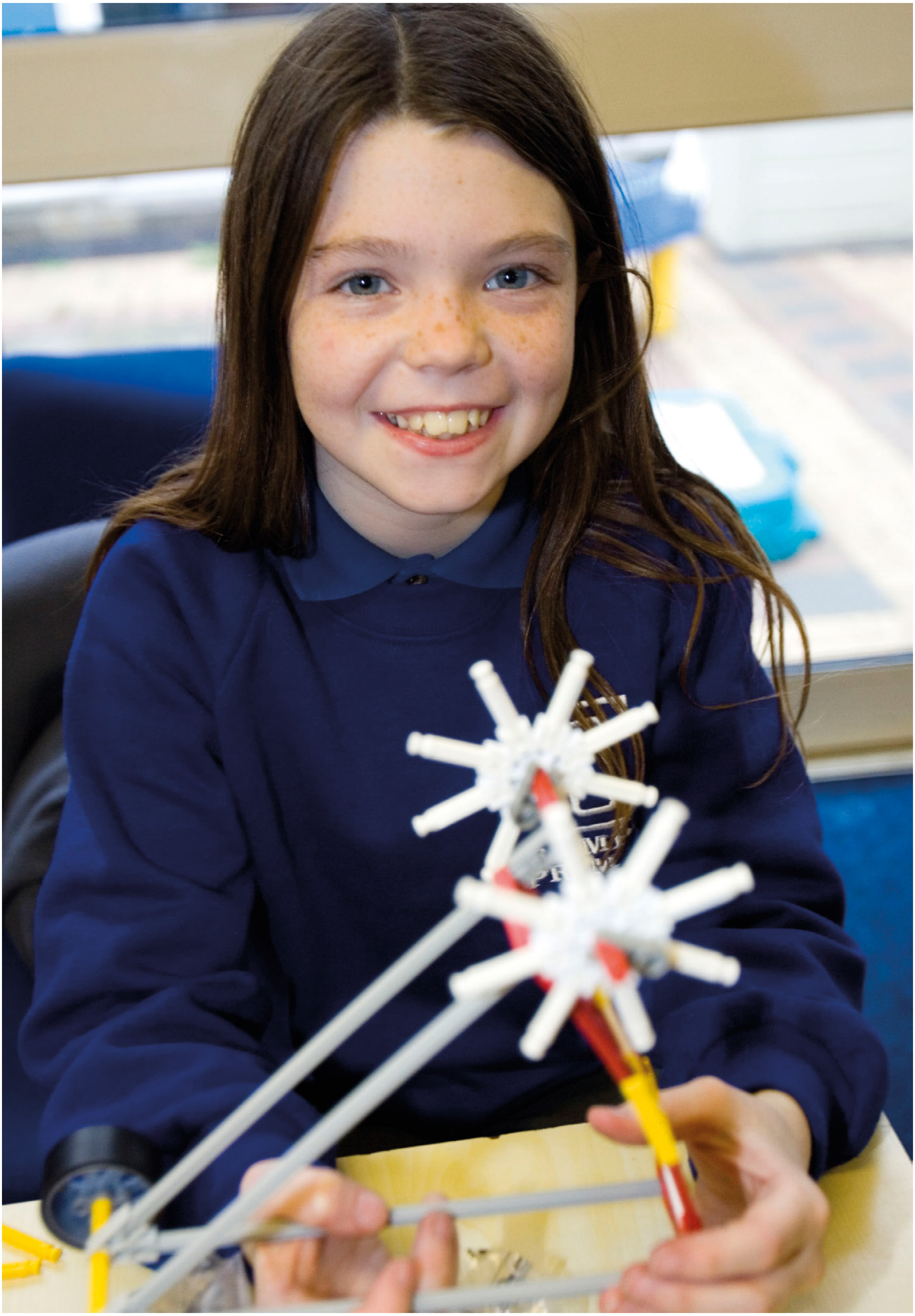
ROYAL ACADEMY OF ENGINEERING

Centre for Real-World Learning at the University of Winchester

Learning to be an Engineer

Implications for the education system

Summary report, March 2017



Learning to be an Engineer
Implications for schools

A report for the Royal Academy of Engineering
Summary report, March 2017

ISBN: 978-1-909327-32-0

This report and the full report available to download from:
www.raeng.org.uk/learningtobeanengineer

Project website:
www.raeng.org.uk/education/schools/learning-to-be-an-engineer

MANCHESTER 1824
The University of Manchester

Primary **Engineer**®

Authors

Professor Bill Lucas
Dr Janet Hanson
Dr Lynne Bianchi
Dr Jonathan Chippindall

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

www.winchester.ac.uk/realworldlearning

CRL is a research centre focusing on the teaching of learning dispositions. CRL undertook the original research, *Thinking like an Engineer*, published by the Royal Academy of Engineering, which identifies six engineering habits of mind.

About the Science & Engineering Education Research and Innovation Hub at the University of Manchester (SEERIH)

www.fascinate.manchester.ac.uk

SEERIH aims to provide continuing professional development that enthuses teachers, young people and their communities about the wonders of science and engineering in the world around us.

About Primary Engineer

www.primaryengineer.com

Primary Engineer is a not-for-profit organisation that brings together teachers and engineers to engage primary and secondary pupils with engineering through projects mapped to the curriculum.

Acknowledgements

Our thanks to:

The education team at the Royal Academy of Engineering

Dr David Barlex, one of our expert advisers, for reading the draft report and making many excellent improvements.

Our expert advisers: Dr Colin Brown, Ed Chambers, Jose Chambers, Marilyn Comrie, Professor Neil Downie, Peter Finegold, Professor Peter Goodhew, Richard Green, David Hill, Lise McCaffery, Professor Adrian Oldknow, Professor John Perkins, David Perry, Chris Rochester, Pat Walters.

Our 'teacher heroes' who inspired their learners to 'think like an engineer' and contributed to the case studies.

Our case studies: Barmulloch Primary School, Bohunt School, Camelsdale Primary School, Christ the King RC Primary School, Gomer Junior School, The JCB Academy, Manchester Robot Orchestra Challenge, Medway University Technical College, New Forest Academy, Reading College, St Ambrose Barlow RC High School, St Thomas' Primary School, University Technical College Reading. (For ease of reference, each is given a letter from A to M in this summary report, enabling readers to see longer accounts in the full report and on the website).

Our 'engineering heroes' who worked with teachers to inspire the next generation of engineers.

The Comino Foundation and Gordon Cook Foundation, which enabled us to provide additional support via the Expansive Education Network and to schools in Scotland.

Table of contents

Executive summary

This report, commissioned by the Royal Academy of Engineering (the Academy), explores the ways schools can create better and more engaging learning opportunities for would-be engineers.

It builds upon the six engineering habits of mind (EHoM): systems-thinking, adapting, problem-finding, creative problem-solving, visualising, and improving. These were identified in earlier research, *Thinking like an Engineer: implications for the education system* (2014).

This report identifies four principles that underpin the kinds of teaching that are most likely to encourage young people to develop a passion for engineering in today's busy schools and colleges:

1. **Clear understanding of engineering habits of mind by teachers and learners.**
2. **The creation of a culture in which these habits flourish.**
3. **Selection of the best teaching and learning methods; the 'signature pedagogy' of engineering.**
4. **An active engagement with learners as young engineers.**

The research demonstrates that teachers:

1. Find the reframing of engineering as a set of habits of mind to be a helpful and practical way of moving beyond the often contested space of individual subject disciplines.
2. Can apply the concept of signature pedagogy in practice, teaching in ways that develop these engineering habits of mind appropriate to their own educational contexts.
3. With targeted professional learning support, can implement and evaluate ways of designing new curricula using these different pedagogies, so beginning a process of improving their own teaching practices.

Learning to be an Engineer identifies some essential elements of a signature pedagogy for engineering: the engineering design process, 'tinkering' (an approach to playful experimentation) and authentic, sustained engagement with engineers. It also describes many positive outcomes for learners taught in this way, including: increased fluency in the key habits of mind, the development of 'growth mindsets', improvements in literacy, numeracy and oracy, enhanced self-management skills, and a better understanding of engineering. It describes many benefits to the capability and confidence of teachers, in particular their engagement with practising engineers.

The report identifies some key barriers to progress and suggests practical strategies for overcoming these challenges. Enablers include: a conducive school culture, positive alignment with existing teaching and learning approaches, effective integration of habits of mind within subjects, appropriate external validation, practical methods of tracking learner progression, availability of engineers in the locality, and above all, proactive school leadership at all levels.

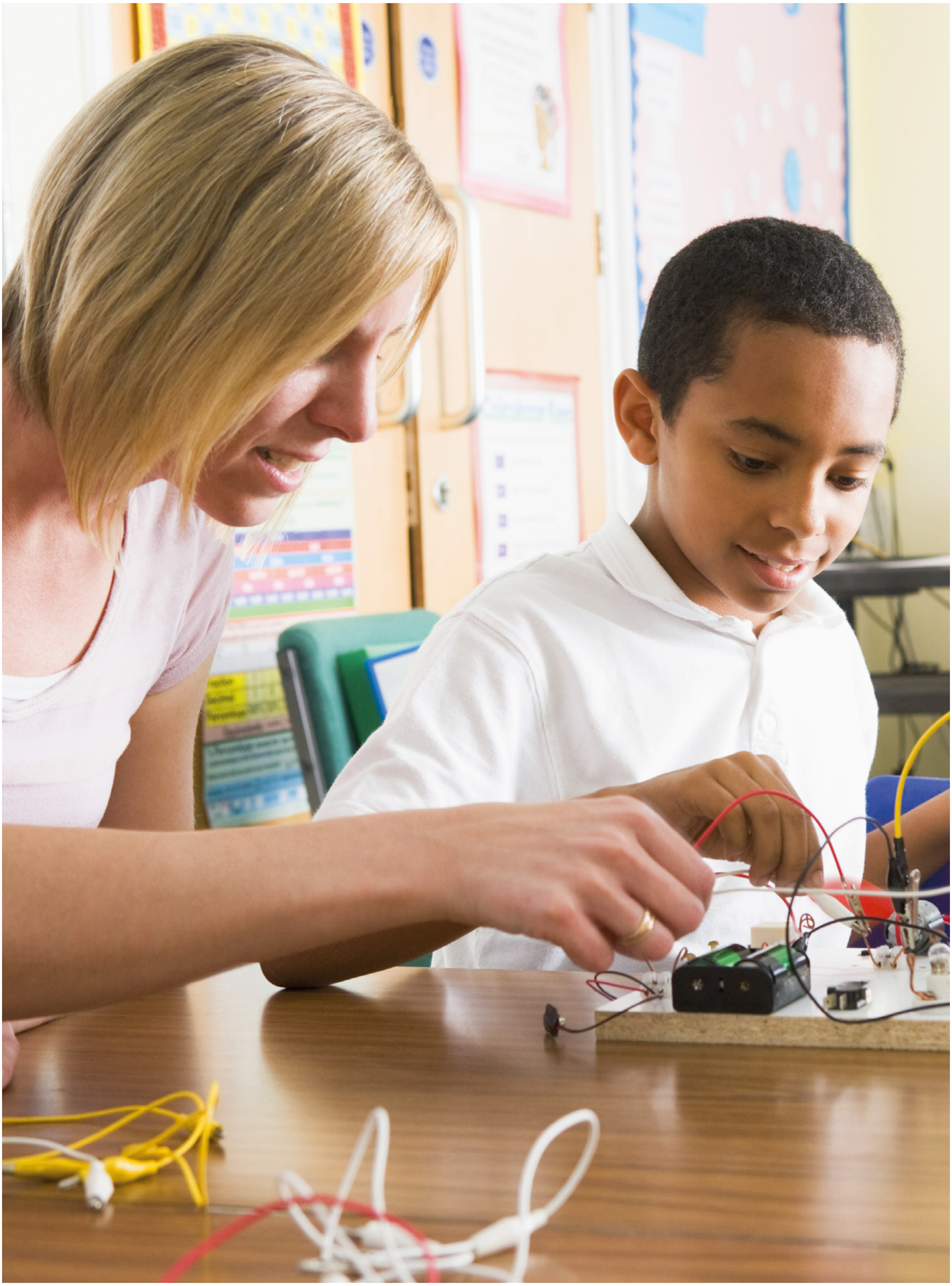
Based on the findings of the report, the Royal Academy of Engineering makes six broad recommendations:

- The need for more extensive promotion of EHoM as a mechanism for improving science capital[1] in young people, and the provision of more resources for teachers who wish to adopt the pedagogic approaches identified in the report.
- The enhancement of existing professional learning networks for teachers to encourage collaborative professional learning and ensure the more rapid spread of effective pedagogies and curriculum design for engineering education[2] in schools.
- The potential synergies between engineering, design and technology (D&T), computing and science, including the use of thematic curricula with real-world contexts, should be actively explored in all stages of the school curriculum.
- A more strategic focus on school leadership in driving change in support of engineering education should be developed.
- More research to understand how progression in EHoM can be measured.
- More research on how more engineers can best be engaged in schools in the ways described in the report.

The research represents the output of a collaboration between the Centre for Real-World Learning (CRL) at the University of Winchester, the Science & Engineering Education Research and Innovation Hub (SEERIH) at the University of Manchester, and Primary Engineer, a not for profit organisation supported by the Institution of Mechanical Engineers (IMechE). Each partner engaged in targeted professional development with schools in southern England, Greater Manchester and Glasgow/East Ayrshire to support teachers embedding engineering habits of mind in their teaching.

1 Science capital is all the scientific knowledge, attitudes and social associations that young people have acquired that influence the extent to which they view STEM careers as being 'for them' (Archer *et al.*, 2016).

2 Throughout our report we use the phrase 'engineering education' as a proxy for ways in which schools and colleges could provide more opportunities for young people to experience engineering.



1. Introduction

1.1 The idea of engineering habits of mind

In 2014 the Centre for Real-World Learning and the Royal Academy of Engineering published the report *Thinking like an Engineer: Implications for the education system,* which was based on research exploring the ways engineers think and act (Lucas, Hanson and Claxton, 2014). Central to this research was a reframing of engineering as a series of six EHoM: systems-thinking, adapting, problem-finding, creative problem-solving, visualising, and improving, see Figure 1.

In the same report we looked at how best such habits could be cultivated in schools. Drawing on extensive research and informed by discussions with experienced engineers and engineer educators, we suggested a number of signature pedagogies (Shulman, 2005) likely to be most effective. At the core of these is the engineering design process.

This report describes the results of a small-scale intervention study spread across two regions of England and in Glasgow and East Ayrshire in Scotland. It documents a proof of concept trial that sought to establish how schools can adopt the EHoM framework, which teaching methods are most helpful and the impact of adopting this approach.

The research began in late 2014 and was completed in summer 2016. It involved 33 schools and one further education college, 84 teachers and over 3,000 pupils. It was a collaboration between the Centre for Real-World Learning (CRL) at the University of Winchester, the Science & Engineering Education Research and Innovation Hub (SEERIH) at the University of Manchester, and Primary Engineer.

Each partner designed a programme of support for schools to embed EHoM using a range of different approaches. While each project had its own distinctive focus, they all incorporated the use of EHoM to promote engineering in schools. Each intervention involved teacher professional development, curriculum planning and the use of one or more EHoM as a focus of activity with a particular group of learners.

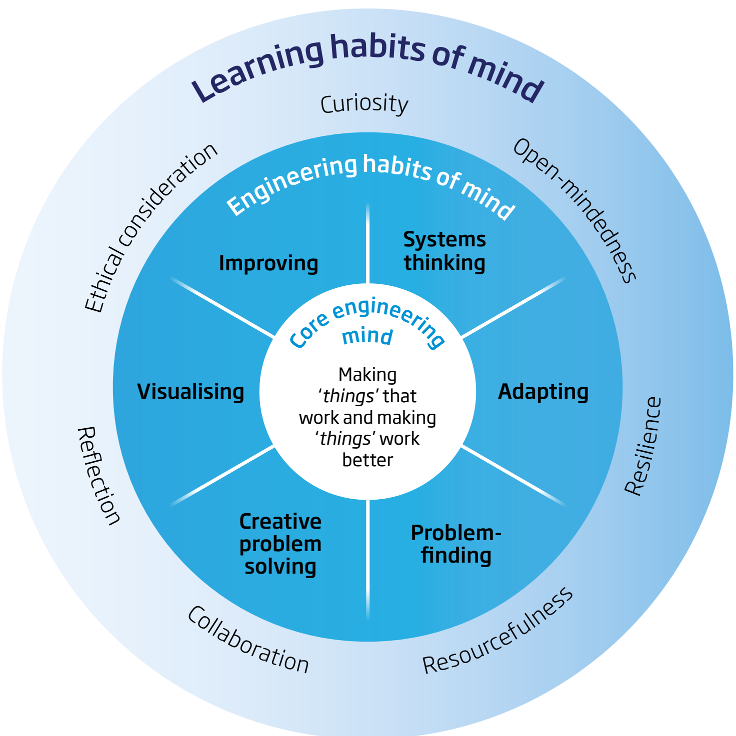


Figure 1: Engineering habits of mind

1.2 Wider educational context

While this research was being conducted, schools have gone through a time of considerable change, affecting their status, curriculum and accountability. A major review of the National Curriculum (Department for Education (DfE), 2013) was completed in England, which affected primary and secondary schools, as teachers engaged with, among other changes, computing as a new subject.

At secondary level, the English Baccalaureate (EBacc) was introduced (DfE, 2016a) and two new accountability measures, Attainment 8 and Progress 8, were introduced from 2016 onwards (DfE, 2016b). The Academy recognised the need to address the impact of changes such as these (Morgan *et al.*, 2016) and we explore the wider context in our full report, as we investigate opportunities for embedding EHoM into curriculum subjects such as computing, D&T, science, mathematics, and other areas.

2. Our approach to the research

2.1 Our theory of change

In moving from our conceptual research to a series of interventions we have articulated a theory of change (TofC) in Table 1.

Essentially we are suggesting that to overcome our current lack of engineers we need to do three things in schools:

- Move away from a focus on disciplinary knowledge (subjects such as maths and science) towards a better understanding of the ways engineers think and act (EHoM)
- Describe the teaching and learning methods most suited to cultivating EHoM, and
- Build teacher capability through professional development.

Our over-arching hypothesis is that while we need to continue to value disciplinary knowledge and practical skills, we also need to think more about the dispositions we want our engineers to acquire.

2.2 Research design and methods

The schools and college participated on a voluntary basis and their teachers engaged in a small test of change to explore how they might expand engineering in the curriculum and cultivate EHoM in their learners. The majority engaged with this as a CPD learning project for which they adopted a participatory action research approach (Reason and Bradbury, 2008), evaluating the impact of their

Table 1: Learning to be an engineer – a four step theory of change

If we

- **reframe engineering education to include desirable engineering habits of mind (EHoM) in addition to subject knowledge, and**
- **clearly articulate the principles and practices through which these EHoM can be cultivated in schools, and**
- **offer teachers targeted support for changing practices along with opportunities to co-design enquiries within the context of a reflective professional learning community**

Then

- **we can better understand what school leaders and teachers need to do to change their practices to embed more effective engineering education**

So that

- **we can share this understanding widely and**
- **more effectively support the process of successful implementation of engineering education in schools**

So that

- **more schools embrace engineering and**
- **more school students have high-quality experiences of engineering education and**
- **more students choose to study engineering beyond school and, potentially, choose careers in engineering.**

interventions on their learners, on themselves and on their school using a number of methods.

2.3 Evaluation methods

We used a number of qualitative methods to explore the teachers' intervention experiences to ensure as much triangulation of data sources and types as possible. We adopted an appreciative inquiry approach (AI) to underpin our philosophical approach to the whole study (Reed, 2007).

2.4 Data analysis and reporting

To understand more about the pedagogic processes underpinning the successful cultivation of EHoM in schools and to learn more about the impact that these interventions have on learners, teachers and engineers we used a 'realist synthesis' approach to seek answers to our research questions about the cultivation of EHoM and their impact on learners, teachers and engineers. Realist synthesis is defined as:

'...an approach to reviewing research evidence on complex social interventions, which provides an explanatory analysis of how and why they work (or don't work) in particular contexts or settings.' **(Pawson *et al.*, 2004:iv)**

A more detailed description of our approach to the research, to evaluation and to the use of data is part of the full report. Extended descriptive case studies for 12 schools were created and are available in the full version of this report and on the Academy's website.

3. The study

3.1 Overview

The three partners each developed a distinctive approach to using the EHoM framework but all looked at pedagogies for EHoM, explored curriculum development and supported teachers through a professional learning community. All the partners encouraged teachers to use participatory action research to structure and evaluate small tests of change in classrooms.

CRL undertook a project, Thinking Like an Engineer (TLaE), embedding EHoM into the curriculum in a small number of schools and a college in England between 2014 to 2016.

SEERIH coordinated the Tinker Tailor Robot Pi (TTRP) project and investigated the development of an ethos of tinkering within computing, D&T and the science curriculum to promote engineering and EHoM during 2014 to 2016 with schools in Greater Manchester.

Primary Engineer asked CRL to support the delivery of a course aimed at primary teachers in Scotland that has now been accredited by the University of Strathclyde as a Postgraduate Certificate during 2015-2016.

A total of 33 schools (22 primary schools, 11 secondary schools) and one FE college participated in our programme to cultivate EHoM, involving 84 teachers and more than 3,000 pupils.

3.2 Thinking Like an Engineer (TLaE)

TLaE developed teachers' understanding of engineering habits of mind, supported teachers in using signature pedagogies to develop EHoM and in creating schemes of work that included EHoM across science, mathematics, computing, D&T and art, and encouraged teachers to draw on the expertise of practising engineers. TLaE involved a blend of training, school support, curriculum development and action research as part of a professional learning community.

3.3 Tinker Tailor Robot Pi (TTRP)

TTRP explored how a pedagogical approach to primary engineering could be established within the mainstream curriculum. TTRP encouraged the sharing of professional practice between teachers and engineers, explored how engineers work and how learning related to engineering is taught in primary schools, and identified opportunities for incorporating engineering in primary schools through science, D&T and computing.

3.4 Primary Engineer in Scotland

In 2015, work began to develop one of Primary Engineer's programmes into a GTC Scotland Professional Recognition Programme in Engineering STEM Learning. The approach was developed by Primary Engineer in collaboration with the University of Strathclyde, Glasgow. Nine teachers from eight primary schools in Glasgow and East Ayrshire were involved. Supported by Primary Engineer and CRL, the teachers completed four assignments, one of which involved interviewing engineers to explore the growth of their EHoM.

Figure 2 below shows the key features of the three interventions diagrammatically.

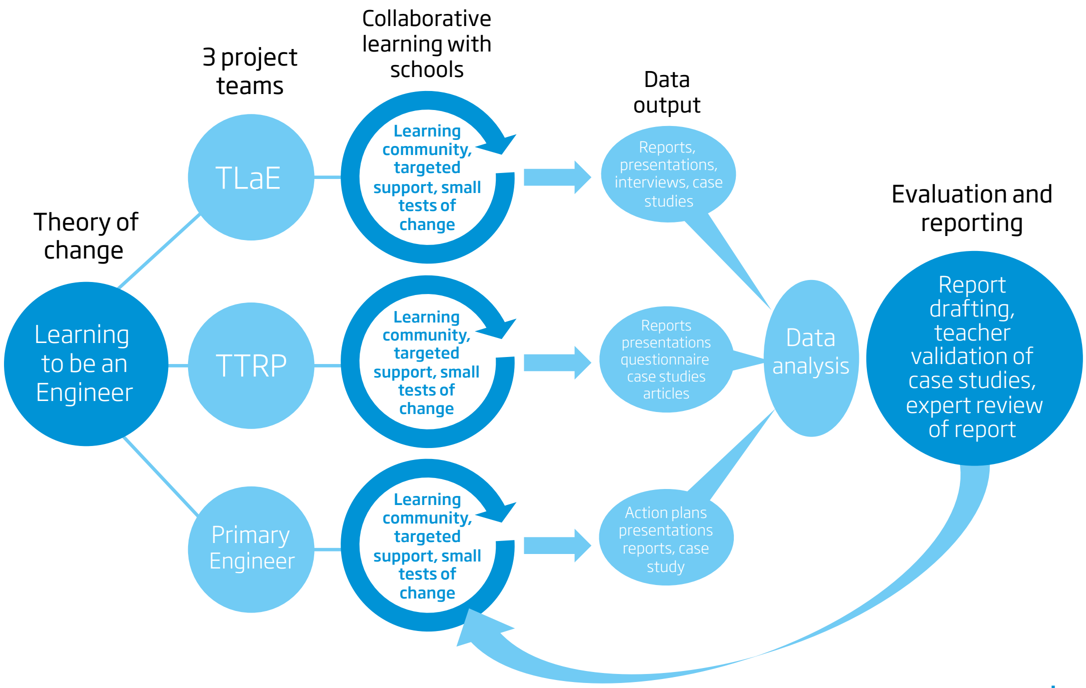


Figure 2: Overview of the three project interventions

4. Cultivating engineering habits of mind

Developing habits is hard. Changing ingrained habits is harder still. Four pedagogic principles guided our cultivation of effective learning habits:

1. Teachers and learners need to fully understand the habit and recognise it when it is being used successfully.
2. Teachers need to create the climate for the habit to flourish, including rewarding it.
3. Teachers need to choose teaching methods that facilitate the practice and transfer of the habit.
4. Teachers need to build learner engagement and commitment to the habit.

4.1 Four principles for cultivating engineering habits of mind

Principle 1: Developing understanding of the habit

The automaticity of habits often makes it difficult for students to see clearly what skills are involved, how to break the habit down into its component parts, or even to name it when they use it or notice it in others. It is important to define and explain the habit so that understanding is developed on a practical as well as a theoretical level (Huntly and Donovan, 2010). Teachers frequently begin this process by talking about their own personal experiences of using the skill or provide examples of well-known figures who have exhibited it. Some used self-report questionnaires, including an EHoM self-report survey to help students gauge their own levels prior to discussing learning goals with them.

Principle 2: Creating the climate for the habit to flourish

A conducive climate can be created by ensuring that the habit is noticed and rewarded, by providing opportunities for repetition, by not seeing lack of success at the first attempt as failure but an opportunity to 'have another go', and by supporting students in self-monitoring the extent to which they are using the habit. Positive reinforcement matters in habit formation. Praising the skill exhibited rather than the individual is an effective method of reward that serves two purposes; it praises the effort necessary for habit change and also provides a further opportunity to make explicit what the desired behaviour entails.

Principle 3: Choosing teaching methods that facilitate the practice and transfer of the habit

One of the aims of our programme was to explore the value of 'signature pedagogies' in cultivating EHoM, (Shulman, 2005), teaching methods most likely to develop the desired engineering habits. The three elements of a signature pedagogy we explored were: the engineering design process, tinkering, and authentic learning with practitioners, such as professional engineers.

A working definition for tinkering was created by TTRP:

'exploring through fiddling, toying, messing, pottering, dabbling and fooling about with a diverse range in things that happen to be available in a creative and productive pursuit to make, mend or improve'.

This definition aligns with that of Beckwith *et al*. (2006) who describe tinkering as 'playful experimentation' and consider it central to innovation and creativity.

Authentic learning with practitioners focuses learners on the practical experiences of engineering. One of the most effective ways of bringing this into the school experience is for teachers to work directly with engineers, to understand how they go about their engineering work. However, the reality of devising and organising authentic engineering learning experiences throws up many challenges for teachers relating to the curriculum, timing and institutional constraints (Strobel *et al*., 2013; de Vries *et al*., 2012).

Principle 4: Building learner engagement and commitment to the habit

We have drawn on the work of Learning Futures (Price, 2013), which helpfully frames engagement as having four characteristics:

Purposeful: learning absorbs the student in actions of practical or intellectual value, and fosters a sense of value and agency, so students behave as proto-professionals.

Placed: learning reaches, and has relevance to, students in the space that they inhabit, connecting with the student's family or community and interests outside school.

Pervasive: learning extends beyond examinations, is supported by family, carers, and peers, and can be extended through independent informal learning.

Principled: learning appeals to the student's passions or moral purpose.

5. Testing our theory of change (TofC)

The first step of our TofC, (page 6), had three elements:

1. Reframing engineering education to include desirable engineering habits of mind (EHoM) in addition to subject knowledge.
2. Clearly articulating the principles and practices through which these EHoM can be cultivated in schools.
3. Offering teachers targeted support for changing practices along with opportunities to co-design enquiries in a reflective professional learning community.

The *Learning to be an Engineer* research strongly validates the first step of our TofC. Teachers and engineers understood, approved of and used the EHoM model. They were able to connect EHoM thinking to their current practices and to the shifting external educational environment. They liked and used the signature pedagogy thinking. They responded enthusiastically to being part of a supportive professional learning community, were able to co-design different curricula using new pedagogies and were able to begin to make changes to their practices.

5.1 Using the four principles to cultivate EHoM

In this section, we explore the experiences of schools in more detail using the four-step structure of our approach to cultivating habits – developing understanding, creating the climate, using signature pedagogies and engaging learners.

How teachers developed understanding of EHoM

Teachers across all sectors used a range of strategies to build learners' understanding of the EHoM including verbal and visual communication techniques, at whole-school and classroom levels. The EHoM were often the subject of whole-school assemblies. Younger learners were engaged through readings from story books such as *Rosie Revere, engineer* (Beaty and Roberts, 2013), while older children listened to talks by local engineers or parents in the profession who were able to discuss the use of EHoM in their work. In classrooms, teachers discussed the meanings of the EHoM. Many used the EHoM self-report survey we created to encourage learners to think about their confidence level in using each EHoM, while others used adapted versions.

Many schools used the original EHoM model (see Figure 1), in the form of a poster produced by the Academy to remind learners of the EHoM names and some teachers developed visual icons for each EHoM, see Case Study A Medway UTC.

How teachers created the climate for EHoM to flourish

Teachers used a range of strategies to create the learning environments conducive to cultivating EHoM and then celebrating learners' achievements. At Christ the King RC Primary School (see Case Study B), a whole-school approach to engineering was designed to engage all learners, teachers and parents and included in the school improvement plan. Staff training and staff meeting reviews, weekly classroom topics, specially created displays, physical spaces for tinkering and top-level advocacy from the headteacher combined to act as a catalyst for the creation of a climate for EHoM.

The challenge of having time within the mainstream curriculum was an issue for many teachers. They capitalised on combining subjects that they described as "stealing time from the weekly timetable".

Offering tangible rewards that could be earned for overtly demonstrating the EHoM was a strategy used by some teachers while others placed emphasis on learning from mistakes and careful use of the language of praise. Some schools adapted their existing school reward systems to accommodate learner displays of EHoM. With older learners, more sophisticated reward systems might be used. In one school learners built up merit points for displaying EHoM that could be used to claim prizes. Elsewhere, visits to collaborating engineering employers were commonly offered to teams who were judged best overall at completing a project.

Most teachers opted to use two well-documented teaching strategies: making the processes of learning as visible as possible (Hattie, 2012) and accepting making mistakes as an opportunity for developing a growth mindset rather than as a sign of failure (Dweck, 2006). We found numerous examples of teachers cultivating a climate of learning from mistakes, including a Year 1 science teacher who made the most of her own experiment that accidently went wrong by modelling an improving mindset. The use of problem-solving activities and 'making' challenges was increasingly evident in classroom learning (see Case Study C New Forest Academy), as well in lunchtime and after-school clubs.

However, changing learner's mindsets is challenging. Teachers reported that some learners struggled to return to a failed project and try again. One teacher recounted how she responded when a high achieving learner had misinterpreted a question and then lost his temper when he realised he had got the answer wrong. Teachers developed phrases and questions that prompted learners to respond more fully and to understand which points were good and why, such as:

"That works really well. Why did you do that?"

"I like what this group has done because they have included X, Y and Z."

"What really impresses me is, if I can see that your design specification is getting better and better."

Allowing children to fail did not come easily for teachers. Some initially struggled with stepping back and allowing children to make mistakes. However, they said they found themselves asking more questions rather than answering them. The change to a process driven outcome to learning was evident in most schools:

"Teachers observed more and identified EHoM rather than looking for a finished outcome." **(Teacher, primary school, TTRP)**

How teachers used signature pedagogies

Schools focused on three signature pedagogies: the engineering design process (EDP), tinkering and authentic learning with engineers.

Engineering design process

The essence of the EDP informed both learning in the classroom and the teachers' own enquiries. When schools used the EDP to organise EHoM learning, they tended to use an adapted or simplified model. For example, Gomer Junior School created the 'gSTEM Wheel', an enhanced version of the D&T wheel of 'plan, do, evaluate' to focus on the processes of improving and 'making things better', see Case Study D.

Tinkering

Within the TTRP project, the enthusiasm around tinkering led teachers to create timetabled tinkering lessons and projects within the curriculum as well as classroom tinker tables, lunchtime tinkering clubs and school trips related to engineering. 'Play-do-review' was a process that emerged within these schools, together with a hands-on making process that allowed children to explore and experiment with a focus or purpose, see Case Study E St Thomas' Primary School.

A number of teachers used similar strategies to encourage making, unmaking and experimentation, without actually naming this process tinkering. One early years teacher described her approach to introduce EHoM during her school's Science Week as supporting 'child-initiated' work, by letting young learners design and make paper aeroplanes. In a secondary science classroom, students' problem-solving skills were tested by asking them to take apart a ball-point pen and see how many different uses for it they could generate. In a FE college a teacher described how he got his students to just start working on a project and to try putting

components together before he gave them the theory.

Authentic engagement with engineers

All schools drew on the expertise and enthusiasm of professional engineers to support the cultivation of EHoM through authentic learning with practitioners. The engineers' involvement ranged from one-off talks with the aim of raising awareness of engineering careers, to extended collaboration between engineers and teachers to plan projects that reflected the real-word challenges that currently face engineers. Support from the university engineering department was an important feature for TTRP schools.

Several secondary schools, especially UTCs, provided examples of ways in which engineers could have significant input into the curriculum by collaborating with teachers on developing extended projects or engineering challenges, which were delivered by the teachers, see Case Study F UTC Reading and Case Study G Bohunt School.

Identifying engineers who might be willing to work with a school can be a daunting proposition, but the Primary Engineer teachers, by engaging with 63 engineers during their project, demonstrated how much enthusiasm there is in the engineering community for talking about engineering and helping local schools.

How teachers engaged learners

The ways in which teachers engaged learners with EHoM was of particular interest to us and we looked at four aspects of engagement mentioned earlier:

Purposeful

Links with professional engineers act as a powerful driver for engagement. When learners participate in activities based on problems faced by engineers in the real world, they are motivated by the idea that they are using the same skills as professional engineers, and understand therefore, that this learning has a purpose, see Case Study H Reading College.

Placed

During the timescale of the project teachers had a golden opportunity to engage learners by building teaching schemes around British astronaut Tim Peake's Principia mission to the International Space Station (UK space Agency, 2016) or the Rio 2016 Paralympic Games.

Pervasive

Pervasive activities encouraging family engagement appeared to be very successful. Posing home-work topics, organising family tinkerthons and tinkering workshops and engaging parents in the School of the Military (2016) appealed to everyone. A STEM festival organised by one school engaged parents so much that many more said they would recommend a STEM career to their children. Several schools participated in external challenges such as the Greenpower Goblin Racing Car Challenge (2016), CREST Awards (British Science Association, 2016) and the Manchester Robot Orchestra Challenge (2016).

Principled

We noted some examples above where the topics chosen by teachers appealed to learners' interests but there were also some examples in the primary schools where learners' passions were sparked by cultivating EHoM, somewhat unexpectedly, according to the teachers.

6. Outcomes for learners

In this section we describe the impact of teachers' interventions on their learners.

6.1 Growth in learners' fluency with habits of mind

In order to develop the teachers' confidence in understanding and then cultivating EHoM, we divided each of the six EHoM into two sub-habits, See Table 2.

Creative problem-solving – generating ideas and working in teams

Teachers were initially challenged by learners who always wanted to get things right first time. However, teachers reported that the ability of learners to tackle open-ended questions more confidently and generate creative solutions to problems did improve.

Sometimes instances of voluntary peer mentoring within a group were noticed.

Primary learners were also observed making more effort to provide peer support to children with special educational needs (SEN); behaviour that was less likely to be observed before the EHoM intervention. Children with SEN appeared to be more engaged when working on STEM tasks.

Improving – experimenting and evaluating

Teachers who focused on the EHoM of improving quickly realised that they needed to establish a belief that improvement is always possible.

Table 2: Six engineering habits of mind and 12 sub-habits

EHoM	Sub-habit 1	Sub-habit 2
CREATIVE PROBLEM-SOLVING is … Generating ideas and solutions by applying techniques from different traditions, critiquing, giving and receiving feedback, seeing engineering as a 'team sport'.	**Generating ideas:** comes up with suggestions in a range of situations.	**Working in team:** has good people skills to enable idea and activity sharing; good at giving and receiving critique/feedback.
IMPROVING is … Making things better by experimenting, designing, sketching, guessing, conjecturing, thought-experimenting, prototyping.	**Experimenting:** makes small tests or changes; sketching, drafting, guessing, prototyping.	**Evaluating:** making honest and accurate judgments about 'how it's going'; comfortable with words and numbers as descriptors of progress.
PROBLEM-FINDING is … Deciding what the actual question is, finding out if solutions already exist by clarifying needs, checking existing solutions, investigating contexts, verifying, thinking strategically.	**Checking and clarifying:** questions apparent solutions methodically and reflectively.	**Investigating:** has a questioning, curious and, where appropriate, sceptical attitude.
ADAPTING is … Making something designed for one purpose suitable for another purpose, by converting, modifying, transforming, adjusting, changing, re-shaping, re-designing, testing, analysing, reflecting, rethinking.	**Critical thinking:** analyses ideas, activities and products; able to defends their own thoughts and ideas in discussion and also to change their mind in light of evidence.	**Deliberate practising:** disciplined; able to work at the hard parts.
VISUALISING is … Seeing the end product, being able to move from abstract ideas to concrete, manipulating materials, mentally rehearsing practical design solutions.	**Thinking out loud:** puts 3D ideas into words as they become pictures or rehearses possible lines of thought or action.	**Model-making:** moves between abstract and concrete, making models to capture ideas.
SYSTEMS-THINKING is … Seeing connections between things, seeking out patterns, seeing whole systems and their parts and how they connect, recognising interdependencies, synthesising.	**Connecting:** looks for links, connections, relationships; working across boundaries.	**Pattern-making:** uses metaphors, formulae, images etc. to find patterns to illustrate new meaning.

In order to improve work when it did not go right the first time, learners first had to demonstrate resilience and perseverance. From early years to further education, teachers provided examples of learners whose perseverance increased during the EHoM intervention.

Problem-finding – checking, clarifying and investigating

Although some teachers thought that problem-finding might be too sophisticated for their learners, they found that by using teaching strategies described in Section 5, learners did increase their capability in this area. Initially, in D&T and STEM classes, teachers reported that learners wanted to move quickly through the design stages since they were eager to reach the making stage. However, during the interventions, teachers noted that learners' confidence to ask questions improved and they became more curious:

"Year 9 pupils were able to apply EHoM to their designs to improve ...in particular pupils benefitted from the opportunity to 'Problem Find' as it forced them to critique their own designs" **(D&T teacher, secondary school, TTRP)**

Adapting – critical thinking and deliberate practising

Teachers at all levels reported that their EHoM interventions supported an increase in more accurate self-reflection in their learners who also appeared to have an increased capability to think critically, linking theoretical and practical knowledge.

Visualising – thinking out loud and model-making

Although there were fewer instances of teachers focusing on visualising, the examples of its cultivation demonstrate how pervasive it can be, from primary, when practical modelling is commonplace, to secondary where it is not too late to acquire sketching skills. One secondary teacher deliberately aimed to enhance his learners' ability to visualise because he recognised that it was an important skill for an engineer to possess, but one that his Year 10 learners lacked.

"When I was able to ask students what was their greatest experience in sketching, a good half of the class had said that they'd had no formal or even implicit training or teaching in sketching, which I would say is a pretty big skill in any of the design technologies or art." **(Mathematics teacher, secondary school, TLaE)**

Systems thinking – connecting and pattern-making

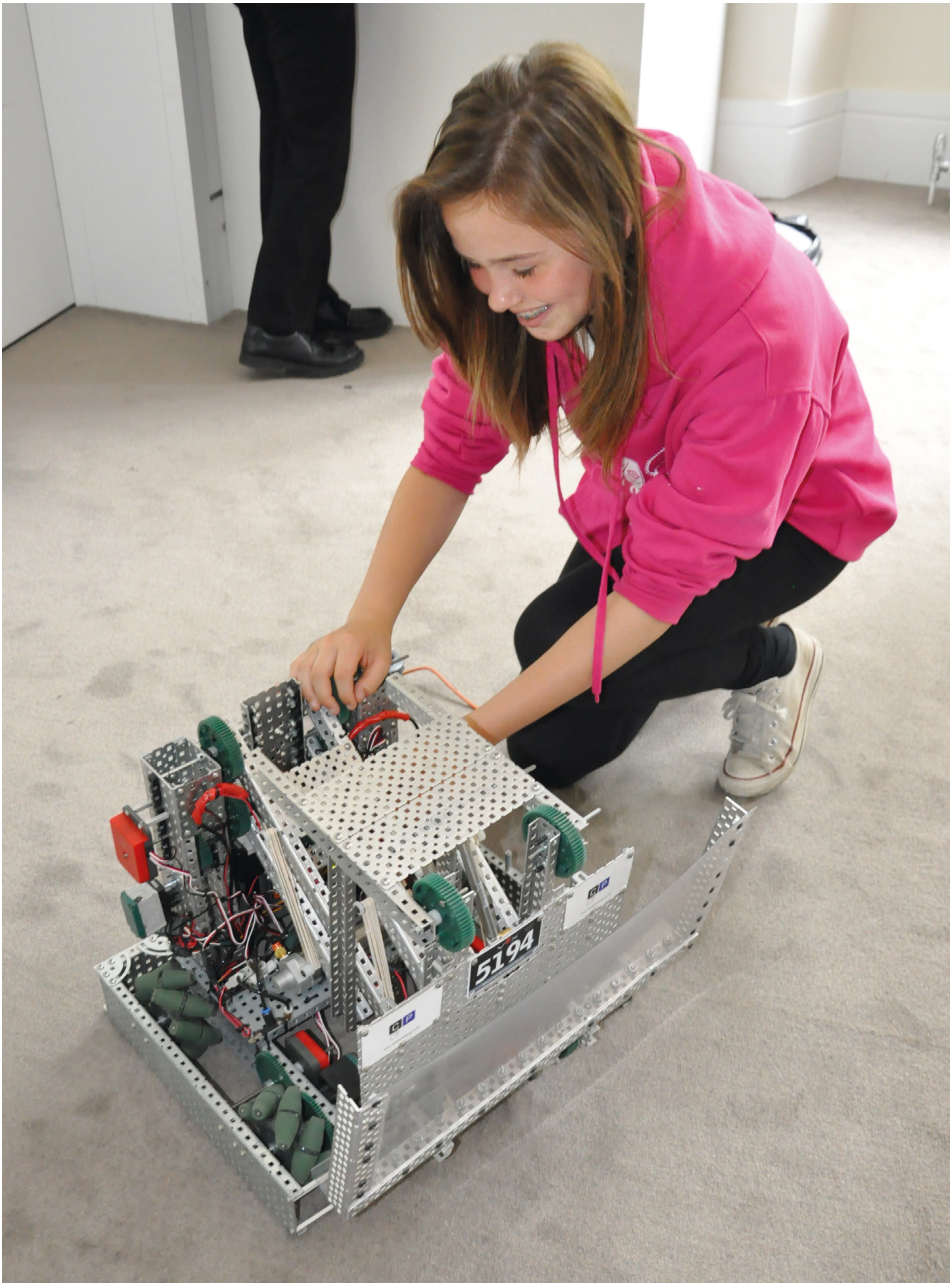
Systems thinking was the most underdeveloped EHoM during our study. In those schools where the engineering design process was used, teachers reported that they saw an improvement in learners being able to connect ideas and see patterns emerging from their data. Although there was limited evidence to support an increase in systems thinking itself, learners' use of the processes or thinking routines associated with an EHoM was enhanced and transferred to other subjects. Teachers began to see EHoM as an integrative factor that could link subjects together.

6.2 Evidence of developing engineering growth mindsets

In many cases, before the EHoM interventions, teachers said learners lacked resilience, perseverance and self-efficacy and were easily discouraged by failure, showing a fixed rather than a growth mindset. But as the project progressed, teachers reported that learners got better at using EHoM the more they practised them and that they demonstrated an increased growth mindset more generally. Teachers also noted changes in their quieter learners who found a voice and took the lead in discussion. They observed pupils transferring these skills in other areas of the curriculum, see Case Study I Camelsdale Primary School.

6.3 Impact on literacy, numeracy and oracy

While we did not specifically aim to investigate the impact of cultivating EHoM on attainment in literacy and


5194

numeracy, some primary teachers noticed improvements in these subjects. In literacy classes teachers reported hearing learners building on each other's sentences while they were engaged in writing tasks. In numeracy, teachers associated the enhancement of learners' reasoning skills in mathematics with the EHoM intervention, and most importantly, they were able to raise aspiration in learners of all abilities through EHoM:

"Now we've understood how far we can stretch children I think we are going far beyond with regards to lots of levels in science, maths, and English in those gSTEM sessions than we are anywhere else, amongst a wide range of children." **(Teacher, primary school, TLaE)**

Teachers reported that learners demonstrated an increased fluency in expressing ideas or opinions. Oracy, learning to talk well and learning well through talk, is regarded by many primary teachers to be of equal importance with literacy and numeracy in supporting attainment (Millard and Menzies, 2016). At secondary level, teachers noticed an improvement in learners' communication skills that was more employment focused. Learners demonstrated an increased confidence to network with employers when they came into the school for careers events and were able to talk in a more convincing manner to them when they went for job or apprenticeship interviews.

6.4 Self-managed learners and impact on classroom management

Overall, teachers reported that children were enthusiastic and motivated and that attitudes towards learning improved during the EHoM sessions. In schools where the focus for EHoM was within tinkering or making process, this led to 'noisy, enthusiastic and engaged' learners. Teachers described how children had more opportunity to 'discuss, evaluate, analyse and problem solve' and that by working together on a 'level playing field' they were able to demonstrate EHoM. Some teachers found the approach took longer and noted that some more academic children found this type of learning challenging and struggled with the creating process. However, less academic children had a 'chance to shine' and demonstrate greater self-management.

6.5 Impact on learners' understanding of engineering

EHoM teaching that was reinforced through modelling by engineers enhanced learners' understanding of engineering and its potential as a career. The engineers' involvement in the curriculum showed learners how the content and skills they were learning were directly relevant to the real world, see Case Study J Barmulloch Primary School. Sometimes, the learners' reactions to the engineer in the classroom caused the teachers to reflect on their own teaching strategies:

"I was amazed at how…much more creative their questions were to the engineer…Was that because he provided more thinking time than I did…? They certainly asked more 'deep' questions to the engineer and they used far more expressive language when asking [engineer] a question. This gave me food for thought." **(Primary Engineer teacher)**

At secondary level, teachers attributed learners' success in external engineering competitions to their enhanced ability to use the language of EHoM when discussing their achievements with employers on the judging panel of awards. Learners and their parents began to understand that engineering is more than fixing cars.

7. Outcomes for teachers

In this section we explore the impact on teachers' own habits and practices, as well as reflecting on the ways in which they engaged with engineers.

7.1 Teachers as risk takers and improvisers

We have already noted the visible outcomes for learners when teachers modelled growth mindset attributes such as learning from mistakes and perseverance in the face of difficulty. However, it was evident that teachers found changing the habit of being 'in control of adverse events' and 'the expert' extremely difficult. Those who managed this shift found it to be very beneficial:

"I took a step back and although this is so hard to do as a teacher, as you feel you have to always be in control, I began to see the pupils flourish with their new found freedom and their self- belief was huge by the end of this project" **(Primary Engineer teacher)**

More significant and riskier behaviour changes for teachers, such as admitting mistakes or being open-minded when receiving learners' ideas, were evidence of further development of the teachers' own growth mindset.

There were numerous occasions when teachers explained how they learnt alongside their students, particularly when they were addressing the meaning of the EHoM and attempting to transfer the use of EHoM into subjects other than engineering. They became more skilled at engaging in 'cognitive apprenticeship' style teaching techniques, such as modelling, scaffolding and coaching (Adams *et al.*, 2015).

7.2 Teachers as collaborators

In most cases teachers were working on their interventions in pairs or groups, so had many opportunities to learn from each other. In secondary schools EHoM brought teachers from different departments together (see Case Study K The JCB Academy), resulting in increased subject integration:

"Everyone was really on board with [EHoM], particularly art and English teachers; they felt included in what we're trying to achieve, because they could see how all those words could be talked about in the context of their subject." **(Director of STEM, secondary school, TLaE)**

Some teachers became recognised within and outside their school as 'the expert' on EHoM and on incorporating engineering into the curriculum, offering CPD sessions to their colleagues.

7.3 Teachers as reflectors

The action research approach underpinning the evaluation of the teachers' EHoM interventions encouraged them to reflect on their methods. This led to further thinking about how to adapt their traditional teaching strategies, which was most evident in two areas: their increased use of facilitation techniques and the enhancement of their questioning techniques.

Teachers also became more skilled at facilitating discussion and helping learners generate ideas through good questioning:

"We know when to ask why, and we know how to ask why in order that the pupils actually do move on with their learning, rather than just asking why for the sake of it." **(Teacher, primary school, TLaE)**

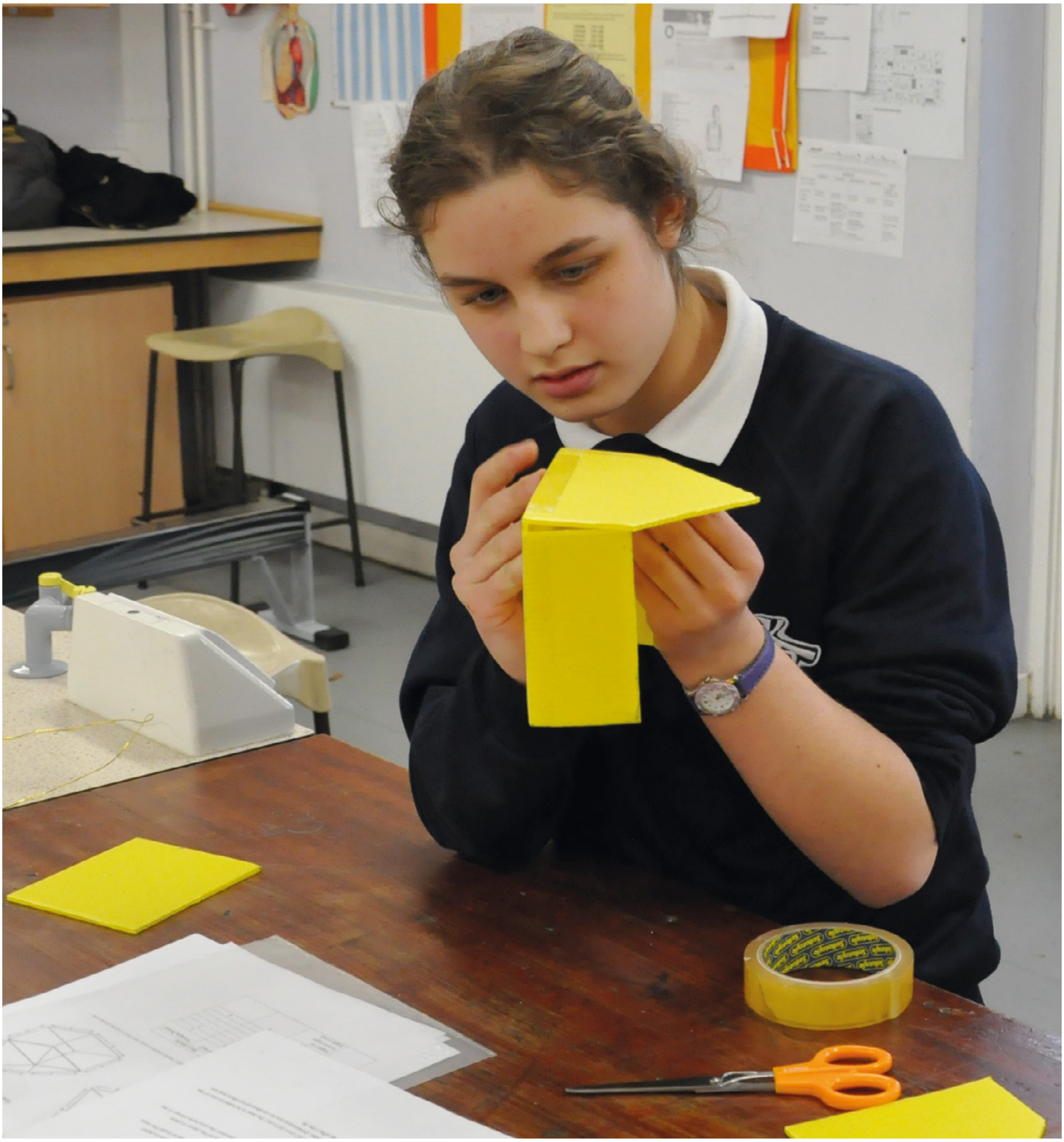
7.4 Teachers' confidence in engaging with engineers

Knowing that EHoM are derived from research with practising engineers appeared to increase teachers' confidence in using them. They gained knowledge that gave them confidence to make links between the subjects and skills that they were teaching and the world outside the school.

Teachers' growing understanding of EHoM also appeared to increase their confidence in approaching engineers about coming into the classroom and contributing to the curriculum.

The experience encouraged curriculum managers to be more direct with employers about how their involvement with a college can be mutually beneficial. Teachers also listened to what engineers were telling them about what it is like to work as an engineer and how teaching needs to change to cultivate this style of thinking:

"I took on board the recommendations from the engineers I interviewed and have more hands on activities, allow the children thinking time, allow the children to ask why – ten times if they must, and allow them to think outside the box."
(Primary Engineer teacher)



8. Enablers and barriers for cultivating engineering habits of mind

By and large the presence of the factors that each of the following headings identifies was an enabler, and lack of them was an inhibitor.

8.1 A conducive school culture

At all levels, EHoM can be cultivated effectively when the school culture is sensitive to the language and practice of dispositional teaching. For example: when the school has a pre-existing interest in growth mindset; when STEM subjects are prioritised by the school; or when engineering is explicitly taught as a subject.

In all cases, successful implementation was closely related to the degree to which head teachers and senior leaders actively bought into the EHoM framework and its associated pedagogies, and saw the value of releasing teachers for professional learning in these areas.

All the Scottish primary schools in the Primary Engineer project included the promotion of STEM in their school improvement plans, as did many of the English primary schools. However, in some cases, teachers felt that science, D&T and computing were undervalued in comparison with the core subjects of literacy and numeracy.

While many teachers involved in TTRP and Primary Engineer were keen to take advantage of being shown how to use technologies in their classrooms, it rapidly became clear that the major learning was less about the use of kit and more about different ways of teaching. Nevertheless, technologies were explored extensively with the teachers in the TTRP project. Hack Events, in which teachers came together to spend time tinkering with a variety of resources, provided the opportunity for teachers to learn about coding, programming and related electronic kit, such as Crumbles (Redfern Electronics), Makey Makey (JoyLabz) and Raspberry Pi (Raspberry Pi Foundation).

8.2 Alignment with schools' approaches to teaching and learning

Where there was explicit support within the school for the signature pedagogy approach, it was easier for teachers to engage with EHoM. The start of the TTRP project coincided with the introduction of the new computing curriculum, the revision of the science curriculum and the revision of GCSEs in England. As such, there was interest from teachers to gain support and advice on the implementation of new programmes of study for programming and 'working scientifically', with some fascinating outcomes, see Case Study L Manchester Robot Orchestra Challenge.

Many schools in all three projects had already been working on growth mindset initiatives, which they came to associate with the EHoM behaviours and characteristics. Once teachers understood the concept of EHoM, they were able to align them with their school's approach to teaching and learning.

8.3 Effective integration of EHoM into primary and secondary curricula

In some cases, primary schools found it more manageable to incorporate EHoM into teaching during one short period, such as during a science week, or outside the curriculum in after-school clubs, while in other cases, EHoM became the main integrative focus during STEM sessions across the whole school. Despite the challenges of content-led curricula, primary teachers did find imaginative ways of carving out time to incorporate EHoM by integrating subjects. At secondary level, we have examples of EHoM integrated into science, mathematics and within D&T, see Case Study M St Ambrose Barlow RC High School. EHoM were also integrated into STEM enrichment programmes. Some teachers underestimated the time they would need for interventions that involved practical activities with children, but that did not deter them from persisting with their intervention.

8.4 Validation from external assessments

For teachers, the existence of an external examination provides an obvious imperative to organise curriculum accordingly. Managerially set key performance indicators can also put pressure on teachers to 'teach to the test'. Therefore, it was suggested that one of the biggest threats to incorporating EHoM is the move from 40% to 60% controlled assessment or examinations, to 100% examination in GCSE subjects. This change will put significant pressure on teachers to focus on examined content. If the cultivation of EHoM is to flourish and be incorporated with the curriculum, it will be important to demonstrate that this enhances learner performance. The prioritising of examined content led some teachers to express concern that projects run in collaboration with employers designed to enhance students' real-world learning might have to give way to exams.

However, unlike mathematics and science, the new D&T GCSE, to be introduced in 2017, will have non-examined assessment (NEA) in addition to a written paper, each worth 50% of the total marks. This is much more demanding than the previous GCSE because it requires learners to deal with uncertainty at the outset of the process. As this is an extended designing and making assignment, there will be plenty of opportunities to demonstrate EHoM. Even when schools are keen to promote engineering, the lack of appropriate STEM qualifications at the right level is seen as a challenge.

8.5 Effective tracking of learner progress

It is a truism of teaching that what gets assessed gets taught, but there is a more subtle point associated with this. As we have shown in our work on creativity with the OECD (Lucas, 2016), it is relatively complex to assess progression in capabilities such as our EHoM, requiring teachers to have not just a sound understanding of the elements and sub-elements of any habit, but also a range of assessment protocols with which they are confident. Teachers were acutely aware of the need to present concrete evidence of achievement if they wished to continue their intervention.

Some schools used our EHoM self-report tool and others adapted it to suit their contexts, but the need to be aware of learner 'reference bias', something we cautioned them against in the training sessions, was noted by many. In some schools, it appeared that it might be possible to record progress in EHoM by adapting existing tracking and recording systems.

8.6 Timetabling, learning spaces and resources for teaching

Many of the innovative approaches to cultivating EHoM demanded a creative approach to timetabling and room allocation, particularly in 11+ settings. In one school, despite having a dedicated STEM classroom, teachers found themselves trying to teach a common STEM programme in a wide variety of rooms, with different seating arrangements and IT facilities, and often lacking storage facilities for models. Project-based learning requires flexible, purpose-built spaces to facilitate interdisciplinary learning and these were often not readily available.

Teachers suggested that it would be valuable to have video resources of engineers talking about engineering and how they have used EHoM, as well as a bank of resources and information about teaching EHoM to share best practice. There are numerous locations of curriculum resources and videos available through websites such as the National STEM Learning Network (2016), Tomorrow's Engineers (2016) or Born to Engineer (2016) and the Design and Technology Association (DATA) (2016) but perhaps they need to be explored more specifically for resources supporting EHoM.

8.7 Availability of engineers locally

When teachers and engineers collaborate to cultivate EHoM we have seen that benefits can accrue to everyone involved. However, we should not underestimate the challenge to both teachers and engineers to initiate and sustain these contacts. While national organisations exist to support teachers, it appeared that the more local the contact, the more effective it was. The interview process undertaken by the Primary Engineer teachers appeared to be a powerful method of creating a bond between the engineer, their employer and the school that led to very positive outcomes for teachers and learners, but it had to be actively managed by Primary Engineer. In the same way that teachers need support to engage with engineers, engineers need support to engage with the school and participate effectively in classroom activities.

8.8 Role of leadership in sustaining EHoM interventions

We began this section with an exploration of culture and we end it by exploring a key determinant of school culture/leadership (MacNeil *et al.*, 2009). The effective cultivation of EHoM requires both teacher and learner to take risks and teachers reported that an essential condition for the success of their interventions to embed EHoM was a supportive senior leadership team (SLT).

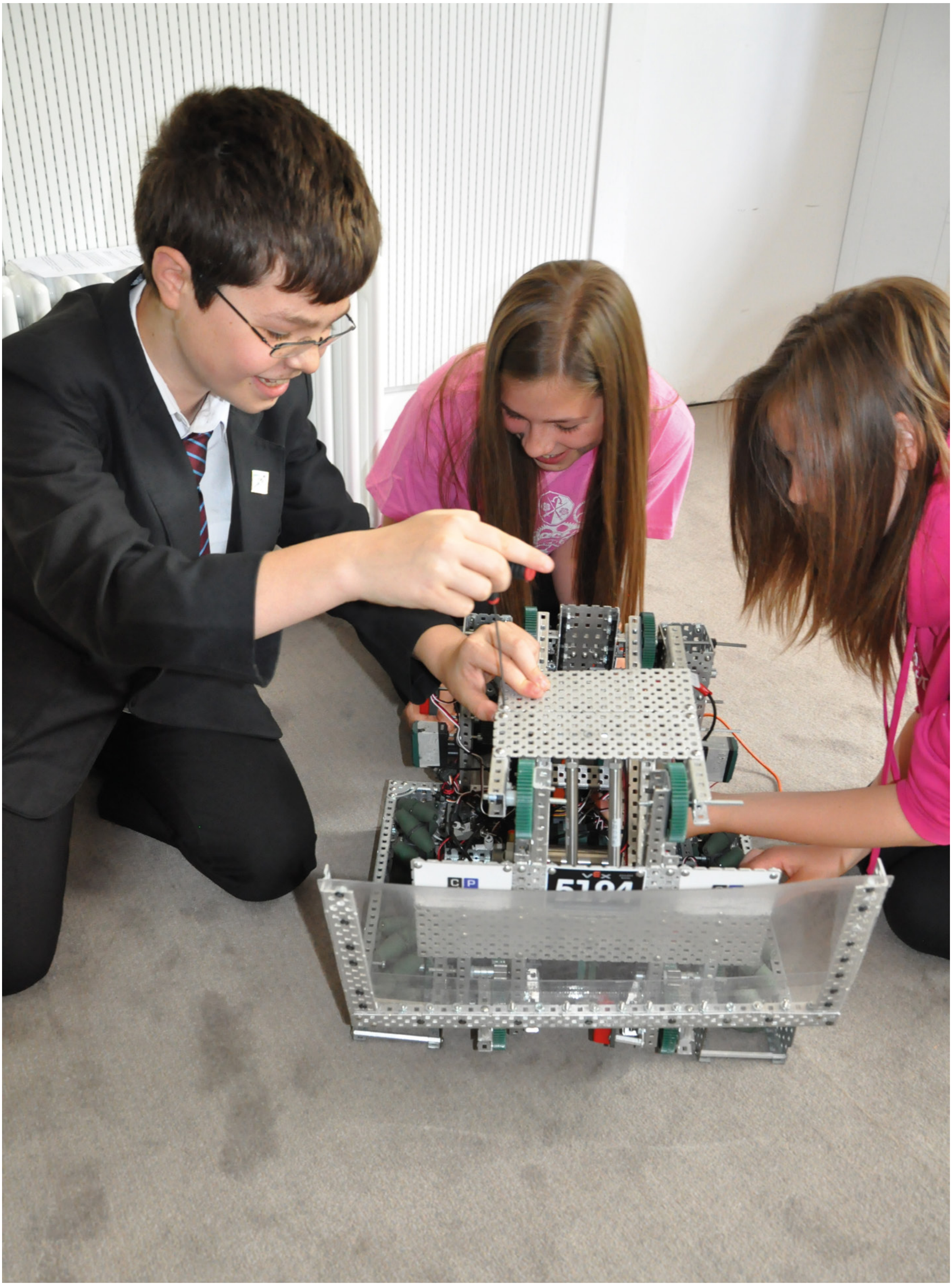
As one teacher reflected, active modelling by school leaders is vital:

"[School leaders] have to take risks themselves and be the role models for change. They have to empower governors and staff through their own leadership until their eyeballs bleed!"
(Teacher, primary school, TTRP)

Since teachers acknowledged that cultivating EHoM pushed them out of their comfort zone, appropriate CPD to support their interventions was essential. In several schools, the headteacher ensured that teaching assistants were also involved in promoting a common EHoM message to learners alongside the teachers. However, achieving common purpose across the whole school was probably easier in primary than secondary schools.

The presence of middle leaders in the participating schools was an enabler that contributed significantly to the successful embedding of EHoM. A key leadership role was played by teachers in posts such as: senior teacher, subject team leader, director of STEM, head of science or faculty manager.

It might be expected that schools such as UTCs would find it easier to embed EHoM. To a large extent this was true. However, we uncovered a number of challenges that might present barriers to cultivating EHoM. UTCs normally have two intake stages, at Years 10 and 12 (age 14 and 17), so learners arrive at the school having experienced at least two years in another secondary school with a range of experiences and abilities due to wider catchment areas. The students might only be with the school for two years and there is a challenge to cover all the subject content that is required to prepare them for GCSEs, leaving very little time to develop new habits or change old ones, according to teachers in University Technical Colleges (UTC).



9. Conclusions and implications

9.1 Conclusions

Our theory of change defined our over-arching hypothesis that dispositional teaching using appropriate pedagogies could develop in young people the habits of mind most valuable for engineers. Furthermore, given targeted support for professional learning, teachers could adopt these pedagogies to enthuse young people about engineering.

Our findings suggest that within schools wanting to implement more engaging engineering education, the three elements of the first step of our TofC are valid:

a) The reframing of engineering education within schools in terms of EHoM in addition to subject knowledge is something that teachers like and understand.

b) It is possible to create the climate for EHoM to flourish at Key Stages 1, 2 and 3 using three elements of a signature pedagogy for engineering – the engineering design process, tinkering and authentic engagement with engineers – to cultivate the desired engineering habits of mind.

c) A professional learning community that offered targeted support for teachers to design, implement and reflect on the impact of small-scale curriculum interventions in a range of different subjects did begin to change their practices.

With reference to the second step of our TofC, we have begun to better understand what school leaders and teachers need to do to embed their practices. We draw the following additional conclusions:

Table 1: Learning to be an engineer – a four step theory of change

If we

- **reframe engineering education to include desirable engineering habits of mind (EHoM) in addition to subject knowledge, and**
- **clearly articulate the principles and practices through which these EHoM can be cultivated in schools, and**
- **offer teachers targeted support for changing practices along with opportunities to co-design enquiries within the context of a reflective professional learning community**

Then

- **we can better understand what school leaders and teachers need to do to change their practices to embed more effective engineering education**

So that

- **we can share this understanding widely and**
- **more effectively support the process of successful implementation of engineering education in schools**

So that

- **more schools embrace engineering and**
- **more school students have high-quality experiences of engineering education, and**
- **more students choose to study engineering beyond school and, potentially, choose careers in engineering.**

1. **EHoM approach** – With support, all schools managed to use the four-step process for cultivating EHoM, locally interpreted and adjusted according to learner age and context. The least developed EHoM was systems thinking.

2. **Developing as learners** – As well as acquiring more confidence and capability in the target habits, there were significant improvements in terms of mindset (perseverance, learning from mistakes, playful experimentation) and the development of confidence as independent learners. The approach produced significant improvements in learners' understanding of engineers and engineering.

3. **Professional learning** – The mutually supportive environment of a professional learning community coupled with supported opportunities for the designing of small-scale tests of change was helpful in enabling teachers to begin to change their habits. But even in a supportive environment, teachers found it difficult to relinquish some of their former practices.

4. **Leadership** – The effective cultivation of EHoM requires a school culture supportive of exploring habits of mind and using interactive pedagogies, complementary summative and formative assessment practices, practical timetabling, appropriate physical space, available local engineers, and proactivity by senior leaders. Effective school leaders recognised the commitment and investment necessary to bring about a wholesale culture change.

5. **Engaging with engineers** – Engineers were most effectively engaged when they had an ongoing relationship with the school, which included extended conversations with teachers, working directly with young people, hosting visits for pupils and parents in their workplaces, and participation in the professional learning of teachers. Extended contact between engineers and schools makes learning relevant and provides adult role models to convince learners and their parents of the value of engineering as a career.

In terms of the third step of our TofC, we have begun to document the extent of the challenge and understand how some external changes might facilitate progress.

In terms of the fourth step we still have a long way to go. Specifically, we need to understand more about successful models of the leadership of the necessary changes required at all levels of the education system.

9.2 Implications

The conclusions of this research are of interest to a wide range of stakeholders. Here we offer a number of suggestions.

The engineering teaching and learning community

a) There is a growing consensus on the supportive role of signature pedagogies for engineering education. It might, therefore, be helpful to focus on the generation of free resources to enable more teachers to make their own small-scale changes. The Academy has already begun to identify strategies for co-ordinating the multitude of initiatives supporting engineering in education (Morgan *et al.*, 2016) and might like to consider how the promotion of EHoM and the development of additional teaching resources could be integrated into this process.

b) With a possible narrowing of choices at 14+ and work already done in developing pedagogies for D&T, it might be helpful to develop a range of case study exemplars of schools that are finding this subject a helpful progression route to engineering from age 11 onwards.

c) Given the opportunities afforded by the computing curriculum to encompass EHoM and the increasing recognition given to the value of integrated STEM programmes, it would be beneficial to clarify for teachers how the interdependencies between disciplinary thinking in computing, science, D&T, and mathematics, as well as creative subjects can encourage them to make rich cross-curricular links.

d) Habit change is hard and calls on more resources than individual schools or associations can find.

There is an urgent need for professional learning, of the kind we have found to be effective, to be provided for teachers in primary and secondary schools. This provision would most helpfully be located in professional learning communities offering multi-disciplinary expert support that facilitates consideration of integrative STEM programmes of study and develops practice in the elements of an engineering signature pedagogy. The national network of Science Learning Partnerships might provide a useful point of entry for developing this provision (Science Learning Partnerships, 2017).

Schools and colleges

e) The role of headteachers in creating and sustaining a climate that is conducive to the development of tomorrow's engineers is critically important. The Academy might like to collaborate with ASCL and other similar organisations to advocate the need to reframe our national challenges with the supply of engineers along the lines of the EHoM, their accompanying pedagogies and their necessary professional learning.

f) Headteacher and teacher organisations, together with subject associations, might like to collaborate to enhance existing science and engineering professional learning networks, of the kind referred to in 9.2d.

Engineering employers

g) Given the importance of engineers' engagement in partnership with schools, employers and schools need to facilitate 'boundary crossing' (Flynn *et al.*, 2016) to ensure successful outcomes of such partnerships, as demonstrated in our projects and earlier in Young Foresight (Barlex, 2012).

h) Engineers have the ability to bring context to the curriculum that can result in the co-creation of exciting curriculum challenges, resources and learning activities. This partnership between engineers and schools works best in an atmosphere of mutual respect, which needs to be nurtured by employers' representatives and engineering education organisations.

Government

i) The government's Industrial Strategy Green Paper (Department for Business, Energy and Industrial Strategy (BEIS), 2017) identifies challenges that need to be addressed to raise skills levels in the UK and offers a unique platform for proposals to fundamentally reframe the curriculum and scale-up the use of educational strategies that enhance young people's passion for engineering, develop their core skills and draw more of them into engineering careers.

j) There are many consequences of the reforms within the education system and it will be helpful for the governments of each of the four home nations to learn lessons from how schools in this report are rethinking their approach to learning for engineering and consider how best such lessons can be built into their respective systems.

k) With the proposal to create new Institutes of Technology (BEIS, 2017:42), the government might like to take note of the excellent pedagogic examples of technical education informed by EHoM offered by the UTCs in our study.

l) There is much diversity of educational provision in England. Given the desire of government to improve the quality of engineering education it might like to provide incentives for contrasting kinds of trusts and academy chains to develop leadership and implementation models in schools for young would-be engineers.

m) The involvement of employers in schools through the Careers & Enterprise Company is to be welcomed (BEIS, 2017:45) but government should note the value of harnessing the expertise of local employers to enhance engineering education in primary and secondary schools (Key Stages 1 to 3), as evidenced by our study, not just to provide experiences of the workplace, or using their technical expertise in curriculum design solely in higher level technical education (BEIS, 2017:43).

References

Adams, R. S., Forin, T., Chua, M., & Radcliffe, D. (2015) How do design teachers across disciplines coach their students in design thinking? *Mudd Design Workshop IX: Design Thinking in Design Education*, 28–30 May 2015, Harvey Mudd College, Claremont, USA. Available at: *http://www.researchgate.net/publication/284684992* [Accessed 07 December 2016].

Archer Ker, L., Dawson, E., DeWitt, J., Godec, S., King, H., Mau, A., Nomikou, E. and Seakins, A. J. (2016) *Science Capital Made Clear*. [Online] Available at: *https://kclpure.kcl.ac.uk/portal/files/49685107/Science_Capital_Made_Clear.pdf* [Accessed 10 March 2017].

Barlex, D. (2012) The Young Foresight Project: A UK initiative in design creativity involving mentors from industry. In: France, B. and Compton, V. (eds.) *Bringing communities together: Connecting learners with scientists or technologists*. Rotterdam: Sense Publishers.

Beaty, A. and Roberts, D. (Illustrator) (2013) *Rosie Revere, engineer*. New York: Abrams Books for Young Readers.

Beckwith, L., Kissinger, C., Burnett, M., Wiedenbeck, S., Lawrance, J., Blackwell, A., & Cook, C. (2006). Tinkering and gender in end-user programmers' debugging. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 231–240). New York, NY: ACM. *doi:10.1145/1124772.1124808* [Accessed 07 December 2016].

Born to Engineer (2016) Were you born to engineer? Available at: *https://www.borntoengineer.com/* [Accessed 06 December 2016].

British Science Association (2016) Welcome to the CREST Awards. Available at: *http://www.crestawards.org/* [Accessed 07 December 2016].

Department for Business, Energy and Industrial Strategy (2017) *Building our Industrial Strategy*. Green Paper. London: Department for Business, Energy and Industrial Strategy. Available at: *https://www.gov.uk/government/organisations/department-for-business-energy-and-industrial-strategy* [Accessed 09 February 2017].

Department for Education (2013, updated 2014) National Curriculum. [Online] Available at: *https://www.gov.uk/government/collections/national-curriculum* [Accessed 14 February 2017].

Department for Education (2016a) English Baccalaureate (EBacc). Policy paper. Available at: *https://www.gov.uk/government/publications/english-baccalaureate-ebacc/english-baccalaureate-ebacc* [Accessed 07 December 2016].

Department for Education (2016b) *Progress 8 and Attainment 8 measure in 2016, 2017, and 2018. Guide for maintained secondary schools, academies and free schools*. Available at: *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/561003/Progress-8-school-performance-measure-18-Oct.pdf.pdf* [Accessed 07 December 2016].

Design and Technology Association (2016) *KS3 D&T Learning Planner and Assessing without levels: Teacher Guide and Resource Bank*. Available at: *https://www.data.org.uk/for-education/curriculum/* [Accessed 02 December 2016].

Dweck, C. (2006) *Mindset: the new psychology of success*. New York: Ballantyne Books

Greenpower (2016) IET Formula Goblin. Available at: *http://www.greenpower.co.uk/racing/goblins/teachers* [Accessed 07 December 2016].

Hattie, J. (2012) *Visible learning for teachers: maximising the impact on learning*. Abingdon: Routledge.

Huntly, H. and Donovan, J. (2010) Is persistence taught or caught? Two contrasting case studies in the context of first year university teaching. *International Journal of Learning*, 17(1), 411–419.

Lucas, B. (2016) A Five-Dimensional Model of Creativity and its Assessment in Schools, *Applied Measurement in Education*, 29:4, 278–290.

Lucas, B., Hanson, J. and Claxton, G. (2014) *Thinking like an engineer: implications for the education system*. London: Royal Academy of Engineering.

MacNeil, A., Prater, D. and Busch. S. (2009) The effects of school culture and climate on student achievement. *International Journal of Leadership in Education*, 12(1), 73–84.

Manchester Robot Orchestra Challenge (2016) Join the quest to make the recycled Manchester Robot Orchestra. Available at: *http://www.robotorchestra.co.uk/* [Accessed 06 December 2016]

Millard, L. and Menzies, L. (2016) *The state of speaking in our schools*. London: LKMco/Voice21. Available at: *https://www.lkmco.org/oracy-state-speaking-schools/* [Accessed 13 November 2016].

Morgan, R., Kirby, C. and Stamenkovic, A. (2016) *The UK STEM education landscape*. London: Royal Academy of Engineering. Available: *http://www.raeng.org.uk/stemlandscape*

National STEM Learning Network (2016). Available at: *https://www.stem.org.uk/about-us* [Accessed 06 December 2016].

Pawson, R., Greenhalgh, T., Harvey, G. and Walshe, K.., (2004) *Realist synthesis: an introduction.* ESRC Research Methods Programme. Manchester: University of Manchester.

Price, D. (2013) *Engaging students. Pamphlet 2, Learning Futures*. Available at: *http://www.innovationunit.org/sites/default/files/Pamphlet%202%20-%20Engaging%20Students.pdf* [Accessed 07 December 2016].

Reason, P. and Bradbury, H. (eds.) (2008) *The Sage handbook of action research. Participative inquiry and practice*. 2nd Ed. London: Sage.

Reed, J. (2007) *Appreciative Inquiry: research for change.* Thousand Oaks, Calif.: SAGE Publications.

School of the Military (2016) Mission Status. Available at: *http://www.theschoolofmilitary.uk/* [Accessed 05 December 2016].

Science Learning Partnerships (2017). Available at: *https://www.stem.org.uk/science-learning-partnerships.* [Accessed 15 February 2017].

Shulman, L. S. (2005) Signature pedagogies in the professions. *Daedelus*, no. 134, 52–59.

Strobel, J., Wang, J., Weber, N.R. and Dyehouse, M. (2013) The role of authenticity in design-based learning environments: The case of engineering education. *Computers & Education*, *64*, 143–152.

Tomorrow's Engineers (2016) Blogs. Available at: *http://www.tomorrowsengineers.org.uk/blogs/* [Accessed 06 December 2016].

UK Space Agency (2016) Principia mission. Available at: *https://principia.org.uk/* [Accessed 06 December].

de Vries, P., Kortmann, R. and van den Bogaard, M. (2012) An authentic learning strategy for engineering students to acquire integrated management competencies. *SEFI 40th Annual Conference* 23–26 September, Thessaloniki, Greece.

ROYAL ACADEMY OF ENGINEERING

Royal Academy of Engineering

As the UK's national academy for engineering, we bring together the most successful and talented engineers for a shared purpose: to advance and promote excellence in engineering.

We provide analysis and policy support to promote the UK's role as a great place to do business. We take a lead on engineering education and we invest in the UK's world-class research base to underpin innovation. We work to improve public awareness and understanding of engineering.

We are a national academy with a global outlook and use our international partnerships to ensure that the UK benefits from international networks, expertise and investment.

We have four strategic objectives, each of which provides a key contribution to a strong and vibrant engineering sector and to the health and wealth of society.

Make the UK the leading nation for engineering innovation

Supporting the development of successful engineering innovation and businesses in the UK in order to create wealth, employment and benefit for the nation.

Address the engineering skills crisis

Meeting the UK's needs by inspiring a generation of young people from all backgrounds and equipping them with the high quality skills they need for a rewarding career in engineering.

Position engineering at the heart of society

Improving public awareness and recognition of the crucial role of engineers everywhere.

Lead the profession

Harnessing the expertise, energy and capacity of the profession to provide strategic direction for engineering and collaborate on solutions to engineering grand challenges.

Royal Academy of Engineering
Prince Philip House, 3 Carlton House Terrace, London SW1Y 5DG

Tel: +44 (0)20 7766 0600
www.raeng.org.uk

Registered charity number 293074