-solving was in the top 3 ranking of respondents from all sectors. Systems thinking was ranked more strongly by higher education respondents and problem-finding was ranked more strongly by higher education and further education respondents.

Here we describe some of the specific suggestions made by respondents about each of the six candidate EHoM in turn.

Systems thinking

Systems thinking was universally liked. To its more detailed description the addition of 'analysing' was suggested (Respondent 12: 50–51). It was regarded as more important by respondents in higher education than other sectors, referred to as a 'sophisticated' HOM (Respondent 10: 106) and less applicable in the primary sector due to the restrictions of classroom environments and budgets:

'There are restrictions around teaching in the classroom environment especially related to having pupils running off with ideas in all directions and having the physical resources to enable the build' **(Respondent 9: 1)**

Problem-finding

Problem-finding was also regarded as a sophisticated EHoM, more likely to be exercised by experienced engineers or by learners after they had successfully built up a repertoire of approaches to problem-solving based on given problems:

'I want them to solve the problems that I presented and then build up a sort of database on that experience that will help them find problems later on.' **(Respondent 3: 70)**

Some respondents wondered whether 'finding' was the best term, suggesting 'formulating' or 'framing as alternatives. But the majority agreed that separating out problem-finding from problem-solving was important.

Visualising

Visualising was seen as an important EHOM for all education sectors to cultivate, since it enabled an engineer to take an abstract idea and communicate the practical solution in a more concrete form:

'To be able to take something abstract and then make it into a practical solution, you have to have that sort of visualisation to be able to do that.' **(Respondent 4: 38)**

Erik Nelson makes this point strongly when he writes about what makes engineers engineers:

Most of the population of are verbal thinkers, but we are predominantly visual….Not only do we represent physics in our minds, we are able to rotate static objects to understand them better. Our engineering designs live in our minds as spatial objects and we can enter our projects whenever we demand.[60]

Improving

A relentless drive to improve products was regarded as a key characteristic of an engineer. It was the result of constant tinkering and experimenting to find better solutions:

'They are never fully satisfied with a product or outcome and will try and modify and improve what they have designed or produced to make it better.' **(Respondent 2: 34–36)**

However, unlike the joke on page 9, this improvement was not just for the sake of it, the underlying drive was to improve the quality of people's lives, to move society forward:

'It's all about making things easier for people's lives. So whether it's a product that you're making simpler to use, or making something quicker to use … I just think its improving people's lives, improving the quality of life.' **(Respondent 4: 42)**

Creative problem-solving

Problem-solving was regarded as one of the most important EHoM by all respondents, although the use of the preceding adjective 'creative' was questioned by some. Those from the primary education sector rated it very highly, but respondents from other sectors were cautious about using creative to describe problem-solving because engineers could be using concepts that are not original and would therefore not see themselves as being creative:

'Therefore the qualification of problem-solving by the adjective creative in EHOM 5 excludes a lot of engineering work.' **(Respondent 11: 87)**

There were also some who saw the potential for the EHoM creative problem-solving to be in tension with systems thinking:

'This is very often where I do think the systems and the creativity can clash' **(Respondent 4: 60)**

They were concerned that being creative and using systems thinking do not go together. Just as with our earlier work on creative habits of mind on page 20 there is a tension for some people between different kinds of creativity, that which requires disciplined thinking and that which seeks the generation of new ideas.

David Barlex, a member of our expert reference group, helpfully takes Sir Ken Robinson's distinction between big C creativity and small c creativity to tease this out further:

'BIG creativity is the province of those few who make highly significant creations in their fields of endeavour eg Einstein, Brunel, Arkwright. But given the team approach to engineering this highly individualistic approach might not pay dividends. Small creativity are the acts of personal creativity in learning and everyday life that are significant for the individual but in no sense unique.

It seemed to me that the creativity of engineers lies between these two extremes. Very occasionally engineers develop a complete new type of outcome. If we think about designing and building a bridge it is unlikely although not inconceivable that a team of structural engineers will come up with a completely new sort of bridge. Structural engineers will have a general understanding of bridges but the bridges they design and build for particular situations are generally different from one another, although of a well-established type, with the differences related to the nature of the situation in which the bridge has to perform.

The differences are not only concerned with the nature of the terrain but also economic and political environment. So part of the creativity of engineering is developing the specific features *general solutions* to identify the detailed requirements needed to meet particular needs of the context being designed for.'[61]

Our own view is that by attaching creativity to problem-solving we effectively give it the engineering context and that all kinds of creativity are required, big and small, divergent and focused. As a consequence of these kinds of discussions, we have also realised that much of the engineer's world is necessarily about holding a series of tensions in balance, something we explore more on page 27.

Adaptability[62]

Respondents had mixed views about adaptability as an EHoM. Primary educators thought that it was too sophisticated a concept and could only be cultivated after engineers had some experience to draw on to make judgements. However, experienced engineers and those from higher education thought that it was an important HoM:

'Adaptability is very important. I mean a lot of engineering is doing the same things only slightly differently.' **(Respondent 5: 107)**

It was also noted that it was phrased differently to the other EHoM, as a quality rather than an activity and in our later version we have changed it to 'adapting' to bring it in line with the other EHoM.

Several respondents suggested that it was unlikely that all the EHoM would be found in one person and stressed the overall importance of the team in successful engineering projects. It was also recognised that teams had to be adjusted as projects progressed to ensure that individuals with the most appropriate EHoM were available at different stages of the project. These two quotations are illustrative:

'I'm thinking back to my [company name] days, where we would have the big picture engineers and they would have a concept of how a factory layout was going to be and where each machine was going to be. But then the actual nitty gritty of getting those machines working and getting system controls in place, that took somebody who had a degree of logic because they had to work through it one step at a time. So that's where I would see a combination of two different types of engineers to get to the end.' **(Respondent 4: 26)**

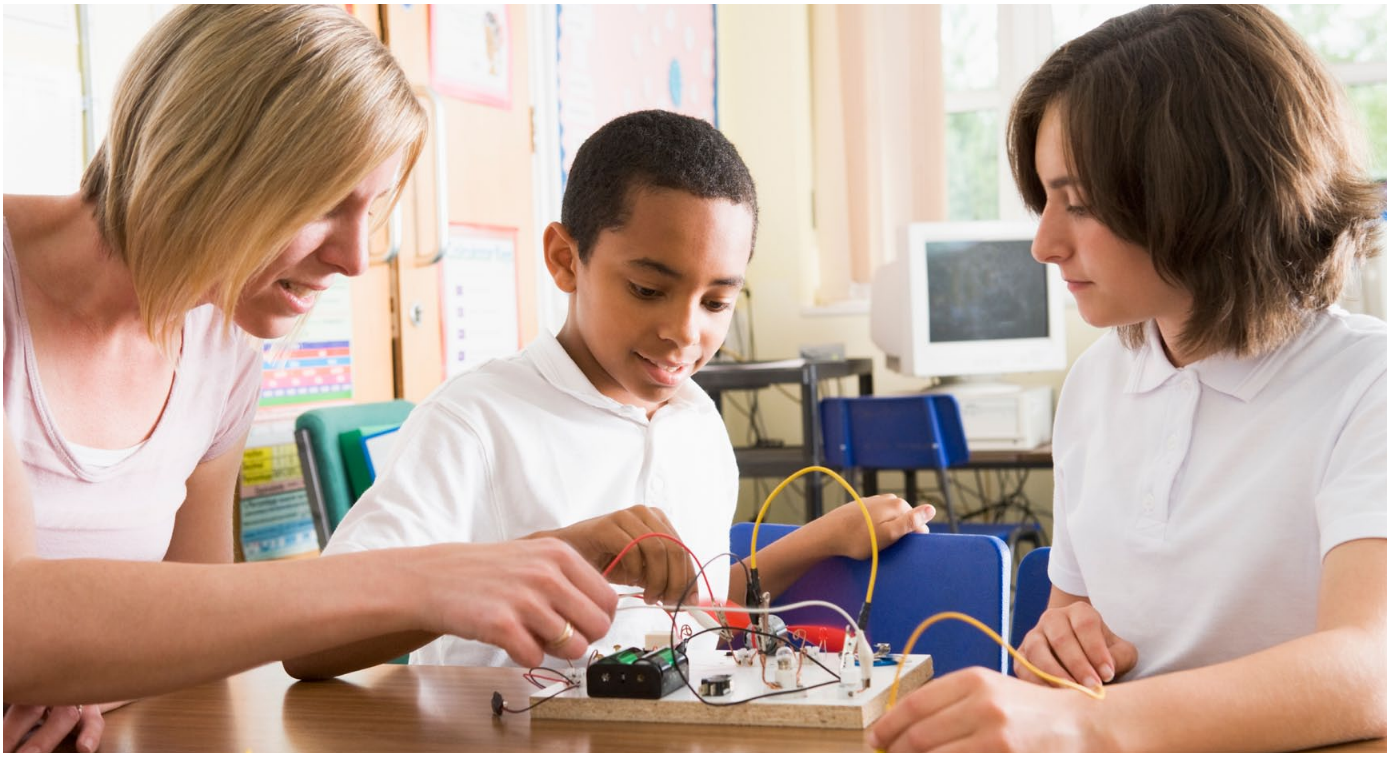
'I think good engineers, certainly in a team, can do that. They can do what they have to do but they can also sort of observe themselves doing it and ask, "Am I using the appropriate skills at the appropriate points in all of this?' **(Respondent 8: 71)**

Some of the phrases used by respondents to describe how engineers think and act suggested to us that some combinations of EHoM might potentially generate tension, for example, between using creativity to invent new ways of doing things and using logic to make things work.

It was also suggested by some of our interviewees that some EHoM might be more relevant at different stages of an engineer's career, for example, both problem-finding and adapting may be habits refined through longer experience in the field. However, on testing this out through the survey, most respondents felt that all EHoM were important at each stage of an engineer's career, from recent graduate to experienced professional.

We also asked respondents to review lists of habits of mind for mathematics and science and identify any of these that should be included within the EHoM list. From the mathematics list, 'pattern-sniffing' and 'conjecturing' were selected. 'Describers' was a term that appealed to those who felt that communication skills needed cultivating within the context of problem solving as a team. Some felt that 'tinkering' was not sufficiently encouraged. From the science list 'curiosity' and 'open-mindedness' were highlighted as being important to engineering.

The outer ring of Figure 11 below includes more general habits of mind derived from our exploration of the literature and our discussions with engineers and engineer educators. We were particularly struck by Sharon Beder's sharp distinction between what engineers used to be associated with – 'short-lived technical knowledge' – and what they now, in her view, need to develop:



The new approach will be more on learning how to learn and less on filling the students with the requisite knowledge.[63]

In this remark, Beder is drawing on an Australian Taskforce on Engineering's recommendation nearly two decades ago that engineers in the second decade of the twenty-first century would need to be better lifelong learners and more adaptable to new learning situations. The habits of mind we include in our outer ring reflect these wider learning attributes – curiosity, open-mindedness, resilience, resourcefulness, collaboration and reflection. They also include a moral component, what we have termed 'ethical consideration' which is an important and commonly included aspect of all professional lives.

The bull's eye emerged strongly at the first session with our expert reference group as being essential in delineating the core of what it is to be an engineer. An earlier version described this core attribute as 'engineering presence of mind – a dynamic tension', building on our earlier more generic model for practical learning in Figure 7.

But the comments from our first reference group meeting persuaded us that, while there are a number of tensions in all engineering work, the essence of engineering is the making of things and processes and that this needs to be at the centre of whatever diagrammatic representation of EHoM we might make. We therefore changed our model. Nevertheless we found there to be common agreement that, especially within the engineering professions, there are engineers, as Iain MacLeod puts, who are able to move between 'two modes of thinking'[64] including:

Creatively different v. Reliably similar

Playing v. Evaluating

Opening up v. Closing down

Synthesis v. Analysis[65]

Systems thinking v. Analytical

Intuitive v. Deductive

Idealistic v. Pragmatic

We were also very drawn to a deeper analysis of candidate EHoM that Iain MacLeod offered. Drawing on work by the Institution of Engineers and Shipbuilders in Scotland, he highlights ten attributes for engineering competence. We have adapted these below:

1. Relentless drive to achieve reliable outcomes – always considering options, the fundamental strategy of all engineers, 'optioneering'; system thinking – exploring whole systems and interdependencies; methodologically literate; a process improver

2. Reflective thinking – exhibiting a healthy scepticism about received and generated information.

3. Flexible thinking – accepting that other people may have better ideas than yours and constantly seeking support from other disciplines if appropriate, seeking/welcoming independent scrutiny and willing to change mind

4. Numerate – motivation and capability to apply scientific methods and apply numerical predictions or measurements to solve problems

5. Confident – always complemented by humility, with confidence coming from the search for reliable outcomes.

6. Environment thinking – consideration of the natural environment, the social environment, sustainability – frequently necessitating multi-disciplinarity.

7. Safety thinking – relentless concern in products and processes – relentless drive to address safety issues for products and processes.

8. Ethical thinking – a fundamental feature of the ethos of professional engineering and a driver of good collaboration and trust.

9. Innovation at the same time as working within known standards – able to distinguish between necessary adherence and generating new approaches.

10. Knowledge/competence seeking – engineers should constantly seek to improve their knowledge and competence within and beyond their areas of expertise.[66]

While we do not use all of MacLeod's vocabulary we hope that the spirit of his words is in our model of EHoM. We have gratefully adopted 'relentlessly' rather than 'restlessly' to describe our specific EHoM – 'Improving'.

MacLeod also suggests that EHoM might be divided into two types, those which are about attitudes and those which are more technical. The literature of change management supports just this kind of distinction and we touch on this on page 47.

David Barlex[67] has helpfully suggested that different stages of an engineering project will call upon different EHoM. So problem-finding will be essential at the start while, for example, more complex aspects of systems thinking may be more relevant further into a project.

We choose to represent our model of EHoM in Figure 11 as series of concentric circles because it allowed us to:

a) distinguish between two sets of habits of mind important to engineers with the more specific ones closer to the middle

b) articulate at its core the driving force of engineering – 'making stuff'.

Unsurprisingly, given what we have already explored about engineers as visual thinkers, no sooner had we broadly agreed the elements of our EHoM than our expert reference group of engineers began to reimagine what any model or aspects of our model might look like. For example, a 'graphic equaliser' image (Figure 12) might be used to plot an individual engineer's EHoM strengths and weaknesses, or to illustrate how different EHoM may be required at different stages of a project.

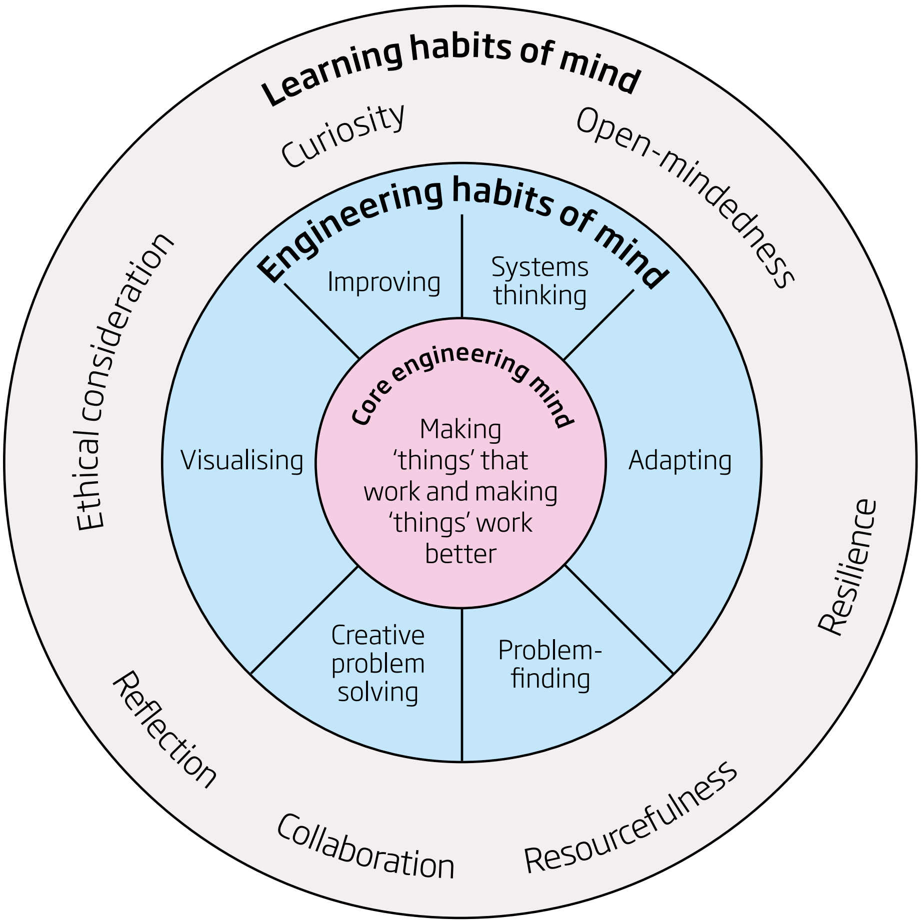


Figure 11 - Centre for Real-World Learning engineering habits of mind, final version

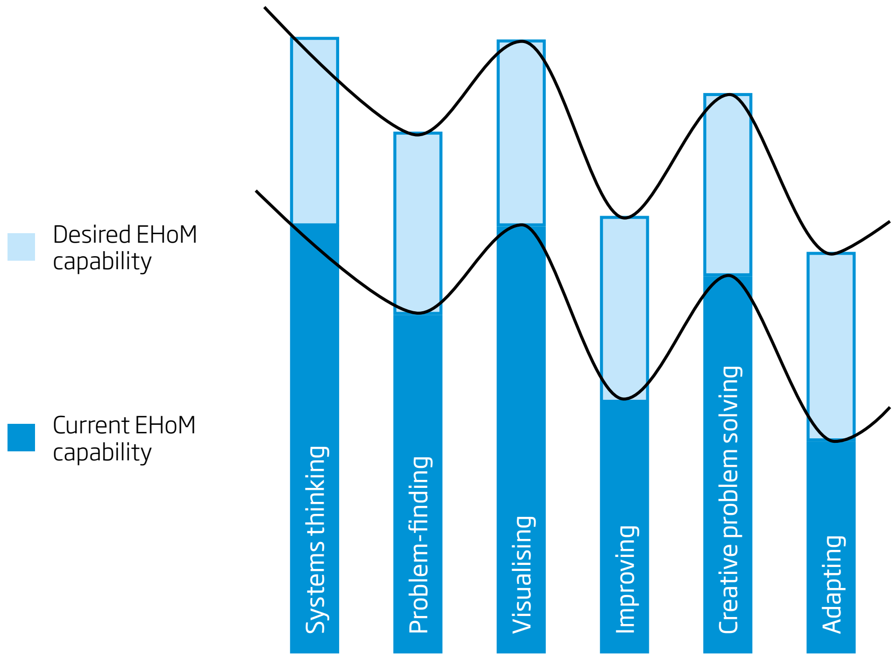


Figure 12 - 'Graphic equaliser' image of engineering habits of mind

4. The state of engineering education today

What are the great engineering challenges facing us today? To what extent is the education system addressing them? To what extent is engineering a topic of public conversation?

Would anyone who is not an engineer and choosing to read this report be able quickly to share a compelling list? We were intrigued to find active debates about this topic in the US. Eugene Meieran came up with a list of twenty-two possible topics[70], of which these are examples – energy conservation, water production and distribution, medicine and prolonging life, security and counter-terrorism, genetics and cloning, global communication, Artificial Intelligence, robotics, preservation of history and preservation of species.

Whether you agree with any, some or all of these topics, our point is simply that they immediately begin to offer compelling answers to the question – 'what's the point of an engineer?' and 'why might I want to become one?'

Talk to young people of secondary age and their impressions of what it is to be an engineer and what will they say? What experiences will have given them their views? Will they have a good impression of the extraordinary range of the fields of engineering? Will they immediately talk about how engineers are playing an important role in helping us to preserve endangered species, to take one example?

Which role models will come to mind? James Dyson, almost certainly? But who else? How young will they be? What gender? By contrast, would a fifteen year old be able to summon up examples of actors, writers, singers, artists, athletes, historians, mathematicians and scientists who exemplify their respective fields? Would they find it easier or more difficult to put names to these kinds of professions or careers?

For many young people their views of engineering will have been largely shaped by their experiences of it as they have grown up. Toddlers of both genders will have played with bricks to make towers and put planks between, say, a chair and a small table, to see if it will bear their weight and not tip them onto the floor. They will have used LEGO® or DUPLO® or any of the many other making games. Toddlers, as we said on page 11, are proto-engineers.

Look at our list of EHoM and you can see this.

Imagine a young child:

Systems thinking – expressing her view that the water which overflows from the bath is like the stream that runs down the hill.

Problem-finding – testing a toy to destruction so that its wheels fall off.

Visualising – making something that looks like whatever they have in mind out of plasticine.

Improving – making a prototype paper glider and gradually changing the angle of its flaps to get it to fly.

Problem-solving – working with friends to make a den out of old boxes and sheets.

Adapting – using a garden seat as an imaginary space rocket launcher.

Still pre-school, they will, perhaps, have had the chance to fix a simple toy that has broken or draw a picture of how they'd like their garden to look or make a space rocket or a car out of paper or make a dam to hold back the sea.

But jump forward to the teenage years and things have changed very rapidly at school with respect to engineering. Most teenagers will have noticed something quite strange. Once they got to primary school all of the fun engineering-type activities we have just listed will gradually have stopped. There may be fleeting sightings

> A significant body of research suggests that despite extensive long-term investments in engaging future engineers, the overall impact has been less than intended.
>
> **Robin Adams and colleagues[68]**

> The problems remain daunting, partially because they are so complex, surrounded by a lack of conceptual clarity, a general confusion about the nature of the engineering enterprise.
>
> **David Goldberg[69]**

of them with adventurous science teachers or in design and technology or as part of a one-off experience.

But increasingly children will learn that 'making stuff' – the heart of what engineers do – is so much less important than knowing stuff or writing about stuff cleverly, that the curriculum will increasingly make engineering invisible.

By the time children become teenagers they will have acquired the justifiable impression that ingestion of large wodges of boring and difficult science and mathematics is going to be required before you can get your hands dirty, engage with interesting practical problem-solving, and be an engineer. These perceptions will be compounded by the current situation which presents engineering as a girl/woman-free zone.

Engineering is about making real things that work and serve a purpose and which, for some but not all engineers, are elegant and aesthetically pleasing and interesting. This involves:

- perceiving and clarifying the need or problem, and/or negotiating a brief with other problem-holders
- investigating carefully contexts, material considerations (pun intended)
- establishing and/or belonging as a good member to teams who design and construct solutions
- generating and evaluating creative solutions in principle
- sketching, model-making, trialling
- designing specs, briefs and overseeing construction
- dealing with clients and costings
- an interest in lifelong enquiry, research, discussion, improvement
- and much more.

All of this can be done in 'junior form' in primary and secondary schools. When we think about how schools can ensure that they are connecting to the essence of what it is to be an engineer – to EHoM if you like – we can see how important it is to have that clear line of sight to the real world of engineering[71]. The satisfaction of designing and building solutions must surely precede and accompany any hard brain-work there needs to be. Yet too often this is not the case.

For young people in the US the Society of Women Engineers does an excellent job in countering what seem to be prevailing views of engineering in England through its website *Engineergirl*.[72] But in England, while there are some outstanding examples of innovative engineering education in all phases, some of which we now describe, the likelihood of a young person leaving formal education imbued with so many exciting engineering-type experiences that they still think and act like the little engineers they were at age three is, sadly, too low.

4.1 Engineering in the curriculum

Engineering as a compulsory subject is not specifically included within the English National Curriculum, although a significant number of schools introduce engineering projects at some stage as vehicles for teaching design and technology, computing, science and mathematics, and for demonstrating the integration between these subjects.

Projects focused on solving an engineering problem like designing a bridge, building a car or launching a rocket can be used to demonstrate the applicability of these subjects to the real world. Bringing 'live' engineers into schools or visiting engineers in their workplace also provide opportunities for children to find out first-hand what the daily work of an engineer involves and to begin to see themselves as engineers in the future.

So where would a primary or secondary teacher who wanted to enthuse their class about engineering in these various ways find inspiration and resources to do this? There are a large number of initiatives available to choose from, ranging from single lesson plans, extended projects, exhibitions and competitions. Here we briefly describe some of the umbrella organisations which provide access to these activities before we look at how some schools have engaged with them.

Tomorrow's Engineers[73] is the principal source for resources, practical activities and challenges aimed at each Key Stage to help schools to incorporate engineering into the curriculum. This programme is supported by EngineeringUK and the Royal Academy of Engineering.

The online STEM Directory[74] supported by the Department for Education (DfE) is another key resource for teachers to locate engineering projects to incorporate into lessons or after-school clubs. The initiatives range from ideas and materials for short, single lesson activities and longer programmes that may be undertaken in collaboration with other schools.

Outside the mainstream curriculum, school-aged children might be introduced to engineering through an after-school club or a competition. Young Engineers[75] provides an important source of support for schools in organising clubs and participating in competitions. Young Engineers manages a network of clubs and promotes high profile engineering competitions such as the Project Eggs Factor, the Young Engineers for Britain and Making Knexions, an initiative designed for secondary schools to link to their primary feeder schools through STEM activities.

As we note on page 32, engineering suffers from an outdated image and is largely hidden from public view, therefore talking to engineers and hearing first-hand about the work they do is an important way of ensuring that children develop a more accurate and current perception about engineering. STEMNET[76] supports the STEM Ambassadors programme through which engineers volunteer to go in to schools. They support teachers in delivering science or mathematics lessons or help with after-school clubs. 90% of all secondary schools engage STEM Ambassadors at least once a year.

An alternative to in-school activity is a visit to engineering companies that open their doors to schools. *See Inside Manufacturing* SIM[77] is supported by the Department for Business, Innovation and Skills (BIS) and has been created to showcase some of the more strategic manufacturing sectors to schools. Companies such as Airbus, BAE Systems, and Rolls-Royce are involved in generating interest in manufacturing careers.

Finally, there are the engineering fairs such as The Big Bang[78], where children can participate in hands-on workshops, talk to scientists and engineers about their jobs and take part in activities such as building bridges with chocolate, testing their speed and strength against athletes or learning about the forces behind rollercoasters.

4.2 Primary education

In January 2013, there were 4.3 million students in English state-funded primary schools[79]. They were most likely to have been introduced to engineering, if at all, through engineering projects in subjects such as D&T, science, mathematics or ICT/computing.

D&T focuses on important tools used by engineers and projects that offer schools a longer exposure to engineering through the D&T curriculum, like those provided by the organisation Primary Engineer[80], make it more likely that EHoM can be introduced and practiced, as in Example 3 at The Redeemer CE School[81].

Other primary schools, such as RA Butler Academy[83], St. Edmund's Catholic Primary School[84] and Shacklewell Primary School[85], have incorporated engineering into their Science Week and have found innovative ways to involve children at all levels and to address cross-curricular themes, not just in science and mathematics but also literacy and history.

Major restrictions on the introduction of engineering at primary level through any subject include teachers' lack of understanding of engineering and their lack of confidence to teach it, which may arise from insufficient training[87]. Nevertheless, for teachers who do want to bring engineering into the curriculum, the activities and projects sourced from the organisations referred to in section 4.1, such as that

Example 3: Primary Engineer and The Redeemer CE Primary School

The Redeemer CE Primary School in Blackburn with 420 pupils from Reception to Year 6 has been working with the organisation Primary Engineer to introduce engineering into its curriculum for six years. Engineering started as an extracurricular activity for a small number of gifted and talented children who attended the local secondary school, Darwin Vale High School, twice a week to use facilities such as laser cutters for their projects. Now, with the support of this secondary school, The Redeemer has incorporated engineering into the curriculum as an extension of D&T for the whole school, including the Reception class.

The children tackle engineering projects using a systems thinking approach that encourages the development of problem solving skills and supports the integration of STEM subjects. This helps children see a purpose for subjects like maths. The 2013 Ofsted inspection rated the school as Outstanding and noted that:

In mathematics, pupils have very well developed calculation skills, including rapid mental recall of number facts. They can use these very successfully to solve problems in a variety of real-life situations[82].

Teams of children from The Redeemer have also been particularly successful in regional and national Primary Engineer competitions.

Some children participate in Primary Engineer's Leaders Award for STEM programme which enables them to interview STEM professionals to find out more about the career pathways of these individuals and the breadth of opportunities in these subject fields. Other children contribute to the science convention at University of Central Lancashire (UCLan) by providing engineering workshops and showcasing their work.

The children's growing familiarity with engineering is then reinforced when they move up to the secondary school that has supported the primary school's engagement with Primary Engineer. The ongoing development of an engineering identity and 'thinking like an engineer' is therefore supported in the children at a time of transition when these dispositions might easily be lost as children aged 11–13 become more vulnerable to stereotyped perceptions of suitable subject choices and careers.

Example 4: RA Butler Academy, Saffron Walden

RA Butler Academy (Infant and Junior Schools) emphasises literature throughout the school. Classes are named after famous children's authors from AA Milne to JK Rowling. So, when they decided to introduce more engineering across the school, they did so using a theme for their Science Week that would reflect their literary traditions. They chose the theme of fairs and circuses and collaborated on a poem that would act as a unifying theme for the children's work.

Reception class children built wind-flowers that danced in the wind (to a design by the Ivydale Science Centre). Year One built a circus arena and filled it with balancing clowns and tumbling acrobats. Year Two built exhibits for the hall of mirrors, including periscopes and kaleidoscopes, along with phenakistoscopes (for viewing in mirrors). Year Three built Ferris wheels and powered them with fans. Year Four built carousels that lifted the cars off the ground the faster they turned, using both electric circuits and clockwork mechanisms. Year Five built electric cars powered by propellers that moved in circles around an arena. Finally Year Six delved into the complexities of parallel circuits and built dodgem cars that moved around an arena with roof and floor covered in kitchen foil.

There was an overall progression of both manipulative skills and scientific concepts. There was also a large amount of cross-curricular work, not only in science and mathematics but also in literacy, history and art. More details from **stevesmyth1@virginmedia.com**.

Example 5: St. Edmund's Catholic Primary School, Tower Hamlets and Shacklewell Primary School, Hackney

St. Edmund's Catholic Primary School in Tower Hamlets has introduced engineering as part of a drive to encourage cooperative and collaborative learning. Children work together in groups in class to produce artefacts that can be used to teach other children about aspects of science. The initiative began as a way of enabling older children teaching younger ones, but has been extended so that even the youngest children in Reception and Nursery classes now build objects. They then explain how they work and what science is involved. Project work is also designed to encourage measuring and estimating skills, appropriate to the mathematics curriculum for the age group.

The projects carried out rely on simple construction methods in card and plastic, with simple mechanisation using low cost motors and components. The project has been run in conjunction with Joined-Up Science[86] with funded by a grant from the Mercers Livery Company.

Similar approaches, also with assistance from Joined-Up Science, have been used at Shacklewell Primary School in Hackney, where Year Five children were given responsibility for constructing an interactive science experience for use by the rest of the school during Science Week.

Example 6: Rocket Factory 1 offered by SPACE4SCHOOLS[88]

Many of the single lesson activities found in the STEM directory use space as a theme to appeal to young children, such as Rocket Factory 1. This is a resource for a lesson in which children design, build, fly and take home their own rocket. SPACE4SCHOOLS bring all the materials needed for the teacher to lead a lesson that integrates science and mathematics, building in learning points related to the mechanics of flight, the design of rockets or materials and their properties. This can be incorporated into Science or Technology subjects in Key Stages 1, 2 or 3.

The children design and build their own rockets which are then taken out for a test flight using a compressed air launcher brought by the organisers.

Both the topic and activity are highly motivating for children of primary age. It involves them in designing and making and encourages them to ask questions. Teachers report greater enthusiasm for science and engineering after the event, which is highly memorable.

in Example 6, can offer a stimulus for sparking children's imagination and setting them on the path to becoming an engineer.

Nevertheless, the single event, however memorable, inevitably limits the possibility of developing EHoM through repeated practice, through making and learning from mistakes or through reflecting on learning.

4.3 Secondary

As children progress to secondary education, engineering becomes a little more obvious in the curriculum. In English secondary schools, engineering provision includes qualifications such as GCSE Engineering, D&T options in engineering, a 14–19 Diploma framework for engineering and A Level in Engineering. There were 3.2 million students in English state funded secondary schools in 2013[89], however, unless they attended an academy specialising in engineering or a University Technical College (UTC), the majority of them would have been unlikely to be offered these engineering qualifications, or experience much involvement in engineering, unless perhaps through the efforts of a committed teacher who introduces it into D&T, science or mathematics or runs an after-school club.

As in primary education, there are some exciting engineering challenges on offer for any secondary school to

Example 7: FIRST® LEGO® League FLL UK[90]

Schools that entered teams to the FIRST® LEGO® League challenge in 2013, entitled *Nature's Fury*, found their students exploring how to engineer solutions to master natural disasters created by storms, earthquakes, waves and other forces of nature. During the *Nature's Fury* challenge teams built, tested, and programmed an autonomous robot using LEGO MINDSTORMS® to solve a set of missions in the robot game. They also had to choose and solve a real-world problem in the project. Throughout their experience, teams were subject to FLL's signature set of core values.

The students were not only challenged to solve very authentic problems but also to consider the impact of these events on people, where they lived and what happens to those who experience these disasters. They also had to behave according to a set of values. These aspects of this engineering experience have the potential to encourage the broader dispositions and attitudes which are essential for the modern engineer and which should influence their thinking as they consider the views of those for whom they are designing and making, and explaining their choices.

Example 8: JCB Academy, Rocester, Staffordshire

The JCB Academy in Staffordshire was the first UTC opened in 2010 offering education to 14-19 year olds. Higher and Advanced Diploma courses are at the core of the programme of study for all students, offering practical, hands-on experience of engineering and business, in addition to English, mathematics and ICT.

The ethos of being in a professional environment is established from the start as the hours are more like business hours than school hours. Students attend from 08.30 to 17.00 and this approach continues throughout their learning experience. Students work in teams tackling engineering and business problems and have one week of work experience placement each year. The curriculum is embedded in real industrial practice involving genuine industrial challenges and developed in partnership with engineering companies such as JCB, Bombardier and Rolls Royce.

JCB students were recently awarded the first Duke of York Awards for Technical Education[95]. The Awards recognise achievements either in GCSEs and level 1 or 2 technical qualifications, or in A Levels and/or level 3 technical qualifications, but they also recognise the completion of work experience placements and the development of wider competences required in the workplace such as communication skills, problem solving and taking responsibility.

Example 9: Ridgewood School, Doncaster

Ridgewood School in Doncaster has academy status and enables 14-19 year olds to pursue a personalised pathway towards an engineering career through a suite of design, technology and engineering qualifications. Engineering is the central element of the curriculum; all students are required to take technology subject. At Key Stage 4 they have three lessons of technology each week and follow one of number pathways including engineering, product design, construction, electronics and systems and control. Engineering is available post-16 through the Edexcel GCE in Engineering.

EHoMs underpin the approach to teaching and learning at all levels of engineering study. The sixth form develops creative problem solving as A Level students work on real-life projects supplied by engineering companies. Students participate in competitions and the school takes a team to Robots USA each year. The school also works with its feeder primary schools to enthuse young children about engineering.

engage in which do specifically aim to develop thinking like an engineer or scientist. Those associated with LEGO® are probably the best known of these, see Example 7.

Despite the undoubted value of challenges like LEGO®, a child's most coherent exposure to engineering at school from the age of 14 is most likely to occur if they attend a specialist academy, a UTC or a Studio School.

There are currently 16 Studio Schools open and a further 28 in development, some of which specialise in engineering[91] but it is in the UTCs that engineering is most likely to be found. Of the 44 UTCs that are open or near completion, 33 have engineering as a specialism[92]. Eventually they will offer opportunities for around 27,000 young people to train as the engineers and scientists of the future.[93]

It is UTCs like the JCB Academy[94] in Staffordshire which currently offer the greatest opportunity for capturing the imagination of future engineers, see Example 8.

Some academies also offer engineering within the design and technology curriculum, for example, Ridgewood School[96] in Doncaster, which has been offering engineering education to its community for over 20 years, see Example 9.

While educational experiences like those at JCB and Ridgewood undoubtedly offer an excellent opportunity to develop all EHoM, it could still be the case that unless they are explicitly articulated to students and consciously modelled by teachers, the full potential to develop the essence of the engineering mindset will still go untapped. It will be interesting to follow the career choices and education routes selected by the students as they leave JCB and Ridgewood and see how long those who enter engineering careers remain in the field.

D&T, together with science and mathematics, has proved to be an excellent vehicle for introducing engineering to large numbers of children through the curriculum, and will continue to do so[97]. The introduction of the National Curriculum 2014 in England now offers promising opportunities for incorporating engineering into the core curriculum particularly in computing at primary and secondary levels. The redrafted computing curriculum for schools will introduce algorithms to children as young as five and programming through to age 16. The Computer Science GCSE will be included in the English Baccalaureate. Rather than focusing on just using hardware and software, a key feature of the new computing curriculum is the concept of 'computational thinking' (CT). This involves concepts and skills at the heart of computing, such as abstraction, decomposition, pattern matching, generalization, inference and algorithm design, which Steve Hunt from the School of Computer Science, University of Hertfordshire, suggests could be applied to all sorts of activities to bring them to life with children at different stages in their school lives.[98]

Low cost resources for schools such as RoB-E are being developed by the Academy to introduce programming and hardware and the low cost computer Rasberry Pi[99] is being bought by thousands of schools. Primary Engineer has already been delivering courses in East Ayshire, Scotland, to train teachers in using CAD/CAM, programming using Raspberry Pi and Scratch Programming and 3D manufacturing using rapid prototyping. A new UK Forum for Computing Education has been formed by the Academy to influence policy and practice across UK governments and schools. [100]

4.4 College

For those who progress beyond compulsory education, but who choose not to go to university, there are a wide range of engineering opportunities offered through FE colleges, apprenticeships or work-based learning.

There are 339 FE colleges in England offering around 2,500 STEM qualifications[101] mainly at levels 2, 3 and 4 in the national qualifications framework. College-based vocational courses that equip students with engineering skills to progress into work as an engineering technician or to further study include BTEC Certificates and Diplomas equivalent to GCE/A levels, NVQ Level 1–3 qualifications, Higher National Certificates or Diplomas or Foundation Degrees. All branches of engineering are covered. 99,740 under-19 year olds participated in a course in engineering and manufacturing technologies at an FE college or other FE provider in 2011/12.[102]

FE colleges also have a mission to provide courses to meet the needs of their local communities, particularly local industry. Employers are closely involved with FE provision, contributing to the curriculum design, providing 'live' project and work placements. Close links with colleges also enhance the employers' apprenticeship schemes and often involve the college in providing bespoke accredited work-based learning programmes for the employer. A recent Ofsted report, however, has noted that, in general, there could be a better match between the colleges' provision and business needs.[103]

Ofsted[104] highlighted features of excellent engineering teaching in colleges that included group work to develop employability skills and projects linked to real-work scenarios that establish a culture of independent learning, however the increasing cost of offering high quality STEM provision and inflexible FE funding regimes has militated against quality provision in the past, particularly in engineering, where the total number of students accommodated is limited by physical space and available equipment[105]. The Government has made a commitment to increasing the quality of vocational skills teaching and is introducing a number of initiatives and funding schemes to enhance it.[106]

It is particularly at this level that the gendered nature of engineering education becomes more obvious, although some colleges, such as Birmingham Metropolitan College[107] are making great efforts to ensure that the interest of female students in engineering is maintained, see Example 10.

Colleges also support employers to deliver apprenticeships and other workplace learning. Apprenticeships are paid jobs that incorporate on- and off-the-job training leading to nationally recognised qualifications. As an employee, apprentices earn as they learn and gain practical skills in the workplace. 13,000 individuals started the engineering framework apprenticeship in the 2011/12 academic year in England[108]. It is at this stage, where young people have made a choice about their career path into engineering technician level that EHoM are perhaps less likely to be found. They know they want to be engineers and this maybe as far as their career aspirations extend, but some employers, like Rolls Royce[109] are determined to ensure that their apprentices develop the habits of lifelong learners that will be essential for updating and reskilling in the future.

Workplace learning covers a broad range of training – from entry level to levels 2 and 3 and other higher-level skills such as leadership and management. This training is mainly delivered through the workplace, but excludes apprenticeships. 57,850 individuals participated in work-based training qualifications in engineering and manufacturing technologies in 2011/12[110].

Many employers understand the importance of supporting the ongoing continuing professional development of their staff but some, like Dstl, have identified that an approach to this training that adopts a holistic approach is essential if employees are going to be able to solve the increasingly complex engineering problems they are going to be faced with in the future. Dstl's development of the 'systems thinker' on which their training programmes are based includes some personal attributes that very similar to EHOM, such as being curious and creative, challenging and responsive[111].

4.5 University

There are many innovative approaches to engineering at university level, some of which we mention here, some in our review of the ways in which pedagogy might be developed to cultivate EHoM. Programmes to foster innovation in university engineering education, such as the National HE STEM Programme 2009–2012 which funded 60 projects in engineering, are beginning to show promise. New curriculum approaches are in evidence, many of which demonstrate how EHoM could be developed in engineering education at this level. The Higher Education Academy (HEA) is sponsoring its third annual HE STEM Conference in 2014[112], offering further encouragement to develop and disseminate good practice.

However, as we have seen, apart from those following the engineering technician career path, most young people are unlikely to be exposed to the idea of engineering as a career until they come to consider entrance to university, providing they have the necessary qualifications in mathematics and science. They are then offered a choice of undergraduate courses in a wide variety of different engineering specialisms. A search under 'engineering' in the UCAS directory of courses located 132 undergraduate degrees, 114 HND, Diploma in Higher Education or Foundation degrees, 18 HNC or certificates and 13 Foundation certificates[113]. These include courses related to the four main engineering disciplines and a host of other sub-disciplines, ranging from acoustics engineering to transport engineering. Many more courses in subjects allied to engineering are offered.

One of the best known teaching and learning methods being used in higher education is the CDIO™ approach to pedagogy. The website which is home to this trademarked approach describes it as:

Example 10: 'Inspiring Tomorrow's Engineers: Young Women in the Know' at Birmingham Metropolitan College BMET

Birmingham Metropolitan College BMET in the West Midlands offers vocational courses and apprenticeships for 16–19 year olds and also offers a programme of undergraduate degrees, higher national diplomas and certificates and foundation degrees in partnership with a number of universities. It attracted acclaim recently for its approach to encouraging female students into engineering.

The 'Inspiring Tomorrow's Engineers: Young Women in the Know' course has been developed by BMET in partnership with Jaguar Land Rover to change outdated perceptions of engineering and encourage more young women to consider engineering and manufacturing careers.

The students, aged 15–18, spend a week touring JLR's manufacturing, design and engineering sites, meet women from all levels of the business to find out about their career experiences and spend a day on work experience with a female mentor.

Example 11: Active Engineering at Aston University[117]

Aston University is committed to an approach to learning and teaching on its engineering courses that it calls 'Active Engineering'. This includes a wide range of learning and teaching methods and styles including problem- and project-based learning, the widespread use of project management and a focus on the development of practical skills to match industry needs. It focuses on building and growing student engagement through challenging project work, along with creating and then exploiting opportunities for multidisciplinary interaction and collaboration.

In Active Engineering, solutions are not all prescribed; learning is adaptive, and in some cases, experimental. Learning is grounded in theory, but is enhanced and internalised through action and experimentation. Active Engineering requires students to work in teams and evidentially learn important skills of communication, collaboration, compromise, challenge, and commitment. A key philosophical driver behind Active Engineering is the CDIO initiative, to which Aston belongs.

The potential for developing EHoM in this learning environment looks very promising.

…an innovative educational framework for producing the next generation of engineers. The framework provides students with an education stressing engineering fundamentals set in the context of conceiving – designing – implementing – operating (CDIO) real-world systems and products. [114]

CDIO's blend is a mix of student projects complemented by internships in industry. It emphasises active group learning experiences in both classrooms and in workshops and laboratories.

A basic CDIO premise is that hands-on experience is a vital foundation on which to base theory and science. To address this, CDIO programs seek to improve the way engineering is taught and learned in four significant ways:

1. They increase active and hands-on learning;
2. They emphasize problem formulation and solution;
3. They thoroughly explore the underlying concepts of the tools and techniques of engineering; and
4. They institute innovative and exciting ways of gathering feedback.[115]

Mark Prince and Gareth Thomson have written a useful case study of the implementation of CDIO at Aston University[116]. On many levels CDIO would seem to be likely to promote EHoM.

The traditional approach to engineering education in universities, a transmission approach focusing on mastering the underpinning science and mathematics basics before attempting problem solving or projects, is slowly changing.

Universities like Aston, Liverpool, Imperial and UCL (University College London) are all providing examples of the teaching and learning approaches that are best suited to developing EHoM.

Providing real world experiences and active learning are expensive, so an initiative to share resources between universities has been developed, the Constructionarium. There would seem to be an opportunity for articulating EHoM more overtly as part of that experience.

4.6 In brief

There are undoubtedly plenty of positive examples of innovative pedagogies that develop EHoM at all levels of engineering education and the statistics are beginning to look more favourable. A Level results for 2013 show there has been a big rise in the number and proportion of young people taking A Levels in mathematics, physics, chemistry and biology and there are more students doing mathematics, further mathematics, physics, chemistry and biology at A Level than ever before – both in terms of number of entries and as a percentage of the cohort[120], which is undoubtedly good news for those offering places to study engineering at undergraduate level.

Furthermore, despite a period of uncertainty about maintaining the number of applications to university, it appears that applications for degree courses in engineering, computer and physical sciences are actually rising, suggesting that these subjects are in demand by applicants[121]. Over the last seven years, the number of acceptances into engineering degrees has increased by over 20% to 25,300 in 2012[122]. So there are signs that the status of STEM subjects and engineering as a career could be on the rise.

Nevertheless, there is also plenty of opportunity to explore how a focus on EHoM might further enhance engineering education.

At primary level, activities like the Rocket Factory 1, or Science Fairs appear to be generating enthusiasm among primary school children for engineering[123]. Pupils participating in STEM Clubs or interacting with STEM Ambassadors report that their attainment in STEM subjects increases and their enthusiasm for STEM careers rises. Feedback received from *See Inside Manufacturing* SIM in 2012[124] was predominantly positive, with 90% of visitors holding more positive views of manufacturing after attending an event.

These initiatives encourage EHoM such as creativity and problem solving, along with more general HoM such as collaboration and resourcefulness. However, as many of the initiatives are single events, there is limited opportunity to explicitly and consistently develop EHoM through repetition and practice over an extended period of time, or to develop the EHoM vocabulary that children need to talk about their learning. The competitions, while clearly highly engaging, may be limiting understanding of the breadth of engineering and its career opportunities, as far as the inevitable losers are concerned[125;126]. It is initiatives like Primary Engineer that take place over a longer timescale that offer greater potential for developing EHoM. One respondent identified how things might be different at primary level:

'children need to be creative by using their knowledge from maths and science teaching and taking a design through numerous situations, the fact that if it doesn't work, you get points for it, it is a major bonus in children understanding that things don't always have to work the first time.' **(Respondent 9: 14)**

The UTCs specialising in engineering education are examples of excellent practice but their numbers are low and their geographical coverage is uneven, thus effectively only providing exposure to engineering to a small minority of children[127]. It was suggested by our respondents that one of the advantages for the UTCs with their focus on engineering was that students realised that they were doing mathematics for a purpose, because:

'they've got to make something, to actually do something for some guy from Rolls Royce.' **(Respondent 6: 26)**

But, for the majority of mainstream secondary education children, access to engineering is again more likely to be through one-off events and competitions, with their inherent limitations for developing EHoM already noted. There is also uncertainty surrounding the impact of these initiatives because very little rigorous evaluation has taken place in order to determine how effective they are in influencing young people to study engineering-related courses or pursue engineering careers[128].

In colleges and universities there are numerous examples of excellent teaching in engineering education[129,130], using, for example, problem/project-based learning with real-world projects supported by employers; active learning that fosters systems thinking and engineering design; peer learning fostering collaboration; or CDIO fostering integration across the engineering curriculum. Any of these approaches have the potential to develop the

Example 12: 'Liverpool Engineer' at the University of Liverpool

The University of Liverpool has launched the 'Liverpool Engineer'. This phrase is intended to encapsulate the special nature of a graduate from any of the programmes offered by its Department of Engineering and provides an engineering education distinctive in the way students engage actively, through design and make, with their learning process. The 'Liverpool Engineer' Degree programmes promote the development of a holistic, systems approach to engineering where technical knowledge and skills are complemented by a sound appreciation of the lifecycle processes involved in engineering and an awareness of the ethical, safety, environmental, economic and social considerations involved in practicing as a professional engineer.

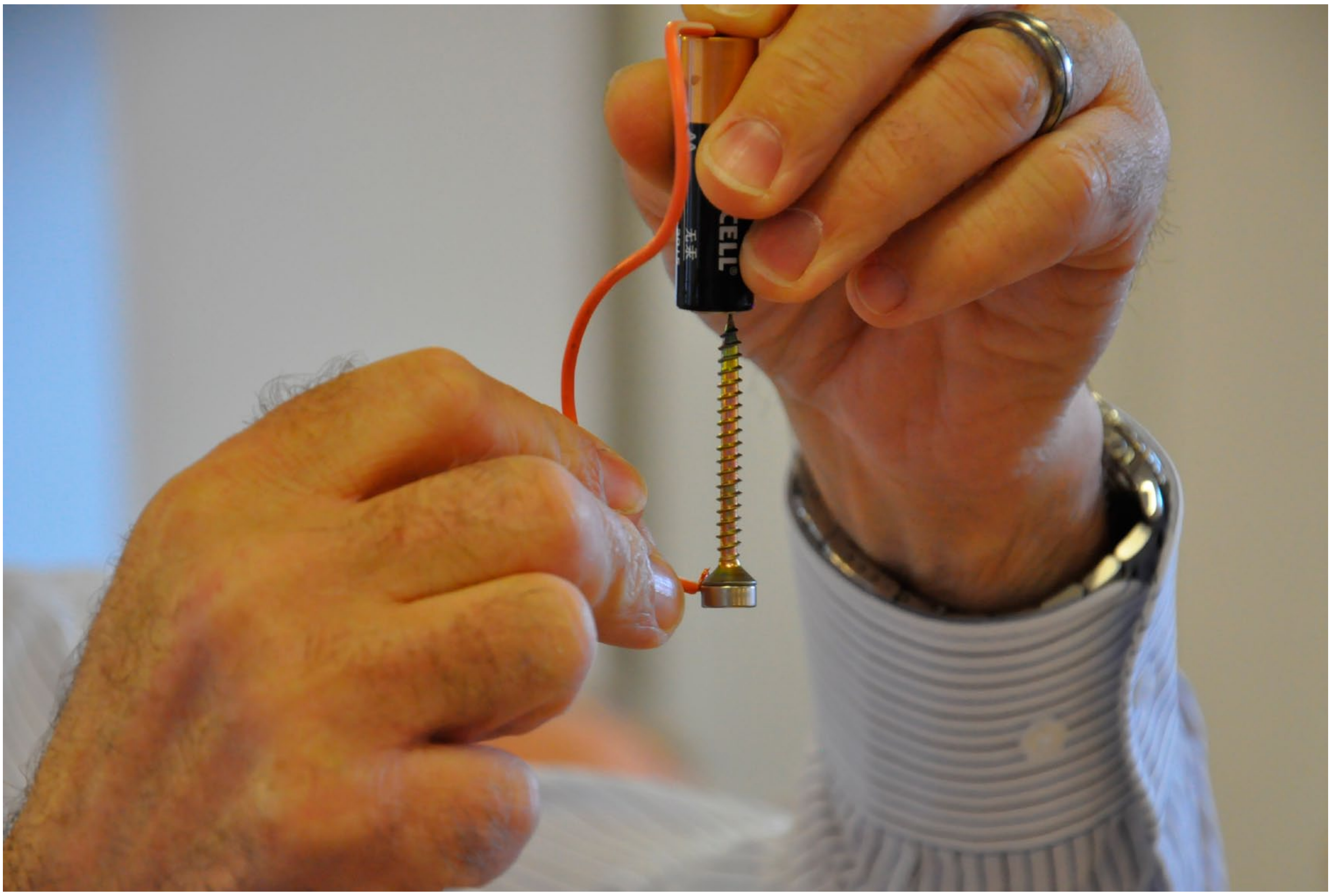
The 'Liverpool Engineer' is defined as: 'a person who is highly adaptable, infinitely resourceful, a good communicator, someone who can work comfortably within a team, and someone who has the perfect blend of theoretical knowledge and practical skills to meet the stiffest challenge'. Second year students participate in the Constructionarium and final year students participate in capstone group projects.

It was interesting to note that the support of two successive Heads of Department was essential to the success of this change process, demonstrating that change in higher education is often a hard won struggle.

Example 13: The Constructionarium[118]

The Constructionarium was pioneered by Imperial College with Expedition Engineering[119] and John Doyle Construction in 2003. It is a hands-on construction experience for students and young professionals. It is where students following civil engineering, built environment or construction management courses learn practically how to establish working links with industry. The basic model provides a learning experience which combines the academic perspective with those of the design professional and practical site delivery. Constructionarium is held as a 6-day working field course. The participants construct scaled down versions of bridges, buildings, dams and civil engineering projects. Students are assessed on the final day in terms of budgetary control, methodology and timely completion. Students from twelve universities participated in 2013.

It offers authentic real-world experience as students work alongside professional engineers.



full range of EHoM. However, even at this level, students are not being systematically exposed to all six EHoM or encouraged to develop an 'engineering mindset'.[131]

The lecture still dominates as a teaching method in higher education and project work does not have 'sufficient disjuncture to cause the learner to exercise reasoning and make judgements' (Survey respondent 3). Projects are still guided too much by the teacher or lecturer and do not encourage problem-finding and improving in particular, as students search for the 'correct answer'. The innovations are often limited to one course or module within a course, rather than having been adopted by the whole department and the departments tend to operate in a silo mentality.

Undergraduate engineering degree courses are still losing students at the end of their first year at a faster rate than other disciplines[132] and there is significant 'leakage' between graduating from an engineering degree and staying in work as an engineer[133]. Furthermore, although in a recent survey of undergraduates currently studying engineering, 80% of respondents were happy with their degree courses, 41% of them said they were already considering alternative careers[134].

It appears that there is still no clear line of sight to engineering from pre-primary to the workplace. Children play at being doctors and nurses; they don't play at being engineers, although as we have said earlier, they are natural engineers when at play. How can EHoM change this?

5. Education to cultivate engineering habits of mind

In the report so far we have suggested that:

- it *is* possible to describe a set of engineering habits of mind with which there is wide agreement
- notwithstanding some beacons of excellence, the teaching of engineering according to engineers, leading engineer educators and consumers does not routinely cultivate the kinds of EHoM we have identified
- engineering education is hugely variable according to the phase of education being considered, with very little, but where it occurs, very innovative teaching going on at primary level and the bulk of engineering education concentrated at further and university level
- engineering education at school can easily give an impression of engineering which is misleading and unattractive
- the methods used to teach engineering where it does appear at school are rarely designed to cultivate the kinds of EHoM we have been discussing
- there is already a clear recognition of the value of authentic, practice-based, experiential learning in engineering courses, especially at further and higher levels.

The idea that engineering education is not fit for purpose is sadly not a new one. Two quotations from some two decades ago are illustrative:

'Most engineering jobs involve design and practice, not theory and research.'[136]

'The typical theoretical science and mathematics-based curricula encourage the analytical approach to problem solving, while system design, integration, and syntheses are what industry needs.'[137]

Both these quotations come from the US, but we could equally have offered similar ones closer to home and from more recent times.

5.1 The implications of EHoM

In this final section we explore the degree to which it might be possible to build on existing global trends in the teaching of engineering by focusing more precisely on the kinds of pedagogical approaches which seem most likely to cultivate learners who might really think and act like engineers.

By pedagogy we mean two things. Formally we have defined it in earlier research for City & Guilds (C&G):

'Pedagogy is the science, art and craft of teaching. Pedagogy also fundamentally includes the decisions which are taken in the creation of the broader learning culture in which the teaching takes place and the values which inform all interactions.'[138]

In practice, pedagogy highlights the fact that teachers need actively to take decisions to seek to deliver the desired outcomes of whatever they are teaching.

This requires them to ensure that the best possible learning methods are selected according to their understanding of the subject matter, the experience of the learners and the resources available to them. Such decisions need to be taken at the strategic level – looking at the blend of methods over the whole course – and at the micro level – when thinking about each lesson or session. Often teachers will also take 'in-the-moment' decisions when learning progresses in ways which they had not expected.

With respect to pedagogy, one of the best explorations of the concept we encountered in our research was an article by John Bowden. In its opening

> I am assuming that useful habits of mind are acquired through repeated exposure to experiences in which they pay dividends. Hence it should be possible to draw up a list of experiences that are suited to repetition without becoming tedious and lead to success in what might be termed engineering-related endeavours.
>
> **David Barlex**[135]

paragraph, Bowden offers some deceptively simple questions with respect to the design of education curricula which are so clear and so strongly indicating an approach which he describes as 'capabilities-driven' which is very close to the 'habits of mind' phrase which we have used throughout this report. We quote them in full here:

1. What should the learner be capable of doing at the end?
2. What kinds of learning experiences and in what combination would best assist the learner to achieve these outcomes?
3. How can the learning environment be best arranged to provide access to these optimal experiences?
4. How can the learning of differing students be catered for?
5. What specifically is the role of teachers in supporting such learning by students?
6. What kinds of assessment of student learning will motivate learning of the kind desired and authentically measure the levels of achievement of the intended learning outcomes?[139]

We have begun to answer 1 from the perspective of an EHoM approach. We now focus on 2 and 5 specifically, with some brief attention to 3 and 4, both of which require a level of exploration which is beyond the focus of this research. The issue of assessment, 6, is hugely important but is completely out of scope. While we have some suggestions to make about the role of formative assessment in general and aspects of this such as feedback, the broader topic needs careful investigation as part of any broader re-appraisal of engineering education.

If you want to educate children to think and act like engineers then it is clear from the line of argument in this report that you might want to start a lot earlier that at age 16 or 19. Specifically, you might want to change the way you teach to adopt pedagogies which explicitly seek to cultivate the kinds of EHoM we have been describing in the last section.

Such a shift in teaching and learning might take three different forms. You could:

1. stand back and contemplate the overall sense of what engineers do and adopt pedagogies which seem, on balance, likely to 'make' engineers
2. look more closely at the six EHoM we have identified and see what educators have found to be most helpful in cultivating each of these in turn
3. approach the challenge from a different perspective by looking at teaching methods which, in other disciplines or subjects or vocational pathways, seem likely to be transferable or useful to teachers wanting to grow engineers.

Let's look at each in turn.

5.2 Signature pedagogies for engineering

There is a concept which may be useful here, 'signature pedagogy'. First coined by Lee Shulman in 2005[140], it refers to 'the types of teaching that organize the fundamental ways in which future practitioners are educated for their new professions'.

'Signature pedagogies make a difference. They form habits of the mind, habits of the heart and habits of the hand. As Erikson observed in the context of nurseries, signature pedagogies prefigure the culture of professional work and provide the early socialisation into the practices and values of a field. Whether in a lecture hall or a lab, in a design studio or a clinical setting, the way we teach will shape how professionals behave…' **[page 59]**

The editors of a recent edition of the *Journal of Management Education* have drawn on Shulman to suggest that, in professional preparation, there are three different apprenticeships taking place at once – cognitive, practical and moral[141]. In other words, as well as mastering a body of knowledge, any professional must also learn how to think, perform and act with integrity in their target discipline.

Shulman holds up a lens to a typical lecture in fluid dynamics in an imaginary engineering school of a university. He describes a teacher only briefly greeting the class before turning to the black or white board on which he furiously writes mathematical equations. All the seats in the lecture room face the front. From time to time the teacher goes through the motions of checking that students are understanding him, but such moments are perfunctory. There is little interaction between students and students and students and the teacher and no reference to the challenges of engineering practice. There is, he suggests, 'little sense of the tension between knowing and doing'; what he is seeing is not the 'signature' of engineering but of one very specific kind of mathematics.

Shulman[142] contrasts the engineering lecture hall with an imaginary design studio in the same institution. Here students gather around work areas with physical models of on-screen designs. They are experimenting and building things, frequently commenting on each other's work. It is not easy to see who the teacher is!

'Instruction and critique are ubiquitous in this setting, and the formal instructor is not the only source for that pedagogy' **[page 54]**.

The second of Shulman's imaginary educational setting is much closer to the 'signature' of an engineering experience which might cultivate the kinds of EHoM we have described earlier.

In seeking to explain the signature pedagogy idea still more precisely Shulman suggests that there are really three levels or structures – 'surface', 'deep' and 'implicit'. At the surface level you might be considering which specific methods – demonstrating, questioning, group working, researching and so on might be most suitable to the aspect of engineering you are seeking to teach. At a deeper level this would also require you to think about the assumptions you have as you use any of the methods just mentioned.

So, for example, you might believe that, only by students experiencing the engineering design process can they become good engineer designers. And in terms of the implicit level there will be a set of beliefs about professional attitudes, values and dispositions which may lead to you take certain ethical and pragmatic positions, for example, on the selection of materials.

We wonder if there are any broad approaches to teaching and learning which might operate on all three levels. A simple if circular answer to this question might be that to learn how to think, act and behave like an engineer you would need to be learning while you were engineering for real.

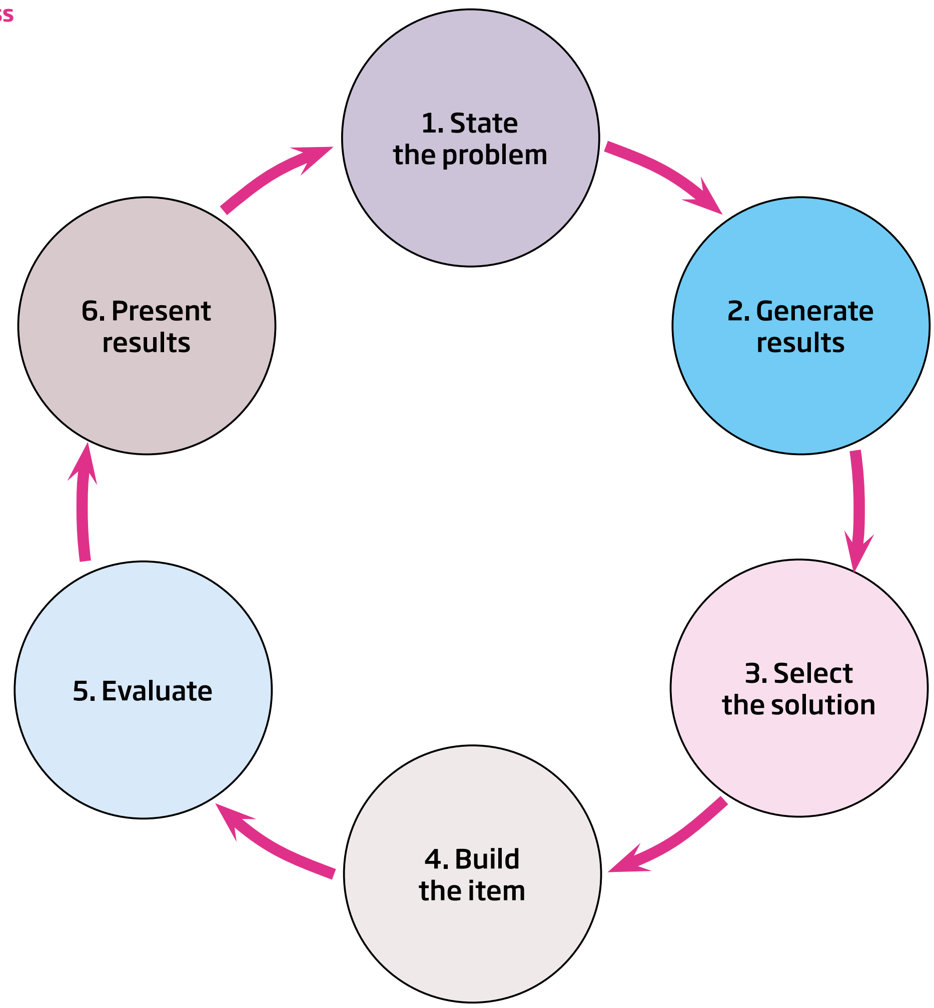
'Going through that problem-solving process, you're constantly looking to see whether you could improve. But then the practical side has to kick in to say, "Okay, you gone about as far as you can, given the budget you've got or the time you've go or whatever, that you really have to, you know, put a lid on it now, and you have to come to some formal conclusion".'
(Respondent 3: 80)

But clearly there are all sorts of practical reasons why this is not practical. But if there were a candidate pedagogical approach it would the engineering design process itself as an organising pedagogical principle. While there are many variations and degrees of complexity inherent in this process, it can nevertheless be easily grasped at all phases of education. In Figure 13, below we share NASA's Elementary school standards-based engineering design process as an exemplar.

While the process has a clarity and circularity, it is not necessarily as straightforward in practice. For allied to the overall process is a concept of 'iteration', that within each of the six stages it may be necessary to redo, to try again, to try differently, tinker, and so on. The engineering design process has been described as 'systematically organised chaos where every step has more than one solution and more than one method'.[144]

Figure 13 - The engineering design process

Source - NASA[143]



Another strong perception we have of the core engineering signature is that 4 – build the item – or as we have termed it in the centre of Figure 11 'making things that work', is core.

When it is expressed as one of six elements of a process, it is possible for its importance to be underestimated and for teachers to translate the model as 5/6 theory 1/6 practice – a great mistake.

For engineers like making stuff, and if we are to be true to this, a signature pedagogy must reflect it strongly.

5.3 Methods likely to cultivate specific EHoM

A second way of looking at this would be to think specifically about which methods might best cultivate our target EHoM.

To ground ourselves here, we asked our expert reference group which EHoM they felt were either under-valued or underdeveloped in education with which they were familiar. Interestingly many spoke of the need to start the development of EHoM early:

'The engineering approach is as much driven by attitude/EHoM as by knowledge. If this is so, then it needs to be a main feature of engineering education. Good attitudes need to start as early as possible. Knowledge assimilation can wait a bit.' **(Respondent 11: 5)**

There were several EHOM which respondents felt were important but undervalued, deserving greater emphasis in engineering education. These included visualising, creative problem-solving and adapting.

Visualising was usefully linked to model making:

'The best ones we have, the best students can not only see things, visualise in different ways, but they've got the motor skills to produce a model – an actual three dimensional one. And although you can do loads of stuff on CAD, the really good ones are the ones who can work out that it can be made and how to actually put the thing together.' **(Respondent 6: 46)**

Creative problem-solving and creativity more generally provoked strong reactions. There were those who thought that developing creative problem solving was the most important EHOM to develop:

'Creative problem-solving is the real standout there. That's my number one'. **(Respondent 10: 78)**

This was predominantly the perspective expressed by those engaged in engineering in primary education. However, those who were responsible for engineering education in post-compulsory education expressed doubts, not about the importance of problem-solving as an EHOM, but about adding the adjective 'creative' to it. These respondents were in no doubt about the importance of creativity in engineering in general terms, because:

'You often have to bring ideas from different disciplines and different divisions to solve the problem'. **(Respondent 1: 50)**

However, there was the possibility that being creative might be in conflict with the requirements to consider previous solutions to problems and to adhere to recognised standards:

'…it is common in engineering to use concepts that are not original. Engineers would not normally think that they were being creative unless at least one of the options involved a new concept. Therefore the qualification of *problem-solving* by the adjective *creative* in EHoM 5 excludes a lot of engineering work.' **(Respondent 11: 87)**

In trying to find a path through this debate, another respondent referred us to the distinction between BIG creativity and small creativity outlined in the *Robinson Report*[145] and suggested that:

'It seemed to me that the creativity of engineers lies between these two extremes…. part of the creativity of engineering is developing the specific features 'general solutions' to identify the detailed requirements needed to meet particular needs of the context being designed for.' **(Respondent 12)**

So, while we have included 'creative' with problem-solving for now, we recognise that further discussion around this EHoM is required, since it clearly raised an important point about engineers' perceptions about engineering:

'I believe engineering to be much more of an "art" than we commonly recognise. Experience and intuition complement scientific knowledge and underpinning. There is quite a contrast to the approach to a problem taken by a competent engineering professional, to that taken by one a "scientist"' **(Survey respondent 40)**

Systems thinking was felt to be particularly difficult to cultivate, perhaps being of most importance the more advanced the level of engineering became:

'The idea that everything you do sort of builds to making you into a rounded, capable person who can link all the knowledge together is the one that perhaps we could work on.' **(Respondent 8: 57)**

There were also some attributes that appear in the outer ring of Figure 11 but may have a specific engineering approach. Reflection is an example of this. A general learning skill reflection also needs to be a core attribute of all professionals, including engineers:

'So at a high level, one of the engineering habits of mind is reflection …. The role of the more specific engineering habits of mind in reflection might be important.' **(Respondent 12: 4)**

How and in what way the concept of design should be incorporated was raised by many. Just as making infuses all EHoM, so, too, does designing.

'I do think it will need unpacking if it is to reveal engineering habits of mind. I also see that there are many professions which would lay claim to design which are not engineering. To overcome this difficulty, I think design must be linked to two other features which would differentiate it from other forms of design. These are systems thinking and utilizing science and mathematics.' **(Respondent 12: 45)**

Respondents identified numerous ways in which the curriculum at all levels was not conducive to developing EHoM; for example, a different approach to doing mathematics was needed, one that offered students 'rich' problems to tackle, not just prompting them to find the right answers. They reported that insight into the professional habits of an engineer was also missing from the curriculum.

Let's now look at each of the six EHoM and suggest some learning methods which seem to work. As with the broader question of a signature pedagogy for engineering where we suggested that the simplest way of cultivating great engineers is to learn engineering for real, similarly with the specific EHoM. The best way to become a systems thinker is to learn systems thinking while doing engineering.

Of course this does not quite work in a 'classroom' setting. Examinations may stress certain aspects which are to be tested. There will be questions about the amount of accompanying theory which will be required and issues of the authenticity of the engineering environment which educational institutions are able to provide.

Nevertheless with engineering, as with many vocational pathways, having a default position to be as real world as possible would seem to be useful. We explore these issues further in the next section on page 53.

Similarly with the cultivation of any new habit there will be three common means by which this can be achieved:

1. by the way teachers model the particular habit and through the language they choose to use
2. by the kinds of teaching and learning methods teachers select allied to the content they select, and
3. by the organisation of the resources – the physical organisation of space, use of tools and social use of other adults, engagement of employers etc.

Systems thinking

We define this EHoM as:

'Seeing whole systems and parts and how they connect, pattern-sniffing, recognising interdependencies, synthesising'.

To understand systems thinking, you have to experience a whole system and see what happens when constituent elements of that system change over time. Interestingly it was Peter Senge[146], an engineer by background, who first comprehensively explored systems thinking as the core element of the way organisations adapt and learn. Senge recently explained systems thinking like this:

'Whenever I'm trying to help people understand what this word 'system' means, I usually start by asking: "Are you a part of a family?" Everybody is a part of a family. "Have you ever seen in a family, people producing consequences in the family, how people act, how people feel, that aren't what anybody intends?' Yes. 'How does that happen?" Well, then people tell their stories and think about it. But that then grounds people in not the jargon of "system" or "systems thinking" but the reality – that we live in webs of interdependence.'[147]

Teachers who are teaching systems thinking talk like this. They move from a whole ocean, city, building, human body to its constituent parts. They notice and point out connections between things.

A famous way of teaching systems thinking at undergraduate level is the 'Beer Game' developed at MIT's Sloan School of Management in the 1960s to teach students how a supply chain works. In the game brewers, distributors, wholesalers and retailers interact attempt to satisfy consumer demand. The game is played in rounds, simulating weeks.

Players have to receive incoming orders, receive incoming deliveries, update play sheets of outstanding deliveries and inventory, send out deliveries, and then decide on the amount to be ordered. Deciding on each round's order amount is effectively the only decision that players are able to make throughout the game. And the point of the game is to demonstrate how a relatively simple system such as brewing and selling beer can easily be disrupted and is, in a very real sense, the sum of its parts.

Games, computer modelling, complex simulations, role playing – anything that enables learners to see at first hand the effects of changes within a system over time – work well in all disciplines of engineering just as they do for management education.

These kinds of approach can be further enhanced and developed when the situation is not merely received and operated by the learners but actively created by them. This might involve learners, for example, undertaking an enquiry to explore a real world problem. The problem, once identified, needs to be explored and then some kind of simulation over time created.

Key tools which may form part of an attempt to cultivate this habit of mind include:

- concept mapping
- behaviour over time graphs
- causal loop diagrams, and
- dynamic feedback systems.

There are many tools available to help teachers, of which the website *ENGINEER? – 101 Ways to Teach Systems Thinking*[148] is an excellent example.

Problem-finding

We define this EHoM as:

Clarifying needs, checking existing solutions, investigating contexts, verifying.

Problem-solving is important but problem-finding is arguably more so. Daniel Pink recently sought to distinguish these two core habits of the engineering mind:

'Problem-solving remains an important skill. No doubt about it. But problem-finding is becoming just as important, if not more so. In purely pragmatic terms, if a customer knows exactly what its problem is, it can probably find the solution on its own. It doesn't need you. But where you're enormously valuable is when the customer doesn't know what its problem is, or is wrong about its problem. There you can make a big difference – by identifying problems the customer doesn't realize that it has, surfacing latent problems, and looking down the road to anticipate problems that haven't yet arrived.'[149]

Problem-finding requires learners to ask questions, to investigate, to check and cross-check. They will need to reframe problems to see if they are dealing with a symptom or an underlying cause.

Teachers who are problem-finders tend to ask questions to which they genuinely do not know the answers. They are comfortable with not having tightly structured tasks to offer their students and happy to live with the uncertainty of not knowing quite which way a project will develop.

The job of the problem-finding teacher is to stimulate curiosity and to create a place of excitement with a range of possible courses of action. Almost inevitably some kind of project-based learning will be important, see page 53 for a fuller description.

An important role for the teacher will be to teach higher order thinking skills so that learners learn how to ask and answer more challenging questions. Lessons in problem-finding are likely to have the teacher acting as facilitator and coach. While there may be whole group teaching, for example where the teacher checks in with the class about key deadlines or introduces a process which may be of use to them all, but predominantly individuals and small groups will navigate their own, interest-led way through some kind of enquiry. One-to-one coaching and challenge sessions with the teacher and other adults may be best use of time. Often the learners themselves will be acting as coaches and teachers to other learners.

Teachers of design – whether in technology or the arts – would recognize these kinds of uncertainties as very much part of the design process. Specific tools and methods will include:

- idea generation
- reframing techniques
- questioning
- researching
- prototyping
- trialling
- team working
- project management.

Ewan McIntosh well encapsulates the shift in teaching practice required for the teaching of problem-finding:

'It takes courage for a teacher to let go of the reins of learning sufficiently to inspire problem finding where the questions are "Non-Googleable." No textbook, teacher or standardized test knows the answer. The teacher's voice is but one of 30, 300 or 3000 guiding, coaxing and coaching through the ether. Yet, this kind of learning surpasses the depth of thinking demanded by many of our more "traditional" modes. Design thinking engenders self-efficacy– the feeling that you can change the world around you, that you can make an impact. In the "real" world, high ambition, tight deadlines and impossible "wicked problems" frame many learning opportunities. So it should be in schools.'[150]

A useful technique in cultivating the problem-finding habit is the use of precisely the kind of 'wicked problems' to which McIntosh refers. A wicked problem is normally defined as:

'a social or cultural problem that is difficult or impossible to solve for as many as four reasons: incomplete or contradictory knowledge, the number of people and opinions involved, the large economic burden, and the interconnected nature of these problems with other problems. Poverty is linked with education, nutrition with poverty, the economy with nutrition, and so on.'[151]

There are many good examples of wicked engineering problems with which students can be excited. A teacher who chooses to start from wicked engineering problems will almost inevitably end up by cultivating students who like problem-finding. At the level of a classroom activity an important shift can be brought about by introducing a thinking routine such as 'see-think-wonder' in learners of all ages.

What do you see?

What do you think about that?

What does it make you wonder?

Thinking routines like this have been pioneered by Project Zero at Harvard[152]. They show how a simple shift in language can signal something larger. David Perkins, also from Project Zero, has undertaken probably the most sustained and thoughtful attempt to anatomise what he calls the 'whole game of learning'. In this kind of learning, problem-finding is the norm. Indeed, unless we are engaged enough to find a problem with which we wish to engage, the topic or approach is clearly not 'whole'. We explore the seven principles Perkins suggests for the design of authentic, real world learning more in the next section on page 57.

Visualising

We define this EHoM as:

Being able to move from abstract to concrete, manipulating materials, mental rehearsal of physical space and of practical design solutions.

Teachers who genuinely themselves use visualisation in their own lives talk in images. They 'translate' the written words into pictures. They offer models, images, cartoons, films and other visual media as well as the spoken word.

They talk aloud what they are picturing as they are grappling with a complex engineering or design work. They sketch and build models. Indeed their classrooms, lecture rooms, studios, workshops are awash with imagery of all kinds. They move from the abstract to the practical and back again with alacrity.

They love nothing more than annotating complex processes graphically or coming up with different visual models for the same concept. It was interesting to the research team to see our expert reference group playing with different visualisations of our suggested EHoM and in doing so they were vividly demonstrating this habit of mind. We included an example of their alternative images on page 29.

Specific methods and techniques that may be helpful include:

- thinking aloud
- mentally rehearsing physical tasks
- modelling
- storyboarding
- using mind maps and other graphic display methods
- using infographics
- using web-based games.

An abstract from a paper describing an attempt to bridge the gap between high-tech engineering practice and low-tech engineering pedagogy, VizClass, is illustrative of this EHoM being consciously cultivated at university level. VizClass is:

'a university classroom environment incorporating a suite of digital whiteboards, a three-dimensional stereoscopic display, and specialized software for engineering visualization. Through observations, interviews, surveys, and examination of student work, we investigated student and teacher attitudes toward VizClass and its effect on teaching and learning processes. Though the project is still under development, initial benefits include increased ability of faculty to visually explain complex problems, increased ability of students to conceptualize engineering problems, and increased engagement of students in after-class collaboration.'[153]

This particular example is high-tech and higher level. But it is easy to imagine a primary environment adopting a similar approach, either high- or low-tech.

Closer to home, opportunities offered by 3D printers for enhancing STEM outcomes in schools are being explored. In England, the Department for Education is funding a project to enable up to 60 teaching schools to purchase 3D printers and use them to train teachers to use them effectively. A report of a pilot involving 21 schools that preceded this initiative found that enabling children to design and then see printed 3D shapes produced from their designs helped them understand the underpinning mathematics and science involved in the design more readily. Seeing tangible results more quickly held the interest of those with poor concentration longer, and also enabled those with greater understanding to improve and adapt their original designs.[154]

Although there is little specific comment in the report about how students' habits of mind were developed, it is easy to see that visualisation, improving and adapting could all be enhanced by the appropriate use of this technology.

However, some of the practicalities, such as the length of time it takes for printing to take place and the need for teachers to learn new technical skills as well as new teaching approaches to take advantage of the technology, mean that 3D printing is not going to change practice immediately.

Improving

We define this EHoM as:

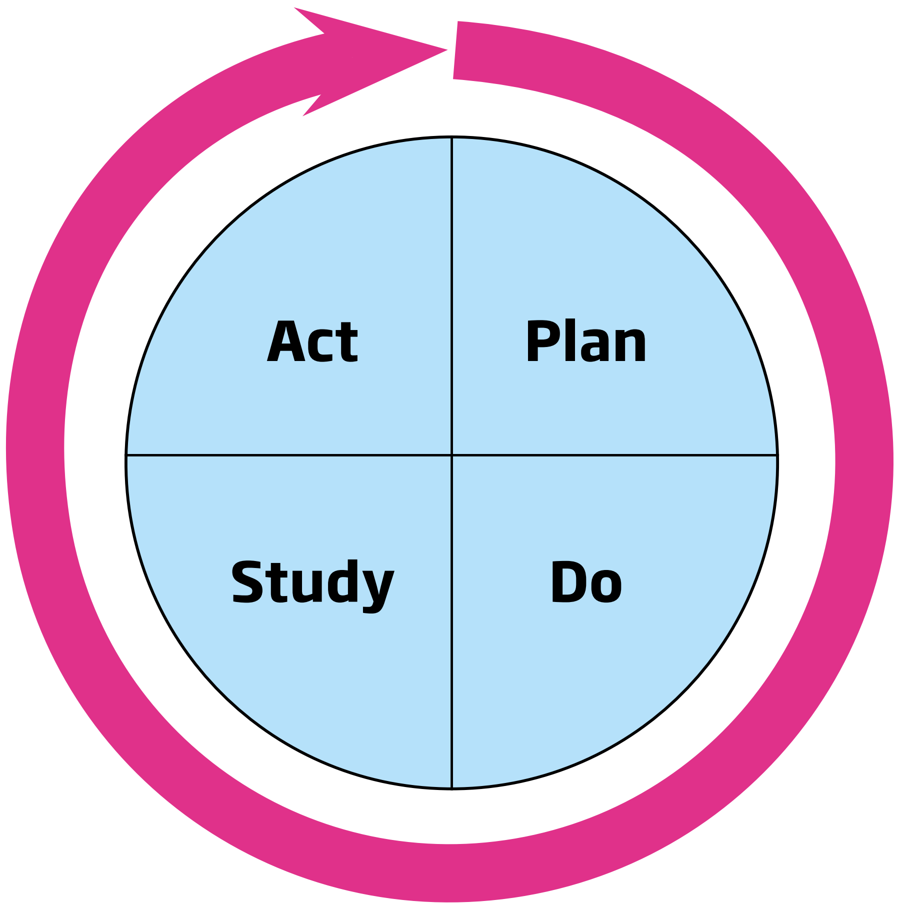
Relentlessly trying to make things better by experimenting, designing, sketching, guessing, conjecturing, thought-experimenting, prototyping

There are two towering figures of the quality improvement movement which swept through many engineering manufacturing businesses during the second half of the last century: W. Edwards Deming and Walter A. Shewhart. Between them and those who have subsequently refined their work, they have defined a process of continuous improvement which fits engineering and engineering temperaments well. Known either as the PDSA cycle plan-do-study-act or PDCA plan-do-check-act, this process lays out four essential ingredients of the improving mind.

For the teacher who really cares about quality, this cycle will hugely inform everything they do. Interestingly Deming, himself a great teacher[155], said that once anyone had grasped his ideas he or she would want to:

- set an example
- be a good listener but not compromise
- continually teach other people, and
- help people to pull away from their current practices and beliefs and

Figure 14 – The quality improvement cycle



> move into the new philosophy without a feeling of guilt about the past.

This could be a description of an engineer educator who is passionate about improving quality. Such teachers will constantly be speculating – how could we improve that? How could I do that differently? They will always be planning small tests of change to see if what they imagine might indeed work. They will be full of questioning – did that work? What has changed? How do we know? Is the change an improvement? Their interest is in the process of designing and making, in prototyping, in testing to destruction, in making mistakes and learning from everything that they do.

In terms of pedagogy there are a number of key current educational thinkers who reinforce these approaches. One whose work is especially significant is Carol Dweck. Dweck's work on what she calls 'growth mindsets' helps us to understand how learning performance improves when learners see themselves set on a journey of improvement. For this to happen, they have to believe that, with sufficient practice, they will be able to learn almost anything. Dweck contrasts growth mindsets with what she terms 'fixed' ones. Growth mindset learners see mistakes as a sign that they are at the edge of their comfort zone and liable to be doing good learning. Those with a fixed mindset think the opposite. They prefer to parade their cleverness and stay within familiar territories.

A powerful way of building the habit of mind of improving quality is to put the focus of all teaching and learning firmly on the processes of learning. This could be on those approaches suggested by the four elements of the quality improvement cycle – planning, hypothesising, analysing, experimenting, reflecting, refining and so on. Or, with a more explicit engineering focus, it might help to focus on the craft of designing and making on analysing every learner's work in progress.

Ron Berger has contributed significantly to our understanding here. He has shown how an ethic of excellence can be promoted through teaching students to see critiquing each other's work as central to the task of producing good high quality work. Sharing work in progress and understanding how to improve it is central to his teaching method. Each of the assignments he sets also assumes an end point where work will be shared by students with outside experts employed in the field of endeavour – an aspect of design and technology. These experts will show by the seriousness with which they approach their task of appreciating the final products how they similarly value quality.

Berger has essentially reframed assessment as an internal lever in students to drive them to take pride in their learning and keep striving to perfect their work:

'Every student walks around with a picture of what is acceptable, what is good enough. Each time he works on something he looks at it and assesses it. Is this good enough? Do I feel comfortable handing this in? Does it meet my standards? Changing assessment at this level should be the most important assessment goal of every school. How do we get inside students' heads and turn up the knob that regulates quality and effort?'[156]

Creative problem-solving

We define this EHoM as:

Applying techniques from different traditions, generating ideas and solutions with others, generous but rigorous critiquing, seeing engineering as a 'team sport'.

Problem-solving is at the heart of the engineering process just as it is at the core of what it is to survive and thrive as a member of the human race! At the start of section 3 we described what we referred to as the young proto-engineer, the child endlessly trying to solve the problems of its environment, walking without falling over, working out how to get up and down stairs, making towers of blocks that stand up and so forth. This is the driving force that drives engineers to want to diagnose, fix, take apart, reorganise and make things. It is the same force that makes human beings the tool creators and inventors which has driven the evolution of civilisation.

Indeed for many engineers problem-solving is synonymous with the engineering design process which we introduced on page 44. The problem solving cycle below is a typical representation of this kind of approach as used in higher education.[157]

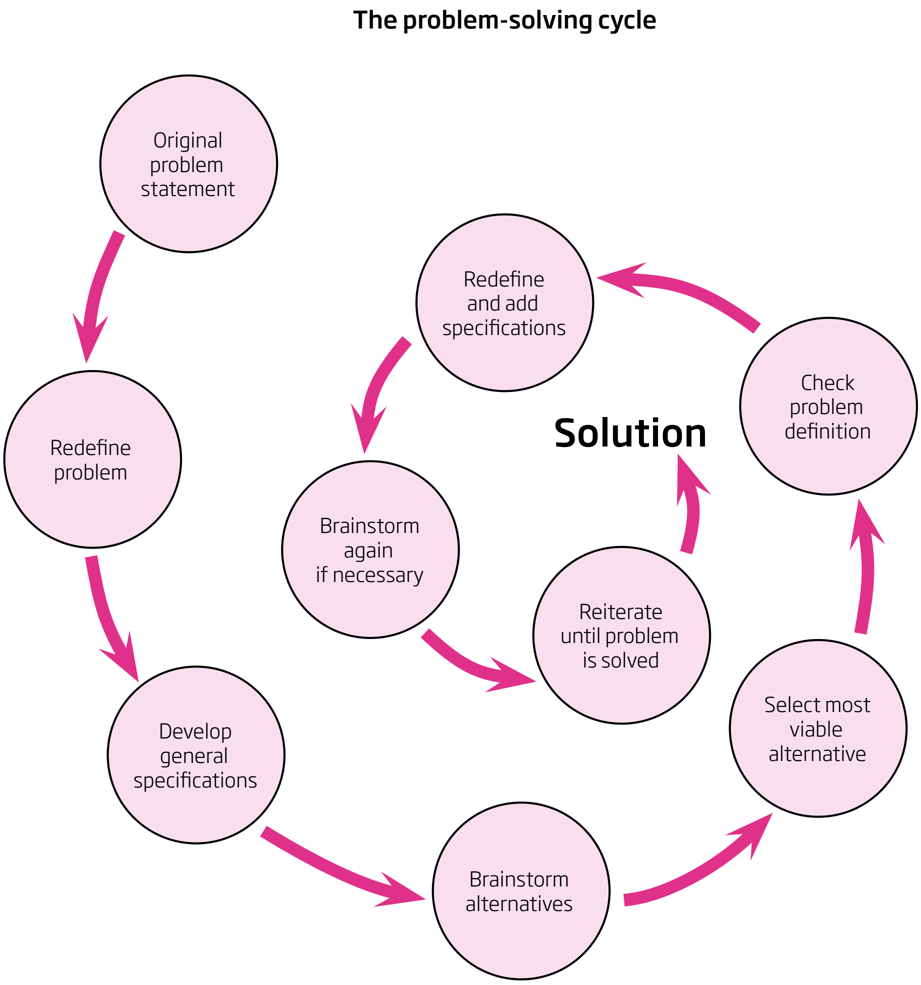
Perhaps precisely because problem-solving is so core to engineering it is important to consider what really good problem-solving looks like and also in our context to see how this habit of mind might be different with the addition of the word 'creative' in front of it.

In research we undertook for C&G into vocational pedagogy, we concluded that problem-solving was an essential element of all vocational education if students were to acquire both reliable expertise and the attendant resourcefulness of the real world of work:

'The evidence is clear that vocational education needs to be taught in the context of practical problem-solving and that high-quality vocational education almost always involves a blend of methods. The best vocational education learning is broadly hands-on, practical, experiential, real-world as well as, and often at the same time as, something which involves feedback, questioning, application and reflection and, when required, theoretical models and explanations.'[158]

One of the best known versions is 'problem-based learning' (PBL), an enquiry-based approach to problem solving that grew out of medical education. It was initially developed out of concerns that, while medical training provided a theoretical grounding in aspects of medicine, it was not good at preparing good nurses and doctors. Problem-based learning seems to be a much better way of preparing medics although we should add a note of caution. A meta-analysis of the effectiveness of PBL showed that PBL was superior when it comes to long-term retention, skill development and satisfaction of students and teachers,

Figure 15 - A typical engineering problem-solving cycle



but traditional approaches were more effective for short-term retention as measured by standardised tests.[159]

A focus on PBL helpfully forces us to consider a key question – what is the optimal blend of theory and practice in any vocational learning and what do we know with regard to engineering education? Or put pedagogically, when is it helpful for learners to have to figure it out for themselves and work out why something happens in the way that it does empirically, when more optimal for an experienced educator to either give them the 'answers' or provide a theoretical framework beforehand.

Real-world problem-solving is at the heart of what is referred to as constructivist approaches to learning as to opposed to more didactic approaches. John Savery and Thomas Duffy usefully summarise these to include:

- the creation of authentic tasks which are anchored to the real world
- high levels of ownership by learners of the tasks they undertake
- learning environments which support and challenge learners' thinking, and
- opportunities for learners to take responsibility as they develop alternative ideas and strategies.[160]

In their thinking about workplace learning, Lorna Unwin and Alison Fuller have helpfully introduced the notion of the 'expansive apprenticeship'. This idea is a development of Yrgö Engeström's ideas regarding the tension between expansive pro-learning and restrictive learning environments. A restrictive apprenticeship is found where organisations want to 'produce' workers as quickly and cheaply as possible. Naturally this does not facilitate the learner to enquire and reflect and may be relevant specifically to engineering apprenticeships.

To develop real-world problem-solving abilities in learners, they need to be given more 'expansive' experiences in order to be able to contribute to business success and to develop worthwhile careers. Fuller and Unwin propose that we must take into account the:

'dual identity of worker and learner, and commit themselves to a model of apprenticeship that has pedagogic, social and economic value.'[161]

A recent investigation of Project-based learning (PjBL) in engineering in UK universities by Ruth Graham[162] cites Newcastle University, Queen Mary University of London, University of Sheffield, University of Manchester, Sheffield Hallam University and University College London (UCL) as examples of engineering schools that have given over part or all of their undergraduate teaching and learning to PjBL.

Graham identifies four broad kinds of PjBL

1. 'Icebreaker' competitions:
Full-time immersive group projects in the induction week/s for new students of the *School of Engineering Science* at the University of Southampton and the 'two week creations' in the *Department of Engineering* at the University of Liverpool.

2. Partnerships with real ongoing constructions:
Final year civil engineering projects where student groups work on large-scale design projects that mirror real local developments, with strong input from the construction company involved, for example, the capstone *Interdisciplinary Group Project* at Liverpool University.

3. Entrepreneurship and product design:
Capstone group projects for students to design an innovative product and develop an associated business plan for taking the product to market. Students tend to be required to deliver an 'elevator pitch' of their ideas to an external industry panel. *Marketing and Business Planning* module at Queen's University Belfast and the *Technology Strategy and Business Planning* module at the University of Sheffield.

4. Video production and showcasing:
Introductory modules where student groups design, produce and showcase a short video providing insight into a

technical engineering subject area. For example, *Civil Engineering* at Imperial College London produced and showcased short videos on London architecture.[163]

The four kinds of ideas listed above are indicative only. While they are drawn from the world of higher education, there is no reason why the approaches they espouse could not be adapted at any phase of education.

Iain MacLeod is clear that we need more PjBL:

'To achieve a twenty-first century standard of engineering the use of much greater proportion of project learning than in traditional curricula is essential.'[164]

Thomas Litzinger and colleagues are similarly perplexed that there is not a more widespread take-up of these kinds of methods:

'Why, when compelling evidence exists for the effectiveness of methods such as peer learning and inquiry-based learning in science education, have such methods not seen greater adoption in engineering?'[165]

Adapting

We define this EHoM as:

Testing, analysing, reflecting, rethinking, changing both in a physical sense and in mentally.

Adapting works in two interesting ways. On the one hand it is what engineers have to do mentally – constantly being prepared to rethink, reframe, reconsider, reinterpret, review, and respond to situations in which they find themselves. On the other it speaks to the physical materials with which many engineers work. They seek to adapt these, combining and recombining, shaping and reshaping to make their desired products.

One is technical, requiring a mind capable of selecting and deploying different tools or approaches. The other is more personal and to do with mindset shift. It requires emotional intelligence, especially when one person's change of mind requires another either completely to rethink their own positions or to try a different route. Engineers like most professionals tend to find the first of these easier.

We should not be surprised by this. Ronal Heifetz has helpfully shown how there are two kinds of change which he calls 'technical' and 'adaptive' challenges[166]. Technical change, the first one, is easier. The skills necessary to perform it are normally known but being applied in a new context. Adaptive changes are harder.

'They can only be met by transforming your mindset, by advancing to a more sophisticated stage of mental development.'[167]

Specific methods and techniques that may be helpful include:

- Reframing
- SWOT and PEST analysis
- Force field analysis
- Gap analysis
- Appreciative inquiry.

One important kind of adapting takes place whenever an engineer is required to put a skill learned in one context into use in another. This could be across the engineering disciplines, say from electrical to mechanical, or from engineering into another discipline with which the engineer is working, for example, ecology. This kind of adaptation is known as learning transfer.

Transfer of learning is, in a sense, the ultimate aim of all teaching. If something learned in one context can be applied and reused in another context, then the learning has truly become useful. We know, from the work of David Perkins and Gavriel Salomon that transfer is assisted by:

- extensive practice in different contexts
- the provision of clear models, explanations and mental models at the point of first learning a new skill
- specifically encouraging learners to consider how they might use what they are learning in other contexts at the point when they first learn something

- making as many connections as possible to the learner's *existing* knowledge.[168]

If those teaching engineers are aware that, whatever method they select, the principles above can infuse all that they do, transfer may happen more effectively.

5.4 Vocational learning methods that work

Thus far we have looked at some signature pedagogies for engineering and explored some of the methods which seem suited to develop each of our six EHoM. Now we look at teaching methods which, in other disciplines or subjects or vocational pathways, seem likely to be useful to teachers wanting to grow engineers.

In an earlier piece of research for C&G, *How to teach vocational education: a theory of vocational pedagogy*[169], we identified a list of vocational methods which work in a number of different contexts and we list these below in Figure 16.

Many items on the list above have been touched upon in the previous two sections although not always specifically mentioned as discrete methods. Each of them has a place at some stage in the education of engineers.

In the process of our research, we encountered five additional methods widely used in engineering education. While these can also be used in other vocational areas we found them to have a specific engineering 'spin' on them which makes them noteworthy. The methods are:

- Modelling and virtual modelling
- Using case studies
- Industry mentoring
- Using capstones
- Flipped classroom

We offer short descriptions of each in turn.

Modelling and virtual modelling
A form of simulation, modelling is particularly important to engineers who are trying to understand complex adaptive systems. Modelling and simulation have become important tools for the engineer to save time and

Figure 16 – Vocational learning methods
Learning by watching and imitating
Learning by practising
Learning through feedback
Learning by being coached
Learning through conversation
Learning by teaching and helping
Learning by real-world problem-solving and enquiry
Learning by thinking critically
Learning by listening, transcribing and remembering
Learning by drafting and sketching
Learning by reflecting
Learning on the fly
Learning by competing
Learning through virtual environments
Learning through simulation and role play
Learning through games

reduce costs when developing and testing prototypes. Computer modelling is used to create a software prototype of the object to be constructed, bridge, car etc. and a simulation is run with the prototype of the real model to test it under various external conditions to see how it would react in real life[170].

Using case studies

A kind of problem-based learning, case studies are normally stories of engineering problems and challenges that are taken from the real world. They are frequently open-ended with no right answer. They might, for example, give an account of a problem or design challenge with multiple ethical or technical issues. The case provides a close to real-world opportunity for trainees to apply the knowledge they are learning on their engineering course.

Industry mentoring

Mentoring by engineers in industry can be valuable for enabling students to gain greater insight into the workplace. Sheffield Hallam University's Careers Service has organised a Career Mentoring Scheme[171] for undergraduate engineering and mathematics students that aimed to enable students to research career opportunities, create a network of contacts and generally enhance their employability skills. It can also help students understand how the engineering knowledge and skills that they are gaining through their degree are applied in industry.

Using capstones

A capstone experience is a kind of extended project, normally located towards the end of a period of learning. It seeks to offer opportunities to apply and synthesise the range of learning which has preceded it. It might be a project, an enquiry, a presentation of work undertaken, a critical exploration of the learning processes undergone during a piece of engineering and so on, designed to prepare students for professional practice[172]. Examples include 'Formula Student', a multi-disciplinary project run by the University of Liverpool's Mechanical Engineering section in which students design, build, test and race a fully functional racing car at an international competition.[173]

Flipped classroom

Problem-based and project-based learning approaches have been aligned with digital technologies to offer an approach known as the 'flipped classroom' that we think provides significant opportunities to develop EHoM[174]. This is a teaching method in which students interact with assigned readings and pre-recorded learning materials, usually videos or screencasts, outside the classroom but normally through a virtual learning environment (VLE) and then participate in group activities within the classroom. Rather than using the class time to impart information, teachers have more time within the classroom to promote group problem solving activities or scaffold student learning using formative feedback and offer more personalised support for those who are struggling. This use of technology to support learning gives students more control over their own learning and also facilitates a greater degree of interactivity between teacher and students. Teachers can create their own resources to flip their classroom or use those available from sources such as Khan Academy[175]. Further studies are underway into the applicability of flipped learning in engineering in universities[176] and at secondary school level[177].

Of course any kind of vocational teaching, especially that which is trying to cultivate our proposed EHoM, is likely to involve a complex blend of approaches suited to student needs and available resources. Nancy Hoffman puts this well:

'[The challenge for vocational teaching and learning professionals is] to build curriculum and assessments that replicate the uncertain, messy, problem-based, people intense, and time limited world of work.'[178]

Of all the approaches to pedagogy we have encountered, the one created by David Perkins seems both thoroughly grounded in the literature and accessible. In a metaphor which could have been chosen with engineers in mind Perkins explores the ways in which educators can make learning whole[179]. He offers seven principles which seem well-suited to both learners and teachers in the real world of engineering education. In Figure 17 below we list these with minor adaptations as we think of engineering.

5.5 Challenging the system

When all is said and done, there is a growing consensus about good practices in engineering pedagogy and these are alive and well in many universities and some colleges. These methods by and large are well-suited to the cultivation of EHoM.

But sadly they hardly exist at all at secondary level and are virtually invisible at primary.

Each educational phase provides different challenges. But it is the two school phases on which we believe the focus needs to be. For when young people do encounter engineering or engineering-like experiences in mathematics, science and design and technology, it too often fails to present a view of engineering which is true to our EHoM.

The Royal Academy of Engineering's own review of change management of engineering education recently concluded that:

> 'The evidence in the engineering education literature suggests that successful educational reform is often associated with a combination of top-down and bottom-up change.'[180]

In terms of opportunities in England there are two areas which may be helpful:

1. **The revision of the National Curriculum for primary and secondary education.**
2. **The support from all the main political parties for some kind of technical baccalaureate (TechBac) which might provide useful opportunities at secondary level for engineering.**

In our conclusions and recommendations which will follow we seek to provide both, as well as some from the middle.

Figure 17 – Playing the whole game of engineering

1. Use extended projects and authentic contexts
2. Make the game worth playing – work hard at engaging engineers, giving them choices wherever possible
3. Work on the hard parts – discover the most effective ways of practising new techniques
4. Play out of town – try things out in many different engineering contexts
5. Uncover the hidden game – make the processes of learning to be an engineer as visible as possible
6. Learn from the team and the other teams – develop robust ways of working in mixed disciplinary groups and seek out relevant engineering communities of practice
7. Learn from the game of learning – be in the driving seat as a learner, developing your own tried and tested tactics and strategies.

Adapted from David Perkins

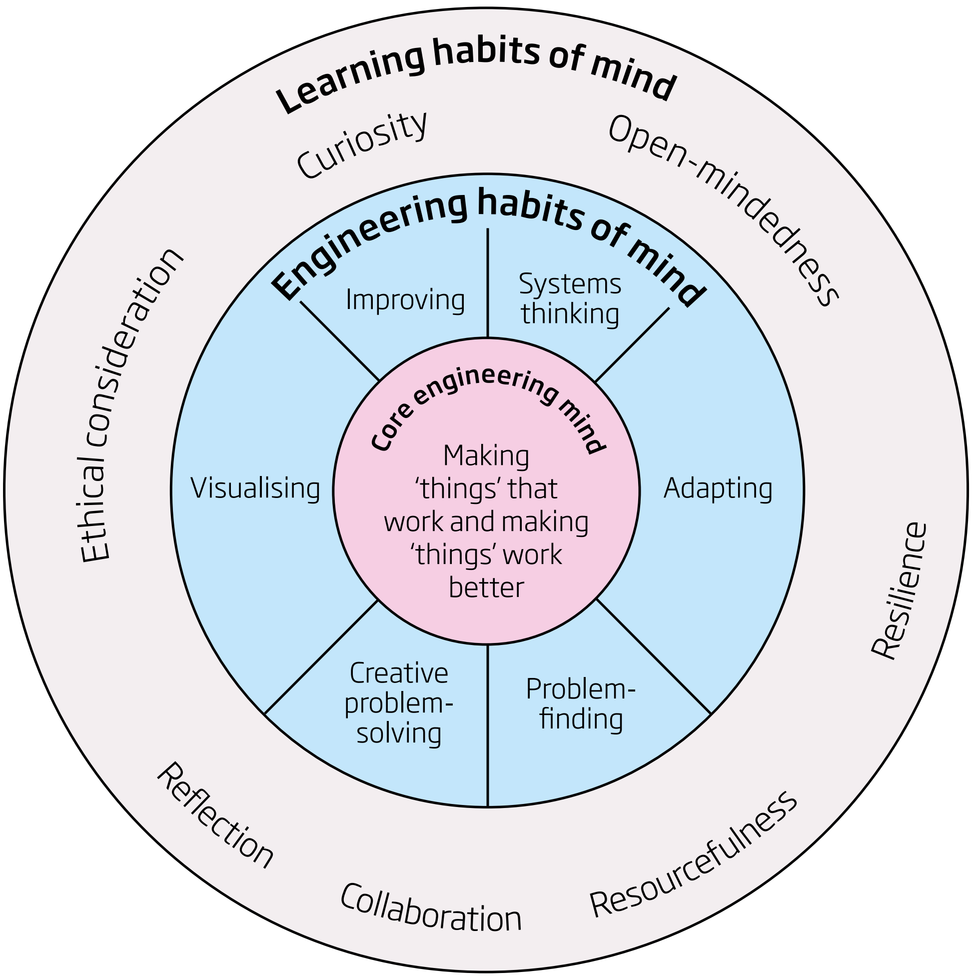
6. Conclusions and recommendations

6.1 Conclusions

We draw three main conclusions:

1. The most important finding from this research is that teachers of engineering really engaged with the question: 'how do engineers think?'. It is a question that seems to matter to them, one which had not been much discussed before and a concept that opened up discussions about pedagogy very effectively. Our model of engineering habits of mind (EHoM) below (see earlier Figure 11) provides a fresh way of exploring the teaching of engineers:
2. At various different levels the engineering teaching and learning community – school, college and university – agrees that understanding more about how engineers think could help teachers of engineering when they are constructing curricula, selecting teaching and learning methods and assessing learner progress on a course.
3. We also conclude that understanding more about how engineers think may also offer some clues as to how engineering careers can be more effectively presented to young people.

In addition to these three general conclusions, we offer some other more specific findings.



6.1.1 What it is to think like an engineer

We found a high degree of consensus in answer to our first research question:

'How do engineers think and act?'

and were able to articulate a set of EHoM for exploration by the engineering community in the UK. Drawing on established thinking in the US about EHoM we developed a candidate set of these engineering habits of mind which were then validated by expert engineers and engineer educators.

We also drew on an established literature in the US about habits of mind (HoM) within science and mathematics. We added to this our own understanding of the development of broader learning HoM exemplified in building learning power and in the research outputs of the Centre for Real-World Learning (CRL).

6.1.2 A need to redesign the education system

We conclude that the answer to our other main research question:

'How best can the education system develop learners who think and act like engineers?'

is essentially best dealt with as an engineering design problem.

The *problem* is that, although there is considerable innovation at HE where there is more of a tradition of experimentation and exploration in pedagogy, there is:

- virtually no engineering at primary level, notwithstanding some highly innovative and oversubscribed engineering education initiatives
- very patchy delivery of engineering opportunities at secondary, although with a few strong examples in UTCs and a few specialist schools
- varied provision at FE, often in under-resourced settings
- little or no explicit acknowledgement that pedagogical methods might be chosen which would cultivate the EHoM engineers told us they valued.

Our *idea* for solving this problem requires the engineering teaching and learning community to consider redesigning engineering curricula – primary, secondary, FE, HE and, potentially, family learning – which *start* from the premise that they are trying to cultivate learners who think like engineers.

In terms of the teaching and learning methods most likely to cultivate EHoM we have identified:

a) some signature pedagogies, in the main related to the engineering design process, which are centrally important,

b) a number of core learning methods relevant to specific EHoM, and

c) a range of proven and underutilised vocational teaching and learning methods.

If such a clarity of pedagogy linked to desired outcomes were achieved it would also make it easier to consider the professional development issues attendant on creating a workforce skilled in the teaching of engineering to younger students.

6.1.3 Thinking about engineers and engineering more generally

We also offer some more general messages from this research which may have relevance both for the engineering teaching and learning community *and* for use with the general public. Some of these messages are overtly positive, others are critical of the status quo. These messages include:

a) how some aspects of thinking and acting like an engineer – making and fixing stuff – are core to what makes us 'homo practicus'

b) how too many primary and secondary schools almost manage to extinguish the prototype engineers latent in young children

c) the value of thinking and acting like an engineer for work and for the rest of life

d) the close relationship between engineering habits of mind and wider employability skills

e) how participation in well-designed project-based learning is an excellent preparation for the kinds of wider life skills that we all need in order to be able to thrive

f) the advisability of having better methods of helping young people to think like engineers at school, college and at university, and

g) how the model of engineering habits of mind may provide a framework for developing a better understanding of engineering among the general public.

If young people, ideally very young children, were exposed to styles of teaching and learning which related more closely to the real world of engineering, we conclude that it is much more likely that young people's interest in engineering as a subject worthy of studying and as a career to explore would be deepened, developed and, in some cases, rekindled.

The current lack of engineers in the UK is normally presented as an issue of supply and demand. But we believe it can be reframed as a lack of clarity, and possibly of understanding, as to how engineers think and act in the real world, their characteristic engineering habits of mind (EHoM).

If the purpose of any education system, especially a vocational one, is to deliver the broad outcomes required of it – knowledge, skills *and* desired attributes or dispositions – then it is essential to have a clarity about what such attributes are (EHoM in our terminology). There is no such clarity about EHoM in the UK and this means that the development of pedagogies most suited to the cultivation of EHoM is necessarily limited.

This lack of deep understanding about the contribution of engineers to society in turn leads to incomplete and sometimes misleading notions of engineering. For many young learners, engineering, if it is encountered at all, is so far removed from its core interest in making and fixing things that it can all too easily sink under the weight of irrelevant theory.

In 6.2 we suggest some ways in which our conclusions might be put into practice.

6.2 Recommendations

The findings in this report are of potential interest to a number of key audiences.

Here we offer a number of recommendations. Some are for the Royal Academy of Engineering who commissioned this research. Others are aimed at:

- those in the engineering teaching and learning community more broadly
- schools
- employers
- the wider public.

6.2.1 Continuing the conversation

The Academy might like to:

- Continue the conversation on 'how engineers think' through a variety of events, seminars, lectures, blogs, films etc. As part of this process it could identify key players who could bring scholarship to the activity and so build a community of deep practice.
- Consider whether more could be done to promote excellence in the teaching of engineering, for example through the process of accrediting degree programmes.
- Develop a language of talking about engineering pedagogy that is clear, simple but precise. Currently the worlds of engineering and social science tend to be put off by each other's choice of words. But both could learn much from each other if they could understand each other better.

As a starting point these conversations might be held with CDIO, Engineering Council and professional engineering institutions, European Society for

Engineering Education, HEA, QAA and RSA.

The Design and Technology Association[181], the British Science Association[182] and the Mathematical Association[183] are natural allies and the Academy may wish to seek to consult with them. There are also charitable bodies, for example some of the Sainsbury Family Charitable Trusts[184], the Comino Foundation[185], the Dyson Foundation[186], or the Ellen MacArthur Foundation[187], who might be interested in supporting a wider dissemination strategy.

6.2.2 The Engineering teaching and learning community

There is a growing consensus about what constitutes the engineering mindset as well as a strong evidence base for the kinds of teaching and learning methods which might develop it.

a) Dissemination of core messages
We recommend that these core messages should be disseminated within the engineering teaching and learning community through a programme of engagement, further enquiry, the production of exemplar video clips and the gathering of case studies of promising practices.

b) Signature pedagogies for engineering
We suggest that, in terms of teaching and learning, 'messy' approaches such as project-based and problem-based learning are actively promoted as methods for building the engineering habits of mind that will enable them – or indeed anyone – to be successful in the complex real world in which they will need to operate. These are 'signature' methods and together create signature engineering pedagogies.

c) Establishing a national hub or centre for engineering pedagogy
We recommend that Academy considers supporting the establishment of a national hub for excellence in engineering pedagogy – perhaps involving a small number of applied academic centres – bringing together those who are expert in teaching and learning with engineers and employers. Such an initiative would help to ensure that engineering is better taught and learned in ways which truly help students to think like engineers.

d) Developing teacher capacities
The Academy might also like to support the development of expertise within the teaching profession by encouraging teachers to undertake small scale professional enquiries into through national initiatives such as the Expansive Education Network[188], possibly in partnership with Primary Engineer[189].

e) Improving transitions
CDIO might be invited to investigate the role of engineering habits of mind in supporting transitions between education sectors for student engineers.

6.2.3 Changing mindsets in schools and colleges

Given the invisibility of engineering in primary and secondary schools a radical change of attitude is required among teachers and, most, importantly, among headteachers, principals and senior leaders. The recommendations in this section are relevant to a significant number of organisations. Although mainly aimed at schools, there are also suggestions for colleges.

a) Seizing the opportunity of the new National Curriculum
From September 2014 onwards, the introduction of the new National Curriculum for England offers an important moment for senior leaders, especially those planning the curriculum, to create more opportunities for engineering through the new programmes of study for computing, mathematics, and science, as well as design and technology. We suggest that organisations involved in the promotion of engineering education might like actively to provide support for schools.

b) Taking opportunities to extend teaching and learning
Increasing numbers of schools are providing extended teaching time – whole days, whole weeks – rather than a diet of short lessons and engineering projects are ideal for this approach. The extended project at

A Level also provides a good location for engineering projects. We suggest that organisations involved in the promotion of engineering education to schools might like to provide exemplar materials.

c) Making school a foundation for lifelong learning

There is another important argument. Given the widely accepted view that schools have a key role in developing wider skills – for example, problem-solving, thinking, creativity – engineering is ideally placed as a means of doing this. Organisations involved in the promotion of engineering education might like to make this case compellingly.

d) Taking stock of innovations that work

UTCs and studio schools have now become an established part of provision in England, albeit in small numbers. This might be a good time to take stock of their approaches to the teaching and learning of engineering and share these more widely across the sector. It will also be important not to leave the development of engineering to this small group of pioneering schools.

e) Putting the E in STEM

The UK continues to lack expertise in STEM subjects at all levels and this report provides an opportunity for the engineering teaching and learning community to offer its distinctive line of thinking to the Department for Business, Innovation and Skills (BIS) and the Department for Education (DfE).

f) Working with others with overlapping agendas

There are specific opportunities for collaboration with:

SSAT – whose Redesigning Schooling[190] initiative has already stressed the need for better vocational pathways.

ASCL – whose Great Education Debate[191] provides a forum for the Academy to share the arguments in this report more broadly with school leaders.

Teach First[192] is now the largest supplier of initially trained teachers and they have a high proportion of talented STEM graduates. An alliance with Teach First might offer the chance to develop a group of ambassadors for engineering education. Teaching schools with an interest in STEM subjects might also be useful partners.

The Education and Training Foundation[193] is supporting the 'Teach Too' initiative which encourages experts from industry to spend time teaching their occupational expertise to others contributing to vocational curriculum development, while continuing to work. This scheme might be an ideal place for engineers to use the EHoM framework to stimulate thinking about engineering.

Gazelle Group[194] – This group of FE colleges is actively promoting the development of STEM centres and might find the EHoM framework an ideal mechanism for initiating wider debate and interest.

City & Guilds has committed to including engineering in the early development of its TechBac® and might be interested in incorporating the ideas in this report.

6.2.4 Employers and the wider public

Engaging with employers is critically important and there is some evidence that engineering graduates are sought after by many non-engineering companies. But, perhaps more importantly to the broader engineering community, it is vital that engineers engage in discussions about the EHoM they value and want.

Beyond formal education it is over the kitchen table, in the garden and in the wider community that a shift in attitudes towards the value of engineering thinking and the kinds of education which may lead to it can be achieved. Family learning activities will be important ways of showing informally how the kinds of engineering habits of mind described in the report can be developed. While most parents and grandparents see the value of technology and the ubiquitous computer, tv and tablet screens, many also have concerns about the increasingly sedentary life styles we lead. Often it is grandparents who have time and motivation to support their grandchildren in undertaking engineering projects in sheds and garages.

And, of course, there is a wider political dimension to all of the issues raised in this report.

a) Building a political consensus
In the run up to the next General Election in 2015 there is a useful window of opportunity to engage with policy-makers from the main political parties. There are also other natural allies with whom concerted efforts might be helpful. *Thinking like an engineer* might contribute to a national conversation during the next year about the value of engineering in society.

Interested bodies include but are by no means limited to:

CBI[195] – which is developing various educational initiatives around STEM, the articulation of wider skills of employability and better engagement of parents

Royal Society – There is a specific chance to influence the Royal Society's Vision for the future of Science and Mathematics Education report and subsequent activities[196].

RSA[197] – The RSA's name when abbreviated hides the fact that it is interested in artisanal activities, commerce and manufacturing. It might be possible to collaborate with its Great Recovery project and emerging interest in promoting maker movement ideas.

b) Engaging employers
We recommend that employers engage in a conversation about the usefulness of focusing on 'how engineers think'; that they encourages staff to share their knowledge with schools, colleges and universities to develop EHoM.

c) Collaborating with providers of family and extra-curricular learning
There are many including the U3A[198], The Maker Movement[199], Fix It clubs, after-school clubs and the many local bodies offering opportunities to experience engineering at first hand.

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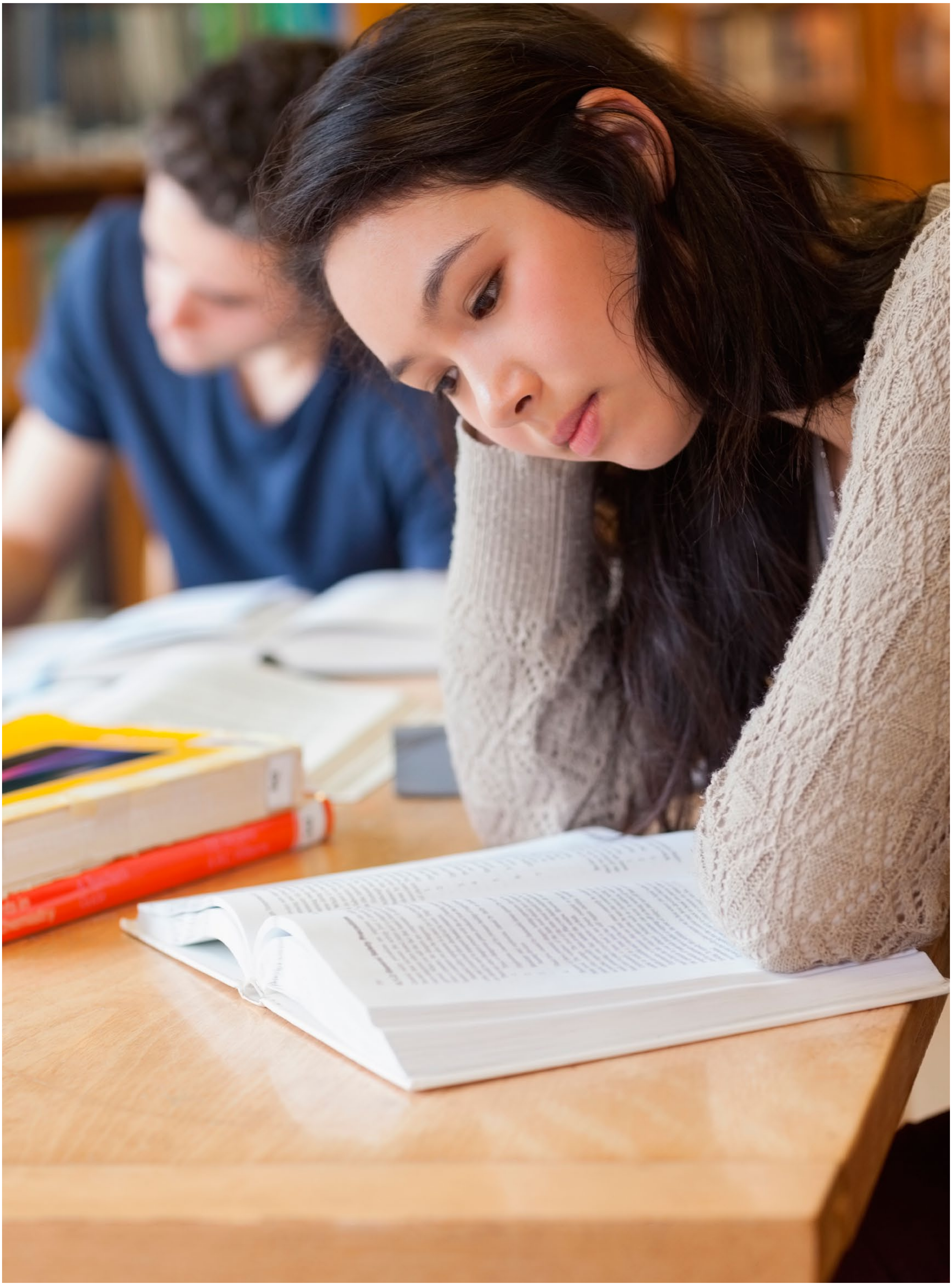

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Appendix 1 Online survey of EHoM

Engineering habits of mind EHOM

Welcome

The Centre for Real World Learning at the University of Winchester has been commissioned by the Royal Academy of Engineering to understand more about how successful engineers think and act and then to consider how best these Engineering 'habits of mind' EHOM might be cultivated at school, college, university or through continuing professional development CPD. We have two research questions:

1. How do engineers think and act, especially when they are working to solve challenging problems?
2. How can schools, colleges, universities and CPD providers select learning methods which are more likely to cultivate EHOM?

After interviewing some engineers and engineering educators, we have identified six engineering habits of mind that should be cultivated to produce successful engineers. We would now like to enhance our data by gaining the views of a wider number of engineers and educators to inform the next stage of our research.

This survey should take you around 20 minutes to complete. There are 22 questions.

We are very grateful to the Royal Academy of Engineering for distributing the survey on our behalf.

Data Protection statement
All data collected in this survey will be held anonymously and securely.

Cookies, personal data stored by your web browser, are not used in this survey.

This survey should take you around 20 minutes to complete. It can be saved part way through if you want to complete it later, but please note that once you have clicked on the CONTINUE button at the bottom of each page you cannot return to review or amend that page.

Please complete the survey by Friday 8th November.

Your background

We would like to gather some details about your background to enable us to look for patterns in responses to our questions.

Your background

1. Are you?
   - **a.** An engineer
   - **b.** An engineering educator in a teaching, lecturing, or training role
   - **c.** Both
   - **d.** Other
2. Please tell us which disciplines of engineering you are most familiar with
3. Are you a registered or chartered engineer?

   Yes No

4. Gender: are you?

Female Male Prefer not to say

5. Age: Are you?

26 or under 27–40 41–55 56 or over Prefer not to say

6. What was the most important factor that influenced your initial interest in engineering?

- Influence of family or friends
- Influence of Careers Advisor
- Good at maths/science at school
- Liked making things
- Good employment prospects
- Wanted to influence society
- Contact with inspirational engineer
- Introduction to engineering at school
- Other

Engineering habits of mind EHOM

Engineering habits of mind EHOM

Through our research so far we have identified six habits of mind that seem to be essential to the way engineers think and act when confronted with challenging problems:

Problem-finding, ie: clarifying needs; checking existing solutions; investigating contexts; verifying.

Visualising, ie: being able to move from abstract to concrete; manipulating materials; mental rehearsal of physical space; mental rehearsal of practical design solutions; thinking in 3D.

Improving, ie: relentlessly trying to make things better by experimenting, tinkering, designing, sketching, guessing, conjecturing and prototyping.

Creative problem-solving, ie: applying techniques from different traditions; generating ideas and solutions with others; generous but rigorous critiquing; seeing engineering as a 'team sport'.

Systems thinking, ie: seeing whole systems and parts and how they connect; spotting patterns; recognising interdependencies; synthesising.

Adaptability[196], ie: testing; analysing; reflecting; rethinking; changing, both in a physical sense and mentally.

We would like to find out how relevant you think these EHOM are to different disciplines of engineering, or at different stages of an engineering project, or to engineers at different stages of their career

7. Please rate the importance of these engineering habits of mind to the **engineering discipline** with which you are most familiar

	Very important	Important	Somewhat important	Not important
a. Problem-finding				
b. Visualizing				
c. Improving				
d. Creative problem-solving				
e. Systems thinking				
f. Adaptability				

8. Please indicate at which **stage of an engineering project** these engineering habits of mind might be most relevant

	At its conception	During its design	During implementation	When operational	All of these
a. Problem-finding					
b. Visualizing					
c. Improving					
d. Creative problem-solving					
e. Systems thinking					
f. Adaptability					

9. Please indicate at which **stage of an engineer's career** these engineering habits of mind might be most relevant to them

	Recent graduate/ recently trained	Mid-career	Senior professional	At all stages
a. Problem-finding				
b. Visualizing				
c. Improving				
d. Creative problem-solving				
e. Systems thinking				
f. Adaptability				

10. Are there any other Engineering Habits of Mind that we have missed and that you think should be included in our list? If yes, please list them here?

Engineering habits of mind EHOM

Engineering habits of mind in education and continuing professional development

Engineering education in some form is delivered in all sectors of education so we are interested in finding out which Engineering Habits of Mind are most relevant to learners at different stages of their education

Engineering habits of mind in education and CPD

11. Please state with which sector of education you are most familiar. Then please respond to questions 12–16 if you are familiar with that sector; there is no need to respond to a question if you are not familiar with the sector

- Primary education
- Secondary education
- Further education
- Higher education
- Continuing professional development of engineers

12. Please rate the importance of developing these engineering habits of mind in students in the **primary** education sector Key Stage 1-2

Very important Important Somewhat important Not important

a. Problem-finding
b. Visualizing
c. Improving
d. Creative problem-solving
e. Systems thinking
f. Adaptability

13. Please rate the importance of developing these engineering habits of mind in students in the **secondary** education sector Key Stage 3, 4 & 5

	Very important	Important	Somewhat important	Not important
a. Problem-finding				
b. Visualizing				
c. Improving				
d. Creative problem-solving				
e. Systems thinking				
f. Adaptability				

14. Please rate the importance of developing these engineering habits of mind in students in the **further** education sector

	Very important	Important	Somewhat important	Not important
a. Problem-finding				
b. Visualizing				
c. Improving				
d. Creative problem-solving				
e. Systems thinking				
f. Adaptability				

15. Please rate the importance of developing these engineering habits of mind in students in the **higher** education sector at undergraduate degree level

	Very important	Important	Somewhat important	Not important
a. Problem-finding				
b. Visualizing				
c. Improving				
d. Creative problem-solving				
e. Systems thinking				
f. Adaptability				

16. Please rate the importance of developing these engineering habits of mind during the **continuing professional development** of engineers

	Very important	Important	Somewhat important	Not important
a. Problem-finding				
b. Visualizing				
c. Improving				
d. Creative problem-solving				
e. Systems thinking				
f. Adaptability				

17. Do you have any other comments about the education sector in which learners should **first** be introduced to Engineering Habits of Mind? If yes, please add them here.

Engineering habits of mind EHOM

Pedagogies for engineering habits of mind

Using EHOM as the basis for considering pedagogical approaches in education, it is suggested, is a more reliable and real-world approach than focusing primarily on a content-based curriculum that is always likely to become out of date. An emphasis on habits of mind fosters greater engagement with learning and helps to ensure that learners are more engaged and better equipped to succeed in the engineering world.

Pedagogies for engineering habits of mind

18. Please tell us about the pedagogic approaches that you believe are most appropriate for developing our engineering habits of mind. If possible please give specific examples, including where appropriate the name of a school, college, university or company that offers a good example of this practice. Give relevant websites where available.

19. If you are willing to be contacted to tell us more about a specific example you have given in Q18, please include your details:

20. In your experience which teaching and learning methods are most commonly used in engineering education currently?

21. How could we further improve engineering teaching and learning to cultivate engineering habits of mind? Please add any further thoughts you may have on this topic

22. If you have any final comments about engineering habits of mind, or more generally about this research topic, please add them here.

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To create a system of engineering education and training that satisfies the aspirations of young people while delivering the high-calibre engineers and technicians that businesses need.

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