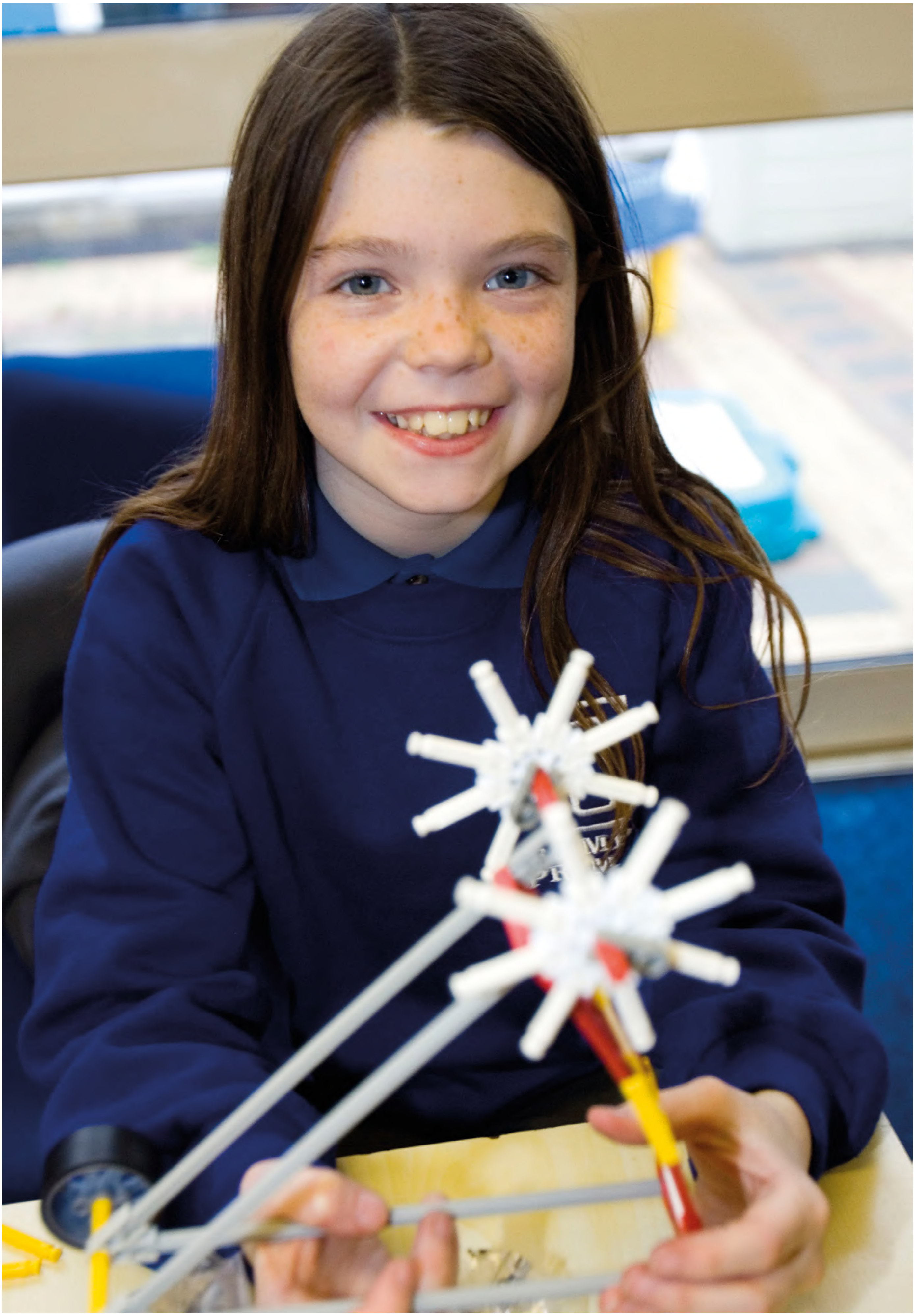
ROYAL ACADEMY OF ENGINEERING

Centre for Real-World Learning at the University of Winchester

Learning to be an Engineer

Implications for the education system

March 2017



Learning to be an Engineer
Implications for schools

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

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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

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The education team at the Royal Academy of Engineering

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Glossary of abbreviations and terms

AI	Appreciative inquiry
ASCL	Association of School and College Leaders
CBI	Confederation of British Industry
CPD	Continuing professional development
CRL	Centre for Real-World Learning at the University of Winchester
D&T	Design and technology
DATA	Design and Technology Association
DBEIS	Department for Business, Energy & Industrial Strategy
DfE	Department for Education
EBacc	English Baccalaureate
EHoM	Engineering habits of mind
EDP	Engineering design process
FE	Further Education
GTC Scotland	General Teaching Council for Scotland
IESIS	Institution of Engineers and Shipbuilders in Scotland
IET	Institution of Engineering and Technology
IMechE	Institution of Mechanical Engineers
Key Stage	The English National Curriculum is organised into block of years called 'Key Stages'
LEP	Local Enterprise Partnership
NEA	Non examined assessment
Ofsted	Office for Standards in Education, Children's Services and Skills
SCQF	Scottish Credit and Qualifications Framework
SEERIH	Science & Engineering Education Research and Innovation Hub at the University of Manchester
SEN	Special educational needs
STEAM	Science, Technology, Engineering, Arts & Design and Mathematics. An international movement that champions the integration of art and design with the other four STEM subjects to enhance creativity and innovation
STEM	Science, Technology, Engineering and Mathematics
STEMNET	Science, Technology, Engineering and Mathematics Network that delivers the STEM Ambassadors programme
TLaE	Thinking Like an Engineer
TofC	Theory of Change
TTRP	Tinker Tailor Robot Pi
UTC	University Technical College
VLE	Virtual learning environment
WISE	A Campaign to promote women in science, technology and engineering

Foreword

The Academy welcomes this important new report exploring how engineering habits of mind – the thinking characteristics, skills and attributes of engineers – can be integrated in the real world of busy schools and colleges to engage the next generation of engineers. This follows an earlier piece of analytic research, *Thinking like an Engineer*, which worked with engineers and engineering educators to develop these engineering habits of minds.

This is particularly important now due to the well-documented shortage of engineering skills in the UK. This shortage not only impacts on the engineering profession, but the whole economy due to the pervasive nature of engineering skills. The engineering community is concerned that young people and the wider public do not understand engineering's valuable contribution to society and the exciting, diverse career opportunities it can offer. Therefore, in order to address the engineering skills gap, it is essential we ignite young people's interest in this exciting, creative profession.

This report provides insight into the key barriers that must be tackled in order to inspire young people throughout their education and improve the supply of engineering skills. Engineering employers, the engineering teaching and learning community, educators and the government must work together to help grow the supply and quality of engineers. The Academy is grateful to the authors for highlighting practical strategies for developing teaching and learning that will encourage a passion for engineering in young people in the UK.

Professor Helen Atkinson CBE FREng
Chair of the Education and Skills Committee

Executive summary

This report, commissioned by the Royal Academy of Engineering, 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).

The report identifies four principles that underpin the kinds of teaching which 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 better understanding of engineering. It describes many benefits to the capability and confidence of teachers, in particular their engagement with practising engineers.

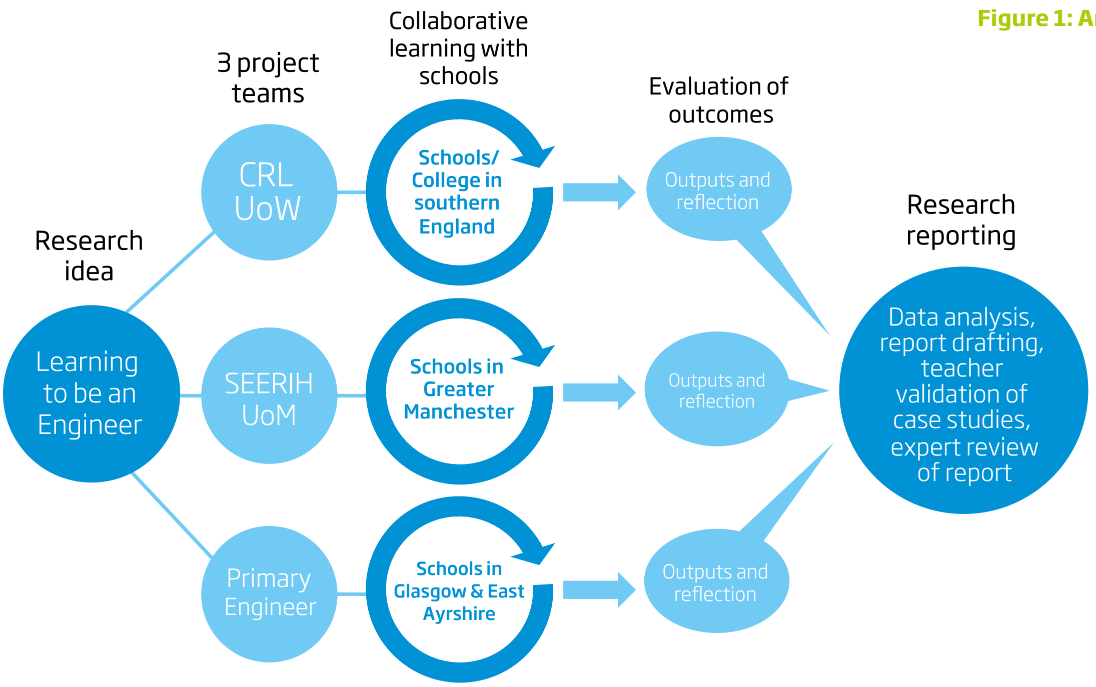
The report identifies some key barriers to progress and suggests practical strategies for overcoming these challenges. Enablers include: a conducive school culture, positive alignment with existing teaching and learning approaches, effective integration of habits of mind within subjects, appropriate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

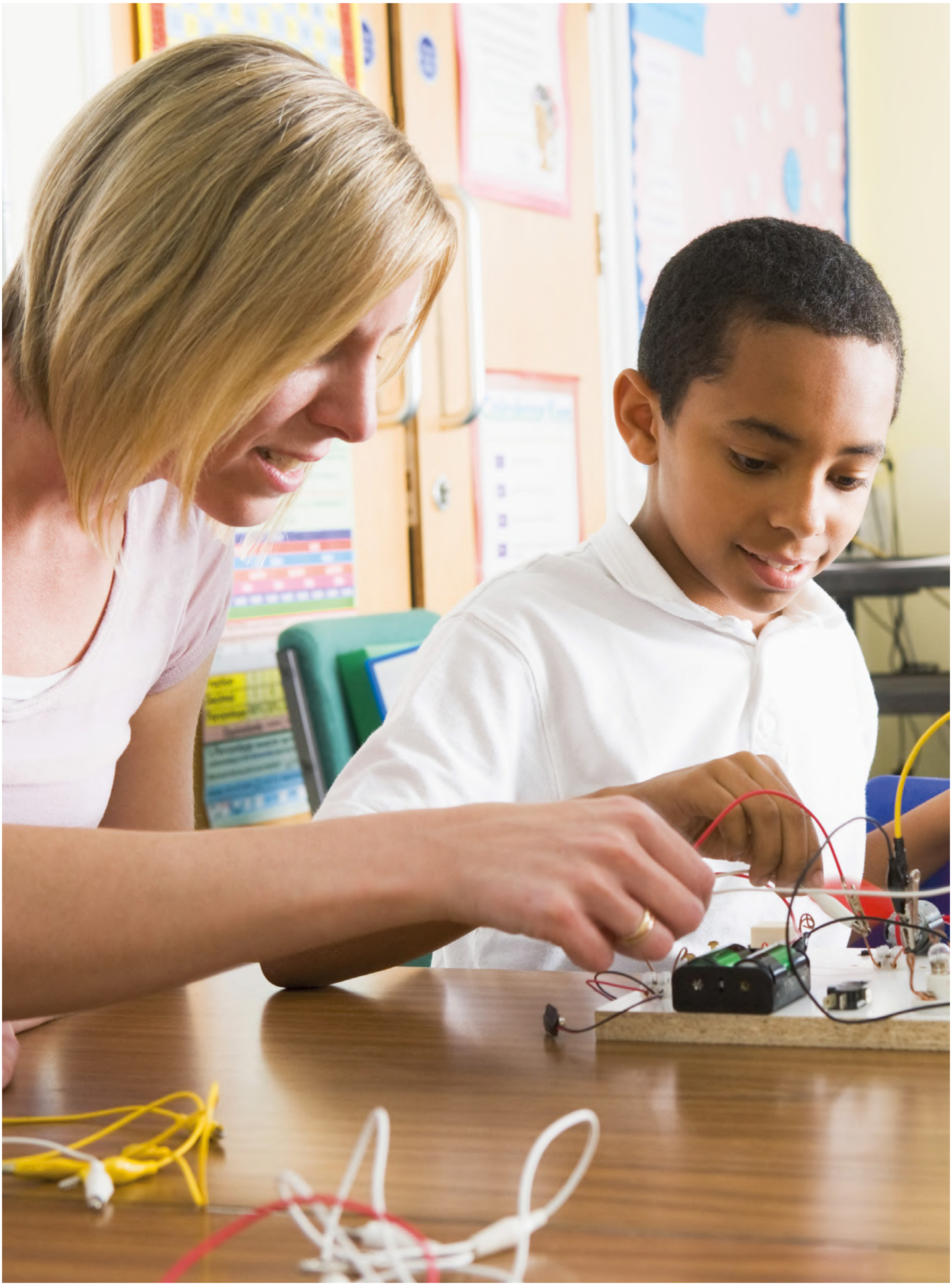
Based on the findings of the report, the Royal Academy of Engineering makes six broad recommendations:

- The need for more extensive promotion of EHoM as a mechanism for improving science capital 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 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 to embed EHoM in their teaching. Figure 1, below, describes the research diagrammatically.

Figure 1: An overview of the research





1. Introduction

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 'engineering habits of mind' (EHoM) – systems-thinking, adapting, problem-finding, creative problem-solving, visualising, and improving, see Figure 2.

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 more than 3,000 pupils. The report was a collaboration between a largely psychology-influenced research group focusing on dispositional teaching at the University of Winchester (CRL), a science and engineering education centre at the University of Manchester (SEERIH), and a third sector organisation, Primary Engineer. All three partners shared the aim of bringing fresh thinking to the challenge of teaching engineering in schools and are united by the belief that primary and secondary education is the most effective period in which to enthuse young people about engineering.

Each partner designed a programme of support for schools to embed

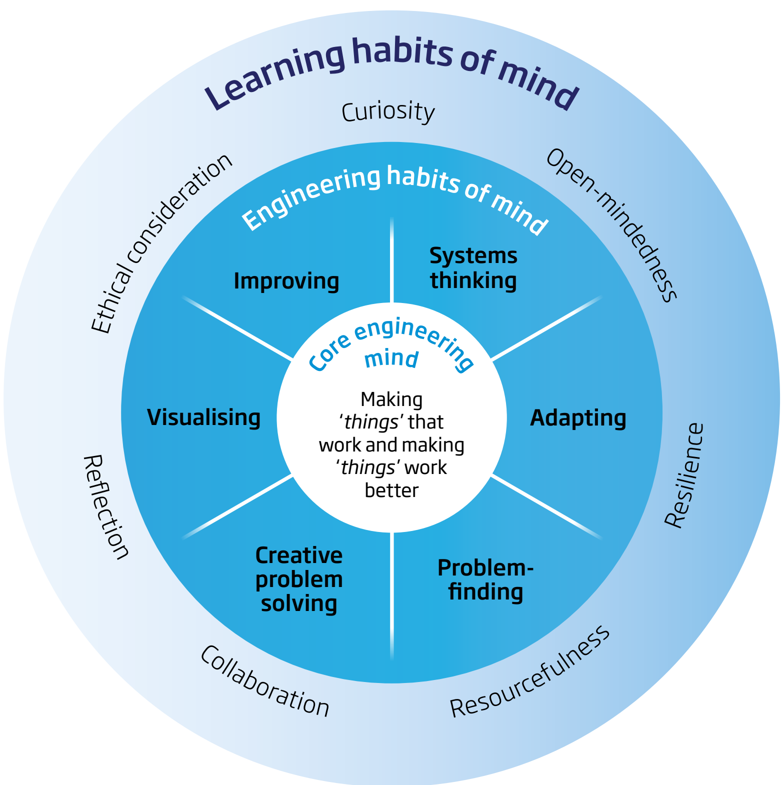


Figure 2: Engineering habits of mind

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. This report provides a combined account of these three projects and the research findings are derived from an evaluation of the teachers' activities and the resources they produced.

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. This is not to suggest that more engineering qualifications are needed in school, but that engineering education could refer to any aspect of the school curriculum or enrichment activity within which EHoM could be incorporated to engage future engineers.

The report also provides a brief overview of the wider educational context within which the projects were undertaken and notes the challenges and opportunities offered by some of the changes currently affecting education in the UK.

2. Wider educational context

2.1 Changes facing schools

While this research was being conducted, schools have gone through a time of considerable change, especially in England. There are three main elements of this change: the status of schools, their curriculum and their accountability. The engineering education community is aware of the potential impact of these changes on the challenge to engage more young people with engineering. The Royal Academy of Engineering suggested that seven areas need to be addressed if 'meaningful increases in the number of young people pursuing engineering as a career' are to be achieved (Morgan *et al.*, 2016:7):

- Perceptions of young people, their parents/carers and other influencers, and attitudes towards engineering.
- Teachers and teaching.
- Under-representation of specific groups.
- Careers advice and guidance, curriculum enhancement and employer engagement.
- Curricula, qualifications, assessment and accountability measures.
- Pathways to progression.
- Facilities and capacity in further education (FE) and higher education (HE).

In our work we focused on how teachers and teaching can change, and in this section we briefly review how the wider educational environment might influence opportunities for cultivating EHoM.

School and college status

In England there has been a continued focus on academisation, with a renewed emphasis on encouraging primary schools as well as secondaries to become academies. Within the overall academy 'brand' two new categories of secondary school have been established that afford opportunities for promoting STEM, (Science, Technology, Engineering and Mathematics): University Technical Colleges (UTCs) and Studio Schools. UTCs are schools for 14–19 year olds that specialise in providing technically-oriented education. Developed in response for demands to increase the nation's advanced technical skills, each UTC is sponsored by employers and a local university. The curriculum includes projects based on real-world problems in collaboration with employers and the school environment emphasises a professional workplace culture. There are now 48 UTCs and by 2018 it is expected that there will be over 55 across England (University Technical Colleges, 2016a). Although recent analysis suggests that they are underperforming when compared to a similar sub-set of secondary schools (Hannay, 2016), their outcomes at this early stage of their development appear to be positive (University Technical Colleges, 2016b). In-depth evaluations of the student experience at UTCs reveal that students are highly motivated by the social experiences and active learning pedagogies provided by the schools, and that impressive outcomes in engineering and other academic subjects have been achieved (Comino Foundation, 2016; Malpass and Limmer, 2012).

Studio Schools are small, typically with fewer than 300 students and also seek to model themselves on a 9–5 workplace experience rather than on a more typical school timetable. There are currently just over 30 schools open (Studio Schools Trust, 2016).

Three UTCs took part in our research, and although a discussion took place with both the Studio Schools Trust and with one studio school, it was not possible to engage this kind of school in the research at such an early stage of their evolution.

Curriculum

There has been a major review of the National Curriculum in England

(DfE, 2013). This change has been coupled at secondary level, with the introduction of the English Baccalaureate (EBacc) (DfE, 2016a). EBacc is a new school performance measure indicating how many pupils get a grade C or above in certain subjects at Key Stage 4 in any state-funded school. The original intention was to advocate a more knowledge-based approach to the curriculum. However, the selection of the core academic subjects comprising the EBacc – excluding arts subjects and design and technology (D&T) – encourages schools to privilege English, mathematics and science and so may limit the range of options on offer to students at age 14. At a time when many are arguing that we need to look for tomorrow's engineers from the whole curriculum and not rely on high performance in mathematics and science (Howes *et al.*, 2013), EBacc may make attempts to enhance interest in engineering more challenging.

Beyond subject knowledge, business leaders have also made clear that the development of key capabilities such as resilience, creativity and curiosity as well as an awareness of working life are important, and that this should be the basis on which we judge the success or otherwise of schools (CBI, 2012). Addressing this priority becomes ever more critical as the demand for 'soft skills' in the labour market increases. An education that focuses on developing soft skills, or dispositions such as perseverance, sociability and curiosity, has the potential for enhancing an individual's success in the labour market in the longer term (Heckman and Kautz, 2012).

New kinds of accountability

Two accountability measures introduced for secondary schools from 2016 onwards, Attainment 8 and Progress 8, may also have unintended consequences that adversely affect interest in engineering. Attainment 8 measures the achievement of a pupil across eight qualifications including mathematics (double weighted) and English (double weighted), three further qualifications allowable within EBacc and three further qualifications that can be GCSE qualifications or any other non-GCSE qualifications on the DfE approved list (DfE, 2016b:5).

Progress 8 is a type of value-added indicator that aims to capture the progress a pupil makes from the end of primary school to the end of secondary school. In it, pupils' results are compared to the actual achievements of other pupils with the same prior attainment (DfE, 2016b:5).

On the surface, both these changes make sense, especially Progress 8, because they offer a means of showing real progress against an agreed benchmark. However, the subjects which count for the value added calculation are a limited set of GCSEs and some options favoured by many potential engineers, for example D&T and music, are not in the core.

2.2 Current issues in education for engineering

The challenge of meeting the demand for engineering skills in the future, let alone ensuring that young people are ready for the world of work by the time they leave secondary education, shows no sign of diminishing.

The *Annual Skills Survey* published by the Confederation of British Industry (CBI) and Pearson (CBI/Pearson, 2016) provides a useful snapshot of employers' perspectives on how well the education system is preparing young people for employment. Employers expect to see a rise in demand for higher skilled employees and a decline in demand for those with lower skills. This predicted demand is particularly high in engineering, science and high-tech industries and the CBI/Pearson report calls for more effective ways to improve the supply of STEM-skilled people. Some suggest that the 'skills gap' has more to do with employers' reluctance to offer appropriate compensation than education provision (for example, van Rens, 2015), but we disagree.

Writing in *Big Ideas: The future of engineering in schools*, Professor John Perkins CBE FREng says that "growing awareness of the need for more radical approaches will be needed if we are to achieve the step change in supply that all agree would be desirable" (Finegold, 2016:2). It is encouraging to see that not only has advice been produced for STEM employers on engaging with education (Royal Society, 2016), but also that industry links with primary education are beginning to be taken seriously. The CBI has acknowledged that business links with primary schools are important but underdeveloped, and that industry can play an important role in supporting primary schools shape children's aspirations and attitudes (CBI, 2015). Furthermore, research by the organisation Education and Employers Taskforce has found that on-going engagement by young people in school-mediated employer initiatives while at secondary school is linked to their potential higher wage earnings during adult life. This is attributed to the development of social networks and access to trustworthy information through employer contacts, which generate realistic career aspirations among young people (Mann and Percy, 2014).

The CBI recommends that businesses should enable teachers to spend time with them as part of their continuing professional development (CPD) (CBI, 2014), a suggestion that is facilitated though the Insight into Industry scheme organised by the Institution of Mechanical Engineers (IMechE, 2016).

It has been suggested that the Primary Futures programme from the Education and Employers Taskforce could support enhancing science, and bring in 'inspiring speakers from industry into the classroom, sparking the interest of young people in different careers and sectors,' (CBI, 2014:32), although the support that primary teachers most sought from industry was the provision of equipment and facilities (CBI, 2014:23).

Despite these encouraging initiatives, the well-documented and broad array of factors influencing learners' progressive loss of interest in studying STEM subjects beyond primary school remains a challenge to overcome. The factors include an increase in passive rather than active learning methods following transition from primary to secondary school, lack of inspirational teachers qualified in STEM subjects, perceived difficulty of STEM subjects and an emphasis on achieving high grades leading to the selection of what are perceived as 'easier options', negative stereotypes of those interested in science as 'geeky', lack of suitable adult role models, lack of relevance and a decontextualised curriculum, poor careers guidance and lack of knowledge of the wide range of career possibilities offered by studying STEM (A.T. Kearney, 2016; IET, 2008; Morgan *et al.*, 2016). There are

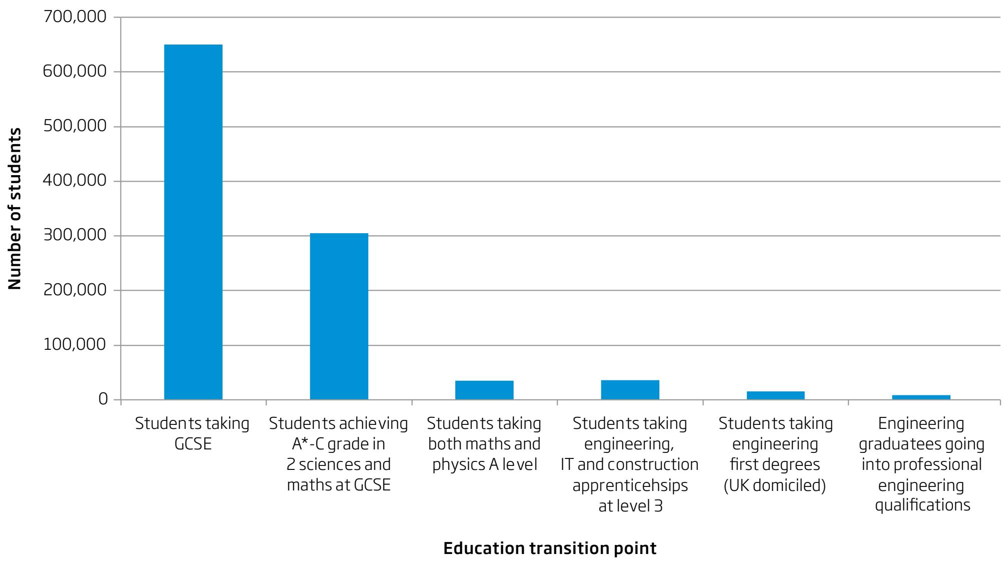


Figure 3: Key transition points for young people across various stages of education towards engineering (Morgan *et al.*, 2016:14)

also strong personal and societal influences, such as an individual's levels of self-confidence and family background (Schoon *et al.*, 2007).

These factors combine to influence the choices young people make as they decide which GCSEs to study and whether to consider entering the engineering profession, see Figure 3.

The progressive decline in interest in STEM subjects post-16 puts UK business growth at serious risk (CBI, 2014). The reluctance of girls in particular to study physics, despite their strong performance at GCSE in this subject, has been the focus of extensive research by Louise Archer and her colleagues who suggest that a critical factor at play in girls' choices is their 'science capital' (Archer *et al.*, 2016a). 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.*, 2016b). These researchers also suggest that school ability groupings or 'setting' may be responsible for an uneven distribution in the growth in numbers taking 'Triple Science', (biology, chemistry and physics as separate subjects) at GCSE that adversely affects students from widening participation backgrounds (Archer *et al.*, 2016c).

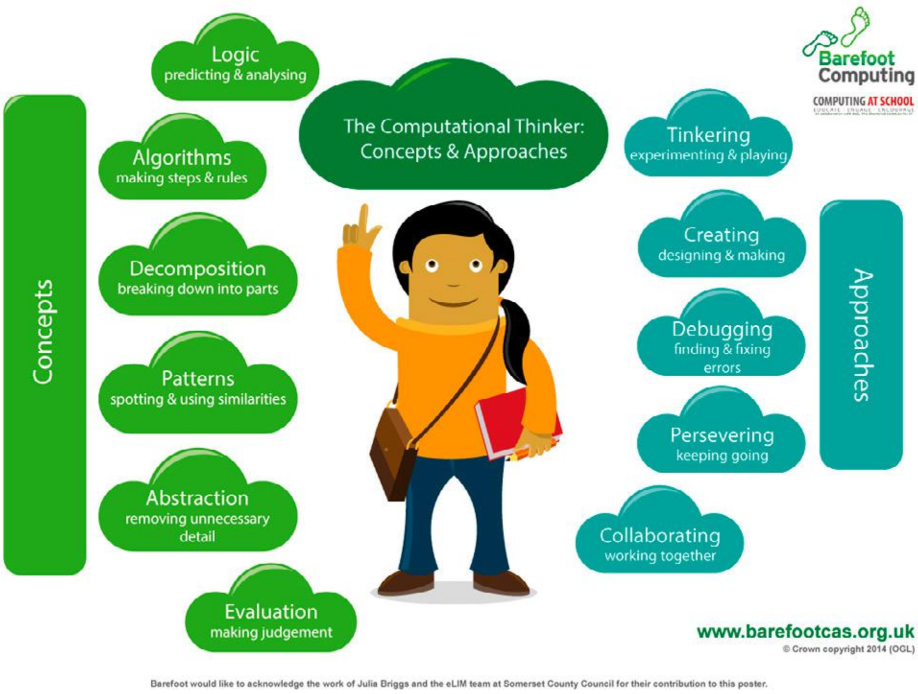
2.3 Opportunities for EHoM in the National Curriculum and the Curriculum for Excellence

There are opportunities for EHoM presented by the revisions to the National Curriculum and also within the Curriculum for Excellence, the curriculum framework for Scotland used by the Primary Engineer teachers in our study.

In the National Curriculum (DfE, 2013), ways of expressing disciplinary thinking in computing, science D&T and mathematics, such as 'computational thinking', 'working scientifically', 'design, make, evaluate' and the use of 'mathematical vocabulary' may all offer a launch pad for EHoM. Within computing – the subject that replaced ICT – the Barefoot Computing project (Computing at School, 2016) has published a model of the primary school 'computational thinker' that is made up of 6 concepts and 5 approaches to working, see Figure 4.

Computational thinking is a way of thinking about solving problems effectively and efficiently and aligns well with the EHoM approach. For example, the *decomposition* of complex problems into smaller more manageable chunks helps pupils better *visualise*

Figure 4: Computational thinking (Computing at School/Barefoot Computing, 2016)



solutions. *Systems thinking* reflects the ability to understand how smaller sections of a problem or system fit with, and interact with, each other and to identify such interactions, it is helpful to understand *abstraction* to help spot *patterns* in systems.

Within science there is another opportunity to incorporate EHoM, offered by the renaming of science enquiry to 'working scientifically' (DfE, 2013). 'Working scientifically' includes five types of science investigations, which overlap with EHoM, covering: observing over time, finding patterns and relationships, identifying and classifying, researching using secondary sources, comparative and fair testing. A strong emphasis is also placed upon pupils asking their own questions, and making their own decisions as they undertake investigations. Furthermore, the revised science curriculum places a greater emphasis on learners' understanding of the uses and implications of science, which could be enhanced through the use of real-world engineering examples.

The D&T curriculum offers the potential for including an engineering experience for learners up to the age of 14, thanks to employers shaping it to reflect their current needs, David Barlex and Richard Green noted (Barlex, 2016; Green, 2015). Unlike core subjects such as mathematics and English, the revised D&T curriculum features learning objectives that are not year-specific, which has the potential to diminish appropriate sequencing of objectives.

Therefore, in an attempt to ensure that D&T learning is appropriately sequenced to achieve progression, the Design and Technology Association (DATA) has produced a Progression Framework 'to help teachers plan activities that build on learners' previous learning and offer an appropriate level of challenge' (DATA, 2016:1). A scan of the framework reveals numerous occasions when EHoM could be incorporated, where often the same language is used. For example, the EHoM improving is referred to under Evaluating across Key Stage 1 and adapting is frequently mentioned in KS2 and KS3.

Furthermore, through designing and making tasks in D&T at Key Stage 3, learners have to make design decisions that relate strongly to EHoM. Barlex (2007) has developed the following graphic, see Figure 5, which provides a summary.

The decision-making that learners need to undertake involves five key areas of interdependent design decision: conceptual (overall purpose

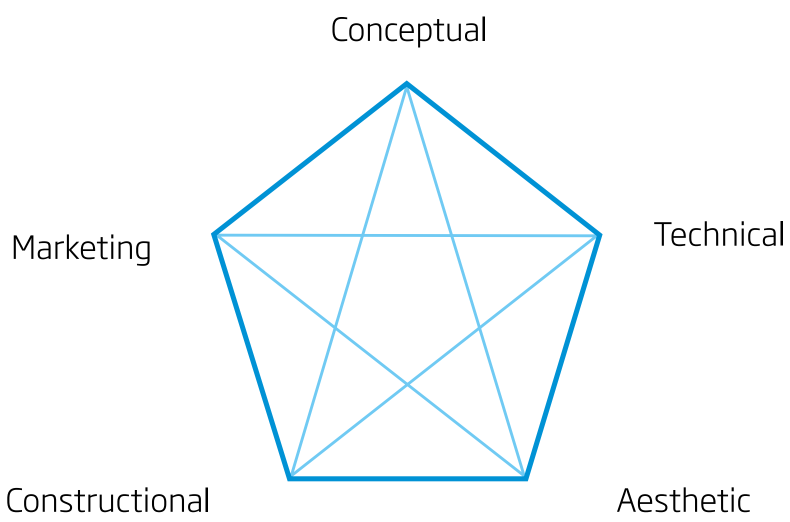


Figure 5: Pupil design decisions in a designing and making assignment

of the design), technical (how the design will work), aesthetic (what the design will look like), constructional (how the design will be put together) and marketing (who the design is for and how it will be sold). The interdependence of these areas is an important feature of design decisions and it is the juggling of these various decisions to arrive at a coherent design proposal and creation of a working prototype that provides the act of designing and making with such intellectual rigour and educational worth and an essential part of technology education.

As for other subjects, while Howes and colleagues (2013) suggest that engineering can provide a highly authentic context for learning mathematics and science, they also suggest that schools may be able to ensure that young people with design interests retain links with STEM, if art is integrated, to create STEAM. This new acronym deliberately puts the arts into our thinking about STEM and organisations have been created to demonstrate the usefulness of this approach, such as the Rhode Island School of Design (STEM to STEAM, 2016). STEAM may offer students who have leaked from the STEM pipeline an opportunity to re-join it, having travelled 'by a different route, to a later rendezvous' (Howes *et al.*, 2013:10). The New Model in Technology and Engineering (NMITE) University under development in Hereford is an excellent example of the bold steps needed to help young people realise this possibility (NMITE University, 2017).

Intended to engage children from the age of three to 18, Scotland's Curriculum for Excellence (Education Scotland, n.d.) is designed to provide young people with the knowledge, skills and attributes they need for learning, life and work in the 21st century. Its broad curriculum expectations would seem to lend itself to the central principles behind developing EHoM more obviously than its English equivalent. In the mathematics curriculum for example, engineering is mentioned 21 times in the Curriculum for Excellence, whereas it is only mentioned twice in the National Curriculum. Emphasis is placed on interdisciplinary learning and open ended tasks, with engineering references featured in mathematics, technologies, science and computer science subjects. The Curriculum for Excellence also makes strong connections between education, training and work.

Throughout our report teachers often refer to the stages of the curriculum within which they undertook their interventions, so for ease of reference we list the stages and their associated learner ages in Appendix 1.

2.4 Integrated STEM programmes

Looking beyond opportunities for embedding EHoM within discrete curriculum subjects, the creation of integrated STEM programmes (focusing on science, technology, engineering and mathematics) raises additional possibilities for EHoM. There is a growing focus on how the interrelationships between these disciplines can be advanced through integrated STEM education programmes, to reflect their interconnected use in the real world (Johnson *et al.*, 2015; Kelly and Knowles, 2016). Integrated STEM programmes at primary level can be particularly important for developing self-belief as a STEM learner although it is claimed that their implementation in schools is under-researched (Rosicka, 2016). Within secondary schools, an evaluation of the integrated STEM pathfinder programme (2008–2009) found that positive outcomes for learners included: increased awareness of the links between STEM subjects, enhanced problem solving, independent learning and investigation skills, and increased positive attitudes towards STEM careers (Springate *et al.*, 2009).

Although there are some examples of integrated STEM in the UK, such as iSTEM+ (STEM Learning, 2017), there is still uncertainty about how it might best be organised and evaluated. Some argue that it is not clear how teachers can foster these connections across STEM subjects in order to make them more transparent and meaningful to learners, so as to improve learning outcomes (English, 2016a:3-4/8), and while an integrative approach to STEM education can lead to a range of positive outcomes for learners, it has been suggested that it is very difficult to find evidence of improvement of higher order outcomes through STEM integration (Howes *et al*., 2013).

Although there is still much to be learnt about the most effective methods for integrating STEM there is some guidance from existing programmes. Teachers have to be comfortable working across traditional subject and departmental boundaries and ensure that learners also are comfortable working with open ended problems. The sequencing of the challenge has to match the learners' abilities, with appropriate scaffolding to develop pre-requisite skills. The challenges must appeal to learners' interests and appropriate assessment approaches have to be found (Denson and Lammy, 2014). Furthermore, the scaffolding must be balanced to ensure that learners understand core concepts, but are also allowed to apply their learning as they choose to solve the problem (English, 2016a:7/8; English and King, 2015). These aspects of scaffolding in particular are also emphasised by Kapur, who concludes that 'productive failure' has an important role in supporting conceptual learning (Kapur, 2016). In engineering education language, Al-Atabi (2014) calls this 'failing smart'. This is an attitude that accepts failure as an essential element of innovation and is reinforced through plenty of opportunities to practice and experience 'fast/cheap failure' in the early stages of the project.

Nevertheless, even in the USA, where the integrative design of engineering challenges is more common, teachers still struggle with assessment. It is suggested that a compelling case can be made for students taking more responsibility for self-assessment, but 'it does not account for the time and skills needed for students to be able develop their own rubrics and other assessment tools' (Denson and Lammy, 2014:10) nor does it take into account high stakes assessment systems such as in the UK. Assessment needs to be revisited to reinvigorate STEM (Howes *et al*., 2013:16).

2.5 Summary

The overall educational context within which we introduced EHoM is therefore one of opportunities and challenges. The net effect of changes to school and college status, new curriculum arrangements and different approaches to accountability has meant that involvement in yet another initiative, in this case, to embrace EHoM, is not for the faint-hearted! Nevertheless, despite the distraction of all these other challenges, we still found schools willing to pilot interventions in their classrooms designed to cultivate EHoM.

3. Our approach to the research

In moving from conceptual research to a series of interventions, we have adopted an approach widely used in community development and healthcare (Davidoff *et al.*, 2015; Weiss, 1997). This requires those undertaking and seeking to evaluate new approaches to articulate their beliefs as to how and why any approach works. Therefore, in this section we clarify our 'theory of change' (TofC) and briefly explain the research methods influencing our evaluation of the teachers' interventions.

3.1 A Theory of Change

Our Theory of Change (TofC) is articulated in Table 1 below. In essence, we are suggesting that to overcome the 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 such as systems-thinking, problem-finding and visualising).
- Describe the teaching and learning methods most suited to cultivating our desired habits of mind.
- Build teacher capability through professional development.

In this study we have focused on: understanding more about the challenges of reframing engineering in a subject-dominated world, the principles and practices involved in cultivating EHoM, the nature of the professional learning required, the kinds of support needed by teachers and school leaders and the conditions which need to be in place to ensure that new approaches to engineering education in schools are embedded.

Our over-arching hypothesis is that while we need to continue to value disciplinary knowledge and practical

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.**

skills, we also need to think more about the dispositions we want our engineers to acquire. To do this, we contend, we need to think more carefully about dispositional teaching and its associated learning methods (Costa and Kallick, 2014). Dispositional teaching specifically focuses on pedagogies through which certain valued dispositions can be cultivated in learners using the formal and co-curriculum.

To this end our more detailed research questions were:

- Which dispositional learning and teaching methods do teachers find most useful for the cultivation of EHoM?
- What impact does engaging with EHoM have on learners?
- Does professional learning within a professional learning community (PLC) help teachers change their habits?
- What school conditions are most favourable for cultivating EHoM?
- How can engineers be involved in supporting teachers to cultivate EHoM?

3.2 Research design and methods

The methodology for this small-scale intervention study was designed in line with our TofC model. We have previously identified the six EHoM and articulated possible approaches to their cultivation (Lucas and Hanson, 2016a; Lucas and Hanson 2016b). This report builds on this earlier work and presents the outcomes of a small-scale intervention study aimed at exploring the process of implementing EHoM in primary and secondary schools, and to a lesser extent with 16 to 19 year olds in further education colleges.

The schools and college participated on a voluntary basis and were recruited largely through convenience sampling on a 'first come-first served' basis in response to advertising by the project teams among their existing partner base of schools. The specific methods of selection and the schools involved are described in the information on each project in Section 4.

The 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). They formulated a simple research question based on the format 'If I do X, will Y happen?' where the X was the aspect of their teaching they planned to change and the Y was the EHoM, or sub-EHoM they aimed to cultivate. Although we defined the format of the question, we did not define specifically how these interventions should be enacted.

Teachers evaluated the impact of their interventions on their learners, on themselves and on their school using a number of methods, including learner self-report questionnaires administered before and after the intervention, teacher observations of learner activity, interviews with learners, and teachers' professional assessment of learner outcomes. They analysed the data they gathered and compiled presentations and reports explaining in what ways and with what effect their intervention influenced their learners' outcomes and their own practice in cultivating EHoM. This reflection enabled them to explore their own 'taken-for-granted' practices and provided context-specific evidence about the process of cultivating EHoM.

The teachers' attendance at learning events organised by each of the three project teams and at joint dissemination events hosted by the Academy was a core component of the study and contributed to a spirit of collaborative enquiry. By sharing their reflections with others, teachers' knowledge about 'what worked' in their context could inform the wider professional community and afford credibility to the personal knowledge being created through the action research (Colucci-Gray *et al.*, 2013). This sharing of experience within a learning community is important in an area like EHoM cultivation, where teachers are attempting to change their classroom practice (Wiliam, 2007). David Barlex (2016) has suggested that, although teachers involved in implementing engineering education have a multitude of support organisations prepared to come into the classroom to talk to children or provide resources about engineering, there are fewer professional organisations through which they can share experiences of providing engineering education.

These two features, teacher enquiry into practice and engagement in a professional learning community, are now acknowledged as essential elements of effective teacher professional development (Cordingley *et al.*, 2015; Stoll *et al.*, 2012; Timperley *et al.*, 2014). We know that the most significant impact on learner outcomes is achieved when teachers generate knowledge by investigating their own practice at the same time as testing out theory produced by others (Cochran-Smith and Lytle, 2001).

3.3 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. AI is a research approach that is 'particularly useful for exploring the potential for building on achievement' (Reed, 2007:180). It focuses on and seeks to understand what is working particularly well when the process or activity being evaluated is successfully deployed. At a time when teachers were managing many competing challenges, AI helped to ensure that a positive atmosphere was maintained when discussing changes associated with the research.

In addition to collating and analysing the teachers' evaluations of their action research interventions we also undertook semi-structured interviews with them and gathered qualitative feedback via a questionnaire. Six schools compiled short reports about their experiences which were published in a special issue of the journal *Primary Science* (Winter 2016/17) called 'Tinkering for Learning'. Although we did not gather data directly from learners, most of the teachers' reports did include evaluation comments gathered from their students.

3.4 Data analysis and reporting

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:

"…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)

We wanted 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 had on learners, teachers and engineers. However, it was important to embed this understanding within the specific contexts of the sites in which the interventions took place. Although we had generated theory about the most appropriate ways of cultivating EHoM, we had to acknowledge that intervention was inevitably going to be tailored by teachers to suit their own beliefs, abilities and resources and then be enacted within the unique social system of their school (Rycroft-Malone *et al.*, 2012). Analysis of the data using techniques associated with realist synthesis offered the opportunity of establishing not simply 'what works' but also 'for whom' and 'under what circumstances'. This perspective, with its explanatory rather than judgmental focus, also aligned with our AI philosophy.

We used thematic analysis (Braun and Clarke, 2006) to code the data and produced a synthesis of the ways in which teachers had cultivated EHoM. We looked for patterns, identifying issues which were frequently repeated in the data but not specific to any one sector, such as 'learning from failure' or factors associated with 'growth mindset'. These themes were then clustered under three major areas for reporting: i) outcomes for learners and teachers ii) the role of engineers in supporting teachers to cultivate EHoM and iii) enablers and barriers for cultivating EHoM in schools. Finally, conclusions and recommendations were derived from our interpretation of these outcomes emerging from the three projects.

Extended descriptive case studies for 12 schools were compiled that described why the school became involved, explained how teachers engaged with the processes of cultivating EHoM and summarised the principal outcomes for learners and teachers in that specific context. Shortened versions of the case studies have been used in this report to illustrate our findings and the full versions are available on the project website hosted by the Academy. We have also used short excerpts from interview transcripts and teachers' reports to illustrate our findings in the report.

3.5 Summary

This was a small-scale qualitative study designed to begin the process of theory validation and deepen understanding about the mechanisms of embedding habit change with regard to teaching and learning EHoM. Given the short length of time during which most teachers' interventions were carried out, and the variety of locations, there are inevitably limitations on the extent to which we can generalise from our findings. However, our use of realist synthesis allows us to offer an explanatory analysis of the degree to which the different interventions did or did not work and make some general remarks about these. Further details about our research approach, including ethical considerations, can be found on the project website.

4. The study

4.1 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, mainly in Berkshire, Hampshire and West Sussex from 2014 to 2016.

SEERIH co-ordinated 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 2014–2016.

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.

Each project organised its own workshops and CPD activities in the three different regions of England and Scotland, as outlined below. 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. A list of participating schools and teachers can be found in Appendix 2. Teachers and supporters from all three projects met at the Academy to celebrate achievements and share their findings in July 2015 and June 2016.

4.2 Thinking Like an Engineer (TLaE)

CRL began recruiting schools and colleges to participate in its two-year project *Thinking like an Engineer* in the autumn of 2014. The project included a blend of training, school support, curriculum development and action research within membership of the Expansive Education Network (eedNET) professional learning community. The aims of TLaE were to:

- Develop teachers' understanding of engineering habits of mind.
- Support 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.
- Encourage teachers to draw on the expertise of practising engineers, for example, STEMNET ambassadors, to ensure that the learning reflects the needs of employers and benefits from the passionate commitment of engineers.

Participation by schools and colleges was invited through a range of channels including the members of eedNET and a flyer circulated to Hampshire schools by the Winchester Science Centre. We sought those who would be willing to engage in a continuing professional development (CPD) activity in which their teachers undertook small scale, classroom based teacher inquiries, based on an action research approach.

During year one (January–July 2015) five schools (one primary, four secondary) and one FE college participated. Teachers were supported by CRL to introduce EHoM in conjunction with subject content and evaluate the outcomes. CRL provided three CPD workshops that covered an introduction to EHoM and action research, an introduction to EHoM resources and the Teachers' Toolkit for evaluation, and a progress check opportunity. The teachers each wrote a short report and presented their findings to their colleagues at the first project dissemination conference in July 2015, which with their permission were shared with other participants on the eedNET website.

In year two (September 2015–July 2016) all participants but one chose to continue and five additional schools were recruited. The teachers continued to implement schemes of work or develop classroom resources to cultivate EHoM. In many cases they expanded their activities and were joined by additional teachers from within their school. In place of the centrally hosted CPD workshops, the CRL researcher visited the schools and undertook interviews with teachers. Together with the teachers' action research reports and presentations, the interviews contributed to the data for findings and case studies in this report. At the second dissemination event at the Academy, draft findings were shared with participants and contributing experts.

4.3 Tinker Tailor Robot Pi (TTRP)

Tinker Tailor Robot Pi started in September 2014 as a teacher and curriculum development project designed and delivered by SEERIH. Involving serving primary and secondary teachers, university academic engineers, business partners and pupils from Key Stage 1, 2 and 3, the focus was to explore how a pedagogical approach to primary engineering could be established within the mainstream curriculum. There was strong interest in fostering teacher dialogue and confidence in the teaching and learning of engineering education by exploiting the opportunities provided within the computing, D&T and science curriculum.

During year one (September 2014–July 2015) eight schools participated, six primary and two secondary (16 teachers). In year two (September 2015-July 2016), five schools chose to continue and seven additional schools were recruited, six primary and one secondary (31 teachers). Both the Director of SEERIH and the Director of CRL are part of a broader network interested in engineering education coordinated by the Comino Foundation and saw the benefits of collaborating on the second year of the TLaE project to promote EHoM.

The aims of TTRP were to:

- Encourage the sharing of professional practice and knowledge between teachers and engineers.
- Explore how engineers 'work' by deconstructing how engineers practice their profession.
- Better understand how learning related to engineering is taught in primary schools.
- Identify where opportunities for a stronger ethos of engineering could be incorporated in primary schools and the curriculum through science, D&T and computing.
- Collaboratively develop, deliver and reflect on teaching and learning opportunities for pupils that work towards identifying a signature pedagogy for engineering in primary schools.

Two complementary questions were posed by TTRP:

- How do we embrace engineering education and an ethos of tinkering using computing, D&T and the science curriculum?
- How can engineering have relevance and resonance within the primary and secondary school curriculum?

Relatively early in the project, the teacher-academic team became interested in how the concept of tinkering supported the project's interests. It was soon noted that tinkering could increase the engagement and understanding of teachers and children about engineering in classroom and staffroom. Further discussion about the concept of tinkering is offered in Section 5.

TTRP supported schools with a two-day 'immersion event' at the start of each academic year in which teachers and academics were able to discuss and design an approach to best suit their context, utilising their personal expertise, as well as meeting project aims, departmental priorities and pupils' needs. Support and guidance were offered to teachers using unfamiliar technologies in the computing curriculum, such as Bee-Bots, Crumbles (Redfern Electronics, 2016), Scratch

(Lifelong Kindergarten Group) and Python, as well as ideas for enriching D&T and 'making' in general. Teachers met periodically through the year as a whole group and with the project team. They also had an opportunity to present their work at a national conferences (the Association for Science Education National Conference) and with the engineering education community at the Academy.

4.4 Primary Engineer in Scotland

Primary Engineer is a not for profit organisation that brings together early years, primary and secondary teachers to share experiences and pedagogical approaches to incorporating engineering in the curriculum. It engages primary and secondary pupils with engineering through projects mapped to the curriculum, where the context has been provided by engineers. Primary Engineer is supported by the IMechE.

In 2015 work began to develop one of Primary Engineer's programmes into a GTC Scotland Professional Recognition Programme in Engineering STEM Learning. The academic level (SCQF Level 11) and assessment strategy of the programme were developed by Primary Engineer in collaboration with the University of Strathclyde, Glasgow. The course development is funded by Skills Development Scotland for three years.

The aims of the programme are:

- To increase teachers' understanding of the STEM 'landscape' through critical engagement with research.
- To develop an understanding of their role within the STEM landscape.
- To develop critical reflection and evaluation of their current practice.
- To develop a critical evaluation of the impact of project based learning.

- To increase their understanding of what engineering is.
- To establish stronger links with local engineering industry to enhance STEM learning.
- To develop pedagogical STEM strategies through engagement with EHOM.

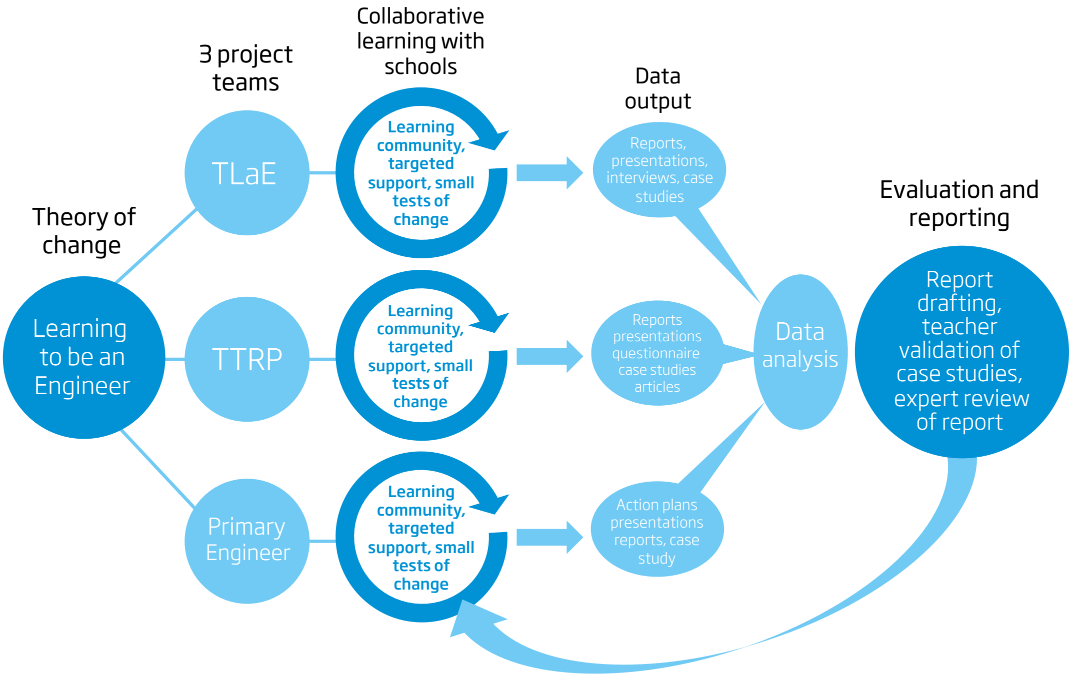
CRL delivered three workshops for the teachers, which covered an introduction to EHoM, developing action research questions, the process of action research, and a progress check opportunity. Teachers completed four assessments which took them on a journey from researching the engineering education landscape and EHoM, to implementing an EHoM intervention in their classroom and writing up the results. Nine teachers from eight primary schools in Glasgow and East Ayrshire were involved in 2015/16.

The teachers agreed their assignments could be made available to CRL to inform the research. The outcomes from their second assignment were of significant value in extending the original research undertaken by CRL with practising engineers to identify EHoM. For this assignment, the Primary Engineer teachers interviewed engineers from a variety of areas and organisations to investigate what inspired them to embark on their careers and their habits of mind.

In total, the teachers interviewed 63 engineers and presented their findings to their peers, Primary Engineer staff and education and industry experts, including Iain MacLeod, professor of Structural Engineering and former president of IESIS, Dr Andrew McLaren, vice dean of engineering at the University of Strathclyde and Dr Lynne O'Hare of the Advanced Forming Research Centre. Two of the most striking findings were that there was overwhelming support for the validity of the six EHoM as being essential ways of thinking for all engineers and the belief that schools are not doing enough to develop these dispositions. A detailed synthesis of the teachers' findings from these highly illuminating interviews is available on the project website. The teachers' fourth assignment, containing their written accounts of their action research, contributed to our understanding of how teachers cultivated EHoM in the classroom.

Figure 6 below shows the key features of the three interventions diagrammatically.

Figure 6: Overview of the three project interventions



5. Cultivating engineering habits of mind

Developing habits is hard. Changing ingrained habits is harder still. From the outset of our work with schools, we were clear that while the TofC underpinning this research assumes that there are a set of desirable EHoM and that there is a growing body of knowledge as to how they can be cultivated, the real challenges lie in changing teacher habits.

In order to deliberately cultivate or change habits it is important to be clear about what they are and how they are formed. In this section we explore some common characteristics of habits and the processes of habit formation in order to enhance understanding of how learning and teaching environments may be arranged to support the development of learning behaviours so they become habitual.

While most habits are essentially neutral, depending on when and where they are deployed by an individual, they may help or hinder effective learning behaviours. For example, perseverance and relating to others in a friendly manner normally help individuals to progress in the classroom and the work-place, whereas being rude and unreliable do not (Wood and Runger, 2016).

Habits have three core defining features: they are automatic responses, they are generated in response to a 'trigger' or cue, such as an event, action or person and they are undertaken in pursuit of a goal that brings a reward (Lally and Gardner, 2013; Wood and Runger, 2016). However, habit formation is a slow, incremental process and habitual behaviour is very resistant to change (Lally *et al*., 2010). There are three key factors that are thought to encourage the development of habits: constant repetition of the habitual action, a stable context in which to perform it, and the provision of an appropriate reward for completing the action (Lally and Gardner 2013; Wood and Runger, 2016).

The factors necessary for habit formation provide us with four pedagogic principles to guide our cultivation of effective learning habits:

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

These four principles for cultivating effective habits informed the professional learning offered to teachers within the project and the targeted support we offered teachers in co-designing their interventions.

5.1 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 with their students about their own personal experiences of using the skill, or provide examples of well-known figures who have exhibited it.

Some teachers used self-report questionnaires to help students gauge their own skill levels prior to discussing with them how they might enhance the skill. We developed an engineering habits of mind self-report survey (Appendix 3) as a means of building understanding and for tracking the development of EHoM in pupils.

Principle 2: Creating the climate for the habit to flourish

It is essential to create a climate that encourages and reinforces the habit for it to flourish within the learner. This climate may 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 learn through 'having another go', and by supporting students in self-monitoring the extent to which they are using the habit.

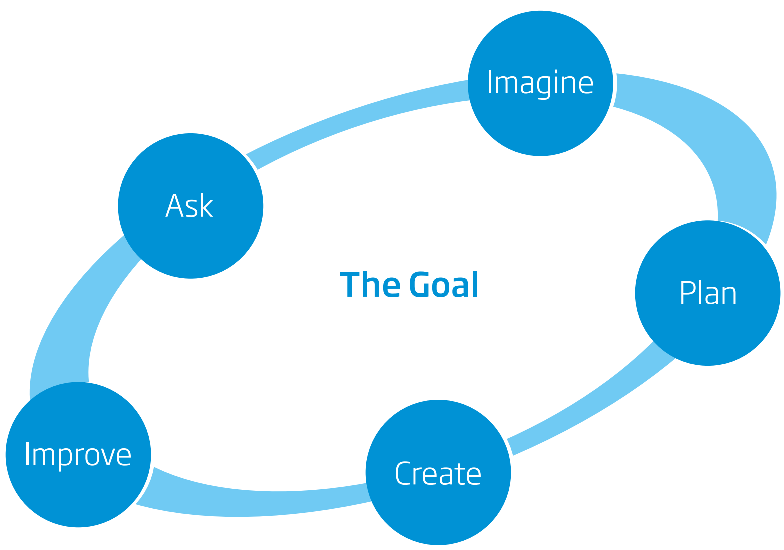
Positive reinforcement is an important element in habit formation, since learners need to experience the rewards and satisfaction associated with the successful execution of the task. Making verbal statements praising the skill exhibited rather than the individual is an effective method of reward that serves two purposes; its praises the effort necessary for habit change and it also provides a further opportunity to make explicit what the desired behaviour entails. It is important that teachers work with parents and carers to ensure that they support these approaches to creating the right climate, since parents' attitude to failure influences their child's growth mindset (Haimovitz and Dweck, 2016).

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. The term 'signature pedagogy' (Shulman, 2005) describes discipline-specific teaching methods that recognise the specific nature of knowledge in the discipline and the characteristic attitudes and attributes of being a professional in that area. Signature pedagogies prepare learners for becoming the practitioners of the future and they support the formation of professional identity needed to forge a career in that profession. Three elements of a potential signature pedagogy for cultivating EHoM that we explored are: the engineering design process, tinkering, and authentic learning with practitioners (such as professional engineers).

We and others argue that the engineering design process (EDP) is one of the core signature pedagogies for developing EHoM (Lucas, Hanson and Claxton, 2014; Kelly and Knowles, 2016; Lottero-Perdue, 2016). Pamela Lottero-Perdue (2016) explored the implications of incorporating the EDP into teaching following the inclusion of engineering in the USA's *Next generation Science Standards* (NGSS Lead States, 2013). She emphasises how failure in the design process is the typical way in which engineers

Figure 7: The engineering design process (EiE, 2016, cited in Lottero-Perdue, 2016:3)



create new knowledge to understand how best to solve problems. The EDP used in the American Engineering is Elementary programme is an iterative cycle involving problem identification, imagining possible solutions, picking a solution and creating the design, testing it and reviewing, and planning for a revised (improved) design, see Figure 7.

However, she also notes the negative connotation of 'failure' in education, for example, 'failing schools' and although teachers may struggle initially with the concept that failure in the classroom can be positive, she suggests that the iterative design failure process can offer a productive opportunity to promote the development of 'growth mindset' (Dweck, 2006). Using an Engineering Mindset Survey with 5th grade students (10 year olds) who had participated in an engineering programme, she found that learning science in the context of engineering, and experiencing failure and improvement, appeared to support the development of a growth mindset in the learners. Although she was unable to demonstrate that the specific use of the EDP was responsible for this, she concluded that further research could explore the effect of using teaching interventions where teachers more explicitly emphasised a growth mindset in engineering.

Tinkering began to emerge as a term that the TTRP project team aligned with engineering and was found helpful in identifying how engineers might practice their profession, in contrast to the approach of scientists or artists. A working definition for tinkering was created, building on the core engineering purpose of 'making things that work and making things work better' (Lucas, Hanson and Claxton, 2014). Tinkering, as conceived for the TTRP project, was:

'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. Since giving things a go and learning from mistakes are encouraged through 'fiddling, messing and dabbling', the thinking of Dorn and Guzdial (2010) and Law (1998), who consider tinkering as being a 'process of trial and error', also aligns closely with the project's view of tinkering.

During the project, teachers and engineers engaged in discussion about the agile nature of tinkering. It is highly iterative; we try things, evaluate our efforts, make revisions and try again. Brandt *et al*. (2009) talk of tinkering in terms of this 'process of testing minor changes'. The outcome can evolve over time, being adapted and improved based on the feedback provided by ourselves as 'tinkerers in the loop'. There are similarities with Martin's (2009) work on 'fussing' which is presented as 'the process of minor change which leads to improvement'.

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, so that they and their learners can understand how they go about their engineering work. If, as we propose, engineers have a specific way of thinking, expressed as EHoM, then surely this interaction should influence engineering pedagogy. 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).

Within these three broad pedagogic approaches there are many more specific methods which can be used to cultivate EHoM. It is worth remembering that small adaptations to teaching, such as beginning the lesson with a challenge, asking open questions, not answering students' questions immediately and deliberately allowing time for experimentation, can also be effective.

Principle 4: Building learner engagement and commitment to the habit

Having ensured that learners understand the habit and the contexts in which it can be used, as well as encouraging a climate in which it can flourish with reward and choosing teaching methods that facilitate its practice, the teacher can finally focus on building learner commitment to the habit. We have drawn on the work of Learning Futures (Price, 2013) that helpfully reframes engagement as having four characteristics:

Purposeful: learning absorbs the student in actions of practical or intellectual value, fosters a sense of value and agency – 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/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.

Having identified the key features of habits and how to cultivate them, we now move on to discuss how teachers managed this challenge in our three projects.

6. Testing our Theory of Change (TofC)

The first step of our TofC draws on our earlier theoretical work in which we offered a reframing of the formal curriculum of schools, introducing the idea of habits of mind to be embedded within subjects. In parallel it drew on and adapted an approach to teaching and learning, signature pedagogies, to offer a more explicit and rigorous approach to selecting teaching and learning methods which were likely to be conducive to the cultivation of our selected EHoM.

These two lines of thought provided us with the first two strands of the first step of our TofC.

- Reframing engineering education to include desirable engineering habits of mind (EHoM) in addition to subject knowledge.
- Clearly articulating the principles and practices through which these EHoM can be cultivated in schools.

We then hypothesised that, based on these two premises, we could offer teachers targeted support to change their practices along with opportunities to co-design enquiries within the context of 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 to implement EHoM approaches in schools.

6.1 Using the four principles to cultivate EHoM

There were many levels at which teachers responded and different ways in which they chose to design small tests of change in their teaching. 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 (described in Section 5).

6.2 How teachers built understanding of EHoM

Shared understanding between teachers and learners involves everyone knowing what the EHoM are, being able to explain them to others and knowing when it is appropriate to use them. 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 in which teachers aimed to sensitise learners to cues so they could recognise the EHoM and occasions when it was appropriate to use them. This use of assemblies not only emphasised the value placed on EHoM by the school but also provided an opportunity to explain, in an age-appropriate manner, what they were, why they were important, and crucially, how they might require a different mindset to put them into practice:

"Whole school assembly on Mondays introduces an EHoM for the week. All staff and children are expected to work towards this. I drop in to classes on a Friday to view work and progress. This is then celebrated at the next assembly and the weekly cycle begins again." **(Headteacher, primary school, TTRP)**

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 created as part of our EHoM Teachers' Toolkit (Appendix 3) to encourage learners to think about their confidence level in using each EHoM, while others used adapted versions.

The teachers recognised that it was important to use specific EHoM terms, in the same way that it was important to use precise language from the curriculum specifications when teaching subject content. However, in both cases it was crucial to make the language accessible to their learners:

"It's really important that students understand the words that are in the specification because that's what's being asked of them. So it's that challenge between diluting it down so that they understand it but continuing to use the word that you mean." **(Director of STEM, secondary school, TLaE)**

To address this challenge, they elaborated on the original EHoM terms by using age appropriate language in parallel with the actual terms themselves. This supplementary language might be 'spoken' by characters with whom the learners would associate, for example, Bill in the Be like Bill meme used in Case Study A.

To deepen understanding of EHoM, teachers provided examples of them in use. They noticed that learners were using the EHoM in the classroom and drew attention to this by emphasising, for example, that when they were improving their work and making things better, they were 'being an engineer'. They also used techniques such as discussing how famous engineers or scientists had demonstrated EHoM, in order to provide the context for EHoM use in their STEM classes. FE lecturers considered it essential for their learners to have this contextual understanding before they could start using the EHoM effectively, even in courses that specifically focused on engineering, since the teaching methods used in FE in engineering, they claimed, did not always provide that context.

Close collaboration with engineers in developing learning projects enhanced contextual understanding because it enabled teachers to stress to learners that employers valued these skills very much. We explore the ways in which teachers engaged with engineers in greater detail in Section 6.4.

Many schools used the original EHoM model, see Figure 2, in the form of a poster produced by the Academy to remind learners of the EHoM names, but some teachers also developed visual icons for each EHoM (see Case Study A). These images could be inserted into PowerPoint presentations to act as reminders to learners that it was appropriate to use the EHoM at a particular point in their work. The icon also acted as a reminder to the teacher to emphasise the EHoM at relevant times in the lesson.

To aid transfer of understanding, teachers reminded students when they could use the EHoM in different subjects, not just in the classes in which they were first introduced, as in this example where the teacher associated problem finding with 'debugging' in computing:

"I showed my class the engineering wheel and discussed that problem finding was something that they felt they were weaker at because they perhaps didn't understand it properly; so we went through what it meant. And in class I've given them lots of examples throughout the curriculum. So, I've tried it in PE, I've tried it in art…They've sort of debugged everywhere." **(Teacher, primary school, TLaE)**

6.3 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 to celebrate learners' achievements. At Christ the King RC Primary School (Case Study B) a whole-school approach to engineering was designed to engage all learners, teachers and parents. In this school EHoM were included in the School Improvement Plan, the Chair of Governors became the lead advocate for the development work and a range

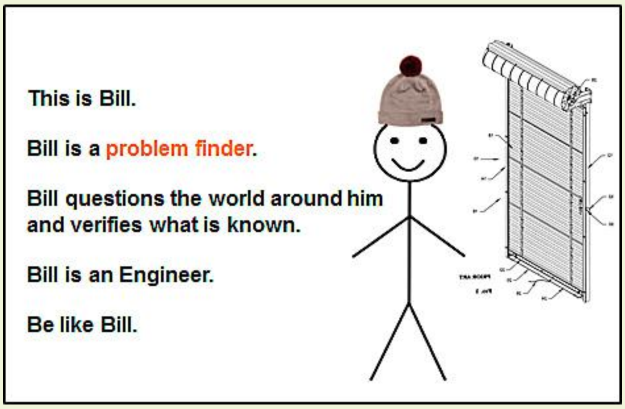
CASE STUDY A:
Medway University Technical College, Chatham, Kent (www.medwayutc.co.uk)

Themes: Principle 1 – Building understanding, icons, social media meme, whole-school assemblies, staff ownership.

Medway UTC opened in September 2015. The technical specialisms of this school are engineering, construction and design. Partners include employers such as BAE Systems, and the Royal School of Military Engineering. One of the drivers for becoming involved in the TLAE project was the recognition that EHoM could enhance students' employability skills.

The initial focus for cultivating EHoM was to raise awareness among staff and students about what the six EHoM are and how they might be used. Whole-school assemblies were organised around each EHoM and the Director of STEM worked with staff to develop their ownership by creating EHoM icons for use on posters and using 'Rewards postcards'. These were used to praise students when they demonstrated an EHoM.

The popular 'Be Like Bill' social media meme was adapted to explain the meaning of each EHoM.



This wide range of strategies to cultivate awareness of EHoM had an important impact on the teachers, particularly those who taught subjects such as art and English, who felt much more included in the overall engineering mission of the school. The impact on learners was less evident at this stage, since it took time for the teachers to build their own understanding of EHoM before they could use them confidently with learners. Nevertheless, when the Director of STEM was interviewing Year 10 students about their career aspirations, she reported that some learners were able to describe their strengths and weaknesses using EHoM language and had used them in their outreach activities with local primary schools.

Images courtesy of Medway UTC

of approaches encouraged and assured a whole school approach. 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 wider promotion of EHoM and tinkering to teachers beyond TTRP participants was achieved in various ways. A staff training opportunity in which all teachers were involved in a making challenge, called a 'Tinkerthon' by teachers, was developed in Seymour Park Primary School. Through this type of experiential activity teachers were encouraged to 'play' and make with a range of resources. They were also introduced to equipment such as Robot Mindstorms and Lego Wedo (Lego Education, 2016) to learn about their applications and gain confidence in programming them. Schools involved parents in Family Tinkering events and with the School

Images courtesy of Christ The King RC Primary School

CASE STUDY B: Christ the King RC Primary School, Salford (www.christthekingschool.co.uk)

Themes: Principle 2 - Creating the climate, school improvement plan, leadership, tinkering spaces

Christ the King RC Primary School adopted a whole-school approach to tinkering and developed the EHoM through this signature pedagogy. With active engagement from governors and senior leaders the children were introduced to an EHoM for the week. In this way, the school family learnt together about what it meant to develop positive learning habits, beyond the science curriculum.

Lesson plans were short and succinct rather than detailed as normal, as it was essential to be creative and responsive to children and their ideas. Teachers were given time to talk, think and experiment together.

EHoM, science, D&T and computer science were integrated. The teachers made a commitment to changing their practice by:

- Reducing spoonfeeding of children's knowledge and support during learning.
- Removing laborious and neatly typed up plans.
- Refocusing planning on resourcing and questioning, e.g. How do we 'hook' the children into the topic? How can we develop cross-curricular skills around the topic?
- subject leaders considering how their subjects integrated with to ensure appropriate coverage of each EHoM and the curriculum objectives.

Celebrating and encouraging creative planning. What resulted for staff was an excitement and thirst to learn together. Teachers and pupils acknowledged that they were investing in failure and that they were embracing learning through trying and failing, and trying again. "Tinkering has made sense to us, it opened a door to our creativity. It has been the thing that has most changed in our classrooms, and when children are making with their hands they are personally seeking to find new ways to learn.... Isn't that what school improvement should be about?"

of the Military (2016), which included engineers to give a greater degree of relevance and purpose.

The challenge of having time within the mainstream curriculum to embed EHoM was an issue for many teachers. They capitalised on combining subjects which they described as 'stealing time from the weekly timetable'. St Thomas' CE Primary School (Case Study E) integrated the focus on engineering and EHoM into their termly topic plans for literacy. They used the story context of 'Rosie Revere, engineer' (Beaty and Roberts, 2013) to exemplify the habits of mind and to engage children with engineering challenges that they had interest and enthusiasm for. Similarly the links to literacy and story were found to be useful in the early years age phase, where the story book 'Dear Zoo' (Campbell, 1982) became the stimulus for children to design, make and refine boxes to transport animals.

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. For example:

"We're using our rewards postcards and we award them for trying... when we praise the students, say, for example, 'that's a really good example of adapting". **(Director of STEM, Secondary School, TLaE)**

With older learners, more sophisticated reward systems were used. In one school learners built up merit points for displaying EHoM that could be used to claim valuable prizes such as a Kindle. Elsewhere, visits to engineering employers were commonly offered to teams who were judged best overall at completing a project. This often happened in conjunction with the employer who had set the problem for the project in collaboration with the school, judging the work or presenting the prize. Their input was thought to incentivise learners to try harder and make it that much more authentic.

These visits to employers also increased learners' awareness of the variety of engineering jobs and their understanding of how EHoM were valued by industry:

"There's always a prize or prizes for the winning outcomes. So the winning team this time around got a visit to the ITV studios in London and looked at all the technical background behind film and television; it's not something we specialise in but it opens their eyes to different fields of computing and engineering that are available." **(Vice Principal, Engineering and Science, secondary school, TLaE)**

Most teachers used 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. She encouraged her young learners to reflect on why it did not work and then prompted them to think about how the experiment could be improved and adapted for the next time.

Learning from failure is key to the engineering design process (see Section 5) and all teachers realised that providing opportunities for learners to make and learn from mistakes could be a significant feature of cultivating a climate for EHoM to flourish. The use of problem solving activities and 'making' challenges was increasingly evident in classroom learning as well in lunchtime and after-school clubs.

"Children worked in small groups collaboratively to solve open ended problems. Lots of peer assessment and evaluation had been promoted throughout all elements of the project. We felt it was very important to allow the pupils to fail, sometimes dramatically before they found a solution. This worked very well with the school's growth mindset approach." **(Teacher, primary school, TTRP)**

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 on his paper:

"He just screwed it up and put it in the bin and I made him unscrew it and stick it in [his book] and said 'You are going to have that there because that reminds you that you don't always get it perfect and its fine for it to be wrong the first time. We're making the mistakes now, so that when you get to your GCSEs you won't make them because you will know to read the question carefully". **(Head of STEM, secondary school, TLaE)**

This teacher and many others knew that they had to use language carefully, explaining how failure can be used to improve, and that improving was the hallmark of a good engineer:

"Whatever you find out, whatever your results are, you can learn something from them. It might not always be the answer you were looking for, but the way you interrogate that information or you use it can always be beneficial." **(Teacher, secondary school, TLaE)**

They developed phrases and questions to use in class 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 without its own difficulty for the 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, such as "How do you think you could...?" and "What do you think you could do next?" The change to a process driven outcome to learning was evident in most schools:

"Teachers set open ended tasks and encourage children to problem solve and observe the process rather than the outcome. Teachers involved in TTRP have been using the language of what a good engineer looks like. Teachers have observed more and identified EHoM rather than looking for a finished outcome." **(Teacher, primary school, TTRP)**

Teachers also recognised that they could not say one thing to learners and be observed by them acting differently, as in this case of accepting learners' ideas:

"How you receive their ideas in the first place will lead to how successful it's going to be, because if you're saying 'nothing is a silly idea' you have to say it in your body language and your tone of voice." **(Head of Science, secondary school, TLaE)**

This style of interaction between teachers and learners contributed to the development of a climate of trust in the classroom which is essential for learning (Hattie, 2012) and the outcomes can be seen in Case Study C New Forest Academy.

6.4 How teachers used signature pedagogies

We encouraged teachers to explore the potential for using Shulman's (2005) concept of signature pedagogies for cultivating EHoM, see Section 5. The idea that to develop engineers we need to teach them in ways that are likely to develop certain habits of mind is central to our TofC. We identified three elements of a signature pedagogy that could be harnessed to cultivate EHoM, the engineering design process (EDP), tinkering and authentic engagement with engineers. In this section we explain how teachers used them, and also how making even small changes to their normal teaching practice could enhance EHoM.

Engineering design process

A few schools used the EDP to organise EHoM learning, but they used an adapted or simplified model. For example, Gomer Junior School created the 'gSTEM Wheel' – an enhancement to the D&T wheel of 'Plan, Do, Evaluate'

CASE STUDY C:
New Forest Academy, Hampshire (www.newforestacademy.org)

Themes: Principle 2 – Creating the climate, teacher modelling, creative problem solving, thinking routines, STEM Ambassador.

New Forest Academy is an 11–18 fully comprehensive academy with around 376 students.

In the first year TLaE, the Head of Learning and Achievement in Science (HoS) introduced EHoM into her teaching with the aim of enhancing learners' creative problem solving (CPS) in science.

In the second year, two additional science teachers became involved in incorporating CPS through extended STEM activities within a Learning Skills programme undertaken by Years 7, 8 and 9.

This approach did not work as well as originally anticipated, so the teachers concentrated on developing CPS in Year 11 Science. Within a week-long programme, they introduced learners to open-ended problems and taught them the SCAMPER model to structure their thinking processes to derive and test creative solutions to problems, including one where they had to adapt and modify a torch for different uses.

In addition to providing thinking tools and strategies, the teachers created the climate for CPS by modelling openness in the way they responded to learners' suggestions by not rejecting any idea, however unlikely it seemed, which contributed to a climate of trust in the classroom.

Teachers noted an increase in learners' ability and confidence to propose creative solutions to problems that were based on scientific principles, for example, by eliminating ideas that would not work.

Students were better able to tackle open ended questions more confidently because they had a toolkit to support them through the process of coming up with new ideas.

In 2016, this excellent work was recognised nationally when Mrs Crowe, Head of Learning and Achievement in Science, won a silver award for Teacher of the Year in a Secondary School, awarded by Pearson.

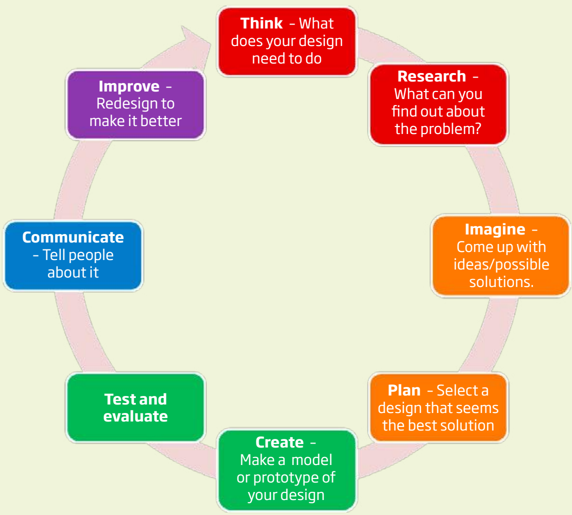
Images courtesy of New Forest Academy

CASE STUDY D:
Gomer Junior School, Gosport (http://gomerjuniorschool.co.uk/gstem)

Themes: Principle 3 – Signature pedagogy (engineering design process), integrated STEM, real-world project-based learning, STEM Ambassador

Gomer Junior School introduced Gomer: Science, Technology, Engineering and Maths (gSTEM) to the curriculum in the autumn of 2015. The Headteacher realised that primary schools could make a significant contribution to fostering children's interest in science and engineering but that this opportunity was largely unrecognized locally. She determined that Gomer Junior would seek to redress this gap by introducing weekly STEM lessons.

These gSTEM sessions are held across the school in every year group each Thursday morning 09.00–12.00. The sessions integrate mathematics, literacy, science and IT with the aim of motivating learners and fostering understanding of real-world applications of STEM subjects by experiencing hands-on activities. Projects with engineering-based objectives are planned using themes derived from current events. For example, The Space Race project featured Tim Peake's Principia Mission (https://principia.org.uk/) and involved programming Crumble-controlled moon buggies. One of the tools used to support learning is the gSTEM Wheel, an adapted version of the engineering design process (EDP).



gSTEM Wheel

(based on an original design by David Hill, Faculty Outreach Co-ordinator, Faculty of Technology, University of Portsmouth.)

The school was also assisted by its STEM Ambassador, Professor Adrian Oldknow.

The EDP, as applied through the gSTEM Wheel, provides a valuable thinking tool for children. They become more curious, ask more thoughtful questions and show greater resilience when things do not work for them initially. Their collaboration skills have increased and they show more respect for each other's ideas. With prompting from teachers, they are able to apply the EHoM learnt in gSTEM sessions to tackle problems in other subjects.

The teachers had to adjust to the demands of project-based learning by 'letting go of the reins', they found that they could use the combination of the gSTEM Wheel and EHoM in their lessons to foster knowledge integration and extended thinking, so the STEM projects were not just about 'making models'.

Images courtesy of Gomer Junior School

to focus on the processes of 'improving' and 'making things better'(Case Study D). The teachers preferred their EDP model because it fostered deeper integration between subjects and extended learners' thinking in engineering beyond 'just making models'.

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. Unlike the D&T practice commonly found, where there is little opportunity for iterative design (Ofsted, 2016a), the primary schools' approach to tinkering is exemplified by 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 an FE college a teacher described how he got his students to start working on a project and to try putting components together before he gave them the theory. The learners' enthusiasm for this new approach also motivated him:

"When I introduced the project and changed things around from the way I normally would have done… [student name] said: 'Oh, I like this because it works more by doing the things.' And then somebody said, 'This is how it works and I can actually see it in front of me' – it motivated me more."
(Engineering lecturer, FE College, TLaE)

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 to raise awareness of engineering careers, to extended collaboration between engineers and teachers to plan projects that reflected the real-word challenges that currently face engineers.

Sometimes parents who were willing to share experiences of working as an engineer came into school, but there are many organisations dedicated to offering support to schools, details of which are curated by the Academy (Morgan*, et al.,* 2016). STEMNET provides schools with access to STEM Ambassadors, who work in STEM roles. Some TLaE schools accessed this support. On a visit to one school, the STEM ambassador, who was a chemical engineer from Exxon, was praised by the Head of science as "brilliant":

"One thing he had to do was design an app, so he said 'I don't know anything about apps, but I need to design an app in order to control everything, in order to do my role, to do this' and I thought he was brilliant because he gave an idea of actually what jobs are and problem solving and he just really embodied it." **(Head of science, secondary school, TLaE)**

University engineering departments often organise outreach programmes for local schools and this type of support was an important feature for TTRP schools. Academics, graduates and industry representatives dubbed engineering heroes and associated with the Faculty of Science and Engineering at the University of Manchester met with teachers during training days and provided an opportunity for them to hear about contemporary engineering in research and business. The chance to reflect on and discuss how the EHoM are realised within everyday working practices gave rich insights into the nature of engineering and teachers said the experience was inspiring.

CASE STUDY E:
St Thomas' Primary School, Stockport
(www.st-thomas.stockport.sch.uk)

Themes: Principle 3 – Signature pedagogy (tinkering), narrative immersion, drama, literacy, science, local community links

St Thomas's applied a 'narrative immersion' approach to the development of tinkering and EHoM that focuses on teaching concepts and skills within a story and uses drama to 'pull' children into the learning process.

The school incorporated tinkering and EHoM across the curriculum in two Key Stage 2 classes. Teachers selected a text that was rooted in a human context (i.e. relationships, roles, situations, encounters etc.) stimulated by the engineers who had inspired them in TTRP. They sought a narrative that offered the children challenges and dilemmas that embodied the nature of engineering-in-practice which led to the selection of 'Rosie Revere Engineer' by Andrea Beaty.

The classroom became the engineering workshop where tinkering tables and lab coats (large white shirts) created visible images to inspire the children. The learning experiences were designed to include different dramatic conventions to encourage the children to connect with the roles, characters, and situations within the text. The theme lasted for six weeks with literacy lessons offering writing, reading, speaking and listening objectives. The science focus was on forces and flight as Rosie struggled to make a flying machine. Key learning opportunities included each child keeping a Tinkering Journal to plan and record their inventing journey.

Children were posed the same problems as Rosie in their Tinkering sessions. Teachers provided resources (junk materials, masking tape, wires, etc.) and children used their tinkering skills to plan, design, build and adapt their designs in order to come up with a solution for Rosie. Following a local community bicycle upcycling workshop that modelled how scrap could be used to produce useful creations, the children held an Invention Fair to present their final inventions to parents, staff and representatives from the upcycling workshop, who then judged their efforts and inventions.

Outcomes for the children's EHoM included improved team-working, resilience, perseverance, creativity, adapting and self-confidence. They also demonstrated increased ability to apply scientific knowledge to real life experiences.

The teachers found that they put more trust in the children, becoming facilitators of learning rather than demonstrators. Planning became less time consuming and they used more child-led activities that resulted in more impromptu or 'in the moment' planning following the children's interests and enquiries, but with clear curriculum objectives in mind. Teaching became more creative and they enjoyed collaborating with colleagues to take risks and try out new approaches.

Images courtesy of UTC Reading

CASE STUDY F: University Technical College Reading, Berkshire (www.utcreading.co.uk)

Themes: Principle 3 – Signature pedagogy (authentic engagement with engineers), real-world projects, co-designed curriculum

UTC Reading is a University Technical College that specialises in computer science and engineering education and was established in 2013. The school partners include Microsoft, CISCO, Network Rail and Peter Brett Associates. UTC Reading is a member of the Activate Learning Group.

Initially the school focused on raising awareness of EHoM among teachers and students and in consolidating the role of industry partners in curriculum development. The school's links with employers feature a number of sophisticated models. Industry partners contribute to whole-school 'core projects' where students worked in groups on different aspects of the project for a day a week during the first and second terms.

The employer's staff acted as mentors to students. This model is being scaled up to involve several employers collaborating on each project. Teachers encourage integration between their subject and the project activity. Employers also design and 'co-teach' and curriculum units with teachers.

Teachers can contextualise the unit with real-world problems as they and the employer co-deliver the unit. Work experience for students in the third term of Years 10 and 12 is the third model through which the school and industry collaborate and the partners offer careers talks and skills workshops. The school is also offering bespoke apprenticeship programmes for employers from September 2016.

Some students still hold outdated perceptions of what engineering is, so it is important to ensure that their minds are opened up to the true nature of engineering. The school is gaining a reputation for the success of its employer engagement, which was recently praised by Ofsted.

The next phase of EHoM integration is to find ways to establish the EHoM methodology into engineering vocational courses and employer-led core projects. It is important that the students become aware of the habits they are developing during these learning experiences.

Students from UTC Reading were among 117 students who were presented with The Duke of York Award for Technical Education in March 2016.

Several secondary schools 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. The partnership between the employer and the school enabled the teachers to feel confident that they were delivering current content and developing relevant skills in learners:

"The whole idea is to plan it with the industry partners so that we get an idea of what they really want; especially Siemens is a big one that we've worked with for a few years now."
(Head of STEM, secondary school, TLaE)

The most extensive partnerships between schools and engineers were evident in the UTCs, as would be expected, since a condition of a UTC's establishment is employer partnership. The most highly coordinated alignment between the school and employers in our project was observed at UTC Reading (Case Study F).

Within an FE college, engineers as employers play a more direct role in advising on curriculum content, assessment and on commissioning education and apprenticeship programmes. One FE teacher took advantage of his contacts with a local employer to plan a project to cultivate his learners' problem solving. The employer came into the classroom and presented a real-world engineering problem to the learners. A few weeks later the students went to visit the engineer on site and had an opportunity to ask him questions about the problem. They then worked in groups to find a solution which they presented to the employer for his comment at the end of the term. The value of aligning even small scale classroom projects to real-world issues to create context for students was important to the teacher:

"It's a simple kind of problem but he'll present a problem that obviously has context because it's on a site just down the road. Next week, we're taking them to the site. We're going to ask questions on the site of the project manager, what happened, what went wrong, and then I'm giving them two two-hour sessions in groups of four." **(Engineering lecturer, FE college)**

Identifying engineers willing to engage with your school can be a daunting task for teachers, but the extraordinary achievement of the teachers in the Primary Engineer project demonstrates how much enthusiasm there is in the engineering community for helping local schools. As part of their programme, one of the assignments for the teachers in Scotland was to contact local STEM companies to interview engineers about their career paths and how they use EHoM in their work. Between them, the nine teachers interviewed a staggering 63 engineers. Further detail on the teachers' findings about the engineers' views on EHoM is provided on the website.

After the interviews, the teachers invited the engineers to come to their school. Valuable relationships were built up and engineers often made weekly visits to the schools. One teacher had two engineers from Rolls Royce (one female and one male) who shared attending her classes for one afternoon a week for six months. They provided information about the career of an engineer and offered subject input to the project:

"The engineer started the session each week, providing theory and knowledge in terms of his/her everyday job and related this to our teaching focus. We worked our way through the 'Professor Links and Tinkerton Tinx' [Jinks, 2000] workbook each week to make the controllable vehicle. This covered aspects of the Curriculum for Excellence; Science and Technology Experiences and Outcomes. This allowed us to provide a real life context for learning as well as using theory and practical aspects of a lesson together."
(Primary Engineer teacher)

Small adaptations of existing practices

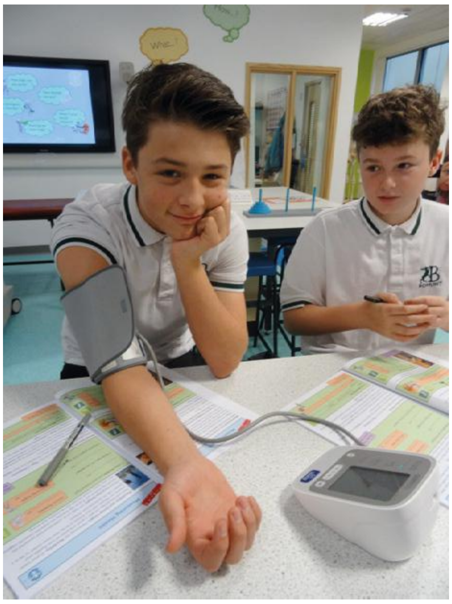
Many teaching strategies used to cultivate EHoM did not require large-scale changes to the curriculum or to teaching methods. Teachers found that making small adaptations to existing strategies were just as valuable (Case Study G). Clear instructions about when to use an EHoM, careful use of questioning techniques and use of routines to develop learners' thinking skills were all found to be effective in facilitating and scaffolding learning and use of EHoM. Direct instruction to use an EHoM when projects started included statements such as:

"Right, this is where you're going to have to think about your problem-finding and problem-solving, so you've got to come up with some ideas before you get on with the making side of it or the designing side of it; think of these concepts beforehand." **(Head of STEM, secondary school, TLaE)**

Teachers encouraged learners to review their progress when completing tasks with reference to the EHoM by asking questions such as "What skill were you using, why did you use that one?" (Head of English, secondary school, TLaE). One of the most important techniques in asking good questions is giving sufficient waiting time before expecting a response, as this teacher found:

"They actually had to think and try coming up with an answer as they knew it was their responsibility. They had time to come up with an answer before the child who always answers the question said his answer aloud, and they felt they could ask me to expand or explain things further to develop their understanding of the situation."
(Primary Engineer teacher)

Teachers in all sectors made use of a range of age-appropriate thinking routines to cultivate EHoM. Mind mapping – a graphic visualising technique developed by Tony Buzan (1974) to organise information and ideas visually to clarify concepts – was used by a Year 3 English teacher during the school's Science Week to encourage learners to make connections, develop their vocabulary and extract information.



Images courtesy of Bohunt School

CASE STUDY G: Bohunt School, Liphook, Hampshire (www.bohunt.hants.sch.uk)

Themes: Principle 3 – Small-scale adaptations to teaching methods, whole-school STEM programme, employer-designed STEM Challenges, EHoM self-report tool

Bohunt School is a mixed 11–16 academy with over 1300 students. The school aims to ensure that young people develop employability skills. It has a strong focus on enquiry learning and 'growth mindset'. EHoM were embedded within a whole-school change programme taught in a double lesson each week to all learners in Years 7, 8 and 9 (Key Stage 3), including those on the language immersion programme.

Initially two teachers introduced EHoM, one cultivated improving and adapting in her Year 7 science class and another introduced problem finding into his Year 7 STEM class. In the second year, more teachers took up the challenge of cultivating EHoM through the STEM Challenges. Each challenge lasted for half a term and was based on content provided by industry partners such as Siemens UK.

The Head of STEM created resources for other teachers to use. One strategy to encourage students to practise the EHoM was to develop a visual cue, in the form of an icon to represent each EHoM, which were inserted into slides at an appropriate point in the lesson and prompted the teacher to remind the children about when and how to use the EHoM. Learners also used a self-report tool to evaluate their level of confidence with each EHoM before and after each challenge.

Teachers cultivating EHoM found that it does not require major investment in kit or specially equipped classrooms, it is the small adaptions that they make to their language and teaching strategies that can have the biggest impact on learner outcomes. Specifically, teachers helped learners realise that failure was part of learning and their feedback was explicit. They developed a range of phrases and questions to use with learners in the classroom that extended learners' thinking.

One science teacher found the tool SCAMPER, a mnemonic for seven creative thinking techniques, (Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, Reverse) developed by Bob Eberle (1996) useful for encouraging her learners to tackle problem solving activities. Its potential for supporting ideas generation in engineering design has been identified by Motyl and Filippi (2014) and it is used in industry, which gave it validity in her eyes:

"We thought, right, this is a model that is accepted and therefore rather than reinventing something that is not used in the wider world, why don't we use this one? Then we came up with a PowerPoint of simply designing activities to teach them each of the skills. So we started off by teaching the SCAMPER skills." **(Head of science, secondary school, TLaE)**

In another school a primary teacher created the thinking frame of 'Ask it – Think it – Speak it – Try it – Break it – Fix it' which he used to exemplify the engineering process. It focused the classroom on the 'how' of the learning process, as opposed to valuing only the finished product.

Another teacher recognised it was important to increase learners' ability to recognise when they could use thinking routines for different purposes and she aimed to create a bank of them to support EHoM cultivation:

"It's all very well getting them to recognise what systems thinking is and whether they can do it or not, but how do you actually help them do it if they don't have a clue?" **(Director of STEM, secondary school, TLaE)**

Engineering teachers used strategies to develop drawing skills to facilitate visualisation. Effective visualising requires learners to have both the skill and confidence to overcome inhibitions about their ability to draw, so training in sketching is helpful in these areas (Booth *et al.* 2016). Teachers recognised that visualising is an important skill in engineering, but discovered that very few learners from age 14 onwards had the confidence to make drawings. One engineering teacher introduced his learners to the technique of 'boxing' to enhance their drawing skills and develop visualisation. Another used flash cards to enhance his learners' ability to identify objects from different angles to enhance their visualisation skills.

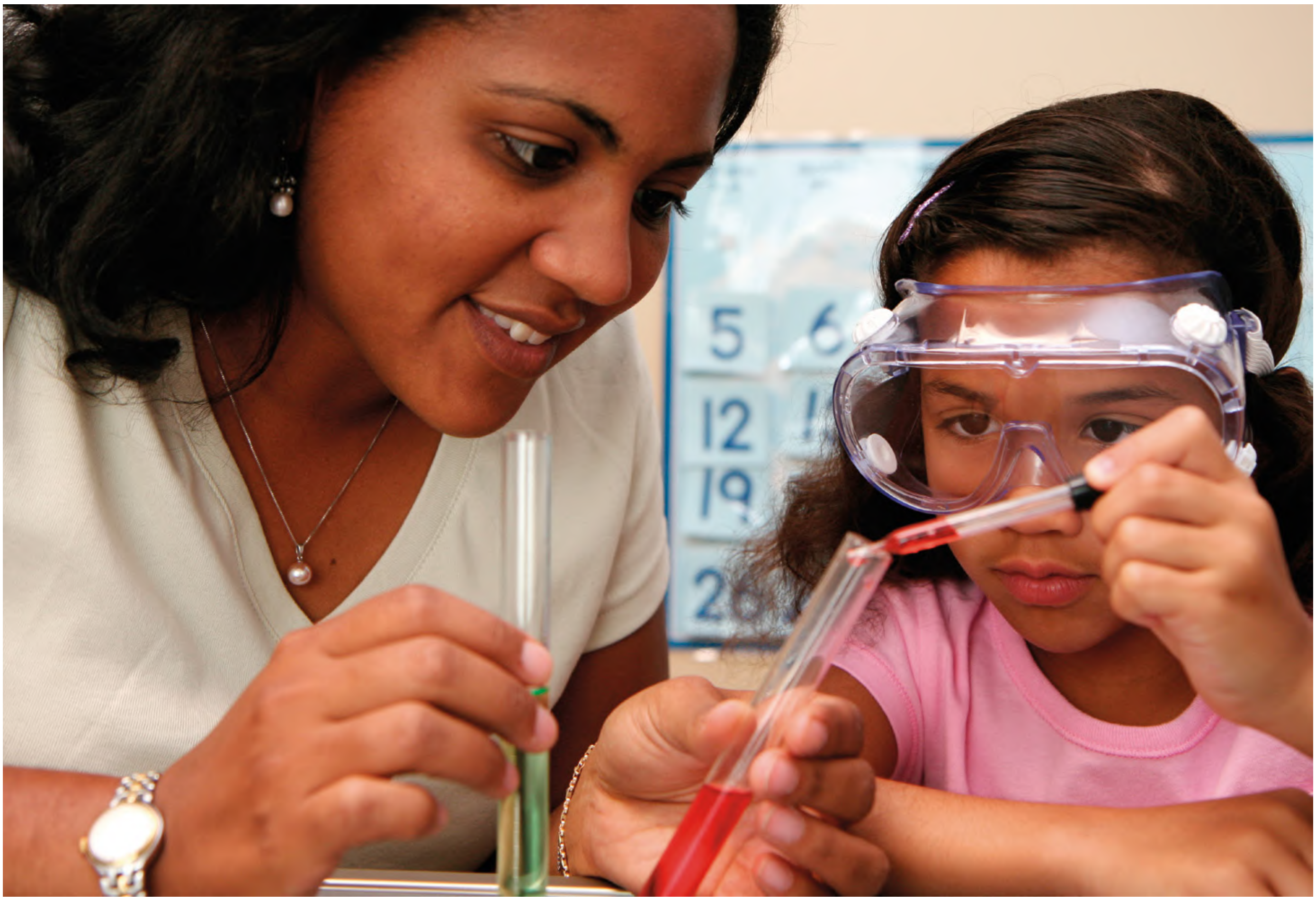
Flipped learning (Bergmann and Sams, 2012) was also used to teach EHoM. This is where, to deepen understanding through discussion or problem-solving activities with a lesson, students accessed learning resources before coming to class. One FE teacher described how he used flipped learning to cultivate problem solving, making resources available on the school's virtual learning environment (VLE) that could be accessed before class in order to solve challenges presented to them in class.

6.5 How teachers engaged learners

The ways in which teachers engaged learners with EHoM was of particular interest to us. The challenge of engaging learners at primary school in engineering activities resides mainly in finding time and space within the curriculum for them to take place. However, cultivating EHoM in secondary school is even more challenging due to a fundamental lack of engagement with science and technology, which is at the root of engineering's problem in attracting young people into the profession. We explored the schools' interventions in this section using the four principles of student engagement articulated by Learning Futures (2012), purposeful, placed, pervasive and principled, previously described in Section 5.

Purposeful

We have already seen how the process of formally engaging with engineers and industry could be regarded as an element contributing to a signature pedagogy for cultivating EHoM (Section 6.4). Links with professional engineers



also drive learner engagement through the creation of purposeful activities. Curriculum topics linked to problems that engineers face in the real-world, and the knowledge that in using EHoM learners are using the same skills as professional engineers, can serve as powerful drivers for engagement:

"We've got to reach out to all these companies … because then if the students see it relating to an actual company, they're more likely to engage with it rather than just going, we're going to make a model, we're going to talk about this… It's making it real-life for them." **(Head of STEM, secondary school, TLaE)**

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.

Examples of EHoM outreach into the community that we were aware of appeared to occur indirectly as a result of teachers' interventions, rather than being deliberately included as an engagement strategy. One UTC used an outreach strategy where Year 10 pupils went to local primary schools to motivate young children about studying engineering, and changed their presentation approach after they had learnt about EHoM:

"Year 10s realised that EHoM could be used to explain to primary school children what engineers do, rather than just tell them what all the different branches of engineering are, when they went on outreach work." **(Director of STEM, secondary school, TLaE)**

Pervasive

Parents play a critical role in promoting their children's interest in engineering and the examples we noted of pervasive activities to encourage 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:

"We had a Star Wars theme…and that got parents involved, and they loved it…it's the best home learning task we've done so far, because they [the children] got themselves really involved in it, it got dads involved, it got mums involved." **(Year teacher, primary school, TLaE)**

A STEM festival organised by one school, in which over 40 local STEM industries participated by offering hands-on workshops and interactive exhibits, engaged parents so much that many more said they would recommend a STEM career to their children as a result.

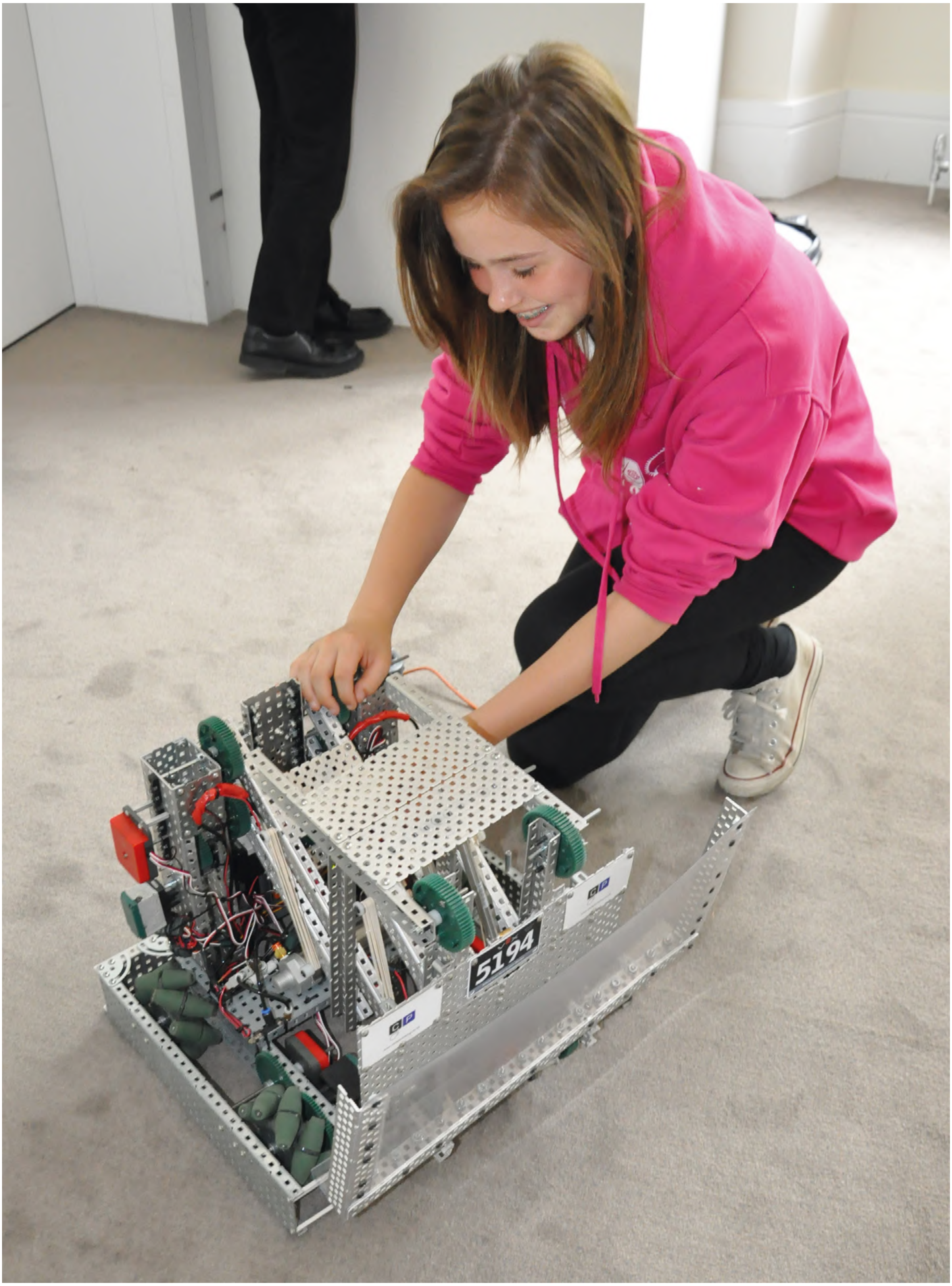
Several schools participated in external challenges such as the Greenpower Goblin Racing Car Challenge (2016), CREST Awards (British Science Association, 2016) and the Manchester Robot Orchestra Challenge (2016). Other schools reported that learners' interest in the school's extra-curricular school STEM club increased dramatically during the period of EHoM cultivation:

"We've got an extra-curricular gSTEM Club which has been running since September which included 25% of the school. So, we were just amazed with the enthusiasm and motivation of children. I think that sort of represents the passion they have for it." **(Senior teacher, primary school, TLaE)**

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:

"Two girls in my class are quite deep thinkers, so the practical actions, which are about helping people in areas of devastation, was on the carpet one time and these two girls both had their hands up. They're not ones that normally offer opinions. And they came up with two really, really good statements of why we need practical actions to go in and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CASE STUDY H:
Reading College, Reading, Berkshire (www.reading-college.ac.uk)

Themes: Principle 4 – Engaging learners, employer-led projects, real-world problems, active learning, flipped learning

Reading College is a further education college and a member of the Activate Learning Group. Lecturers find that even when students have elected to study engineering courses in FE, there is no guarantee that they will have a good understanding of what engineering is, so participation in TLaE offered lecturers an opportunity to reflect on their teaching and develop methods that might not only cultivate EHoM but also enhance students' understanding of engineering and develop their employability skills.

Six lecturers from the Department of Engineering who participated in TLaE often encountered disengaged young people who had been conditioned through their earlier education experiences to reject learning approaches that required curiosity resourcefulness and resilience. So they embedded EHoM into their teaching on the BTEC Level 3 Diploma in Engineering. They each focused on a specific EHoM and incorporated range of teaching strategies that included:

- Presenting stories of 'engineering heroes' who overcame challenges, to cultivate understanding of resilience
- Designing an employer-led project to cultivate students' problem solving Using flipped learning to cultivate inquiry-led problem solving
- Encouraging students to tinker and put components together before receiving theory input
- Using flash cards to enhance visualisation skills.

The lecturers' combination of active learning strategies and real-world contexts proved engaging because learning had a purpose, it was relevant to the engineering workplace and students were working like professional engineers.

By standing back and giving students opportunities to tinker and ask questions, they fostered their problem solving ability, and their enthusiasm for thinking like an engineer.

help these communities, not just give them money. And it was the look on the other people's faces when they looked at those two girls who hardly ever say anything, going, you know, 'Wow. Yeah. I hear what you're saying'." **(Year teacher, primary school, TLaE)**

Although the motivation of girls to study STEM is an important issue, we did not set out to study it specifically in this research. However, one teacher suggested that EHoM might benefit girls' engagement by giving them words which they can identify:

"My own intuitive feeling is that having these habits of mind would...I'm thinking about the girls in this school... actually help them, because it breaks this idea of being an engineer down. It gives them a word that they can identify with." **(Director of STEM, secondary school, TLaE)**

Even when students arrive at FE college to study engineering they may still not be fully engaged with the subject and its potential career opportunities, so Case Study H Reading College, embodies many examples of engaging older learners through EHoM.

6.6 Summary

The teachers demonstrated that it is possible to cultivate EHoM and generate enthusiasm for engineering among primary and secondary school children by using the four principles associated with developing habitual behaviours and dispositions. They used a range of strategies to build understanding and create a climate within their classes and across the school that demonstrated the value of the EHoM to learners. They also found that the use of three elements of a signature pedagogy for engineering – the engineering design process, tinkering and authentic engagement with engineers – enabled them to cultivate the desired habits of mind and foster interest in engineering. But even small changes to their teaching practice could enable engineering habits of mind to flourish.

7. Outcomes for learners

In this section we describe the impact of teachers' interventions on their learners. We focus on the degree to which learners were able to use EHoM, the development of engineering mindsets, impact on literacy, numeracy and oracy, on classroom management and on learners' understanding of engineering.

7.1 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 (Table 2). These 12 sub-habits included behaviours that the teachers were more likely to recognise as everyday dispositions that they tried to cultivate in their learners. We thought that the teachers would be more willing to try an intervention based around a familiar disposition and also that they would be more attuned to noticing any small changes in their learners during the relatively short time period that they had to carry out the interventions.

Our evidence from teachers suggests that findings concerning learner skills, understanding and dispositions towards STEM are similar to Springate *et al.*'s (2009) findings. These relate to learner dispositions arising from a secondary level integrated STEM programme, including increased problem solving, independent learning, investigation skills, team-working and communication skills. In our case, however, these results can be seen at both primary and secondary levels. Our analysis of the teachers' action research reports and interviews

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 rehearing 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

showed that they observed changes in their learners' behaviour during the interventions, suggesting that learners did develop an enhanced understanding of the EHoM, and increased confidence and competence in trying to use them.

This section continues with an exploration of how these changes in learner behaviour in our study relate to our EHoM frame.

Creative problem solving – generating ideas and working in teams

Teachers commonly reported that they were initially challenged by learners who always wanted to get things right first time and who were reluctant to put forward new ideas for fear of being wrong or being mocked by their peers. However, teachers reported that the ability of learners to tackle open ended questions more confidently and generate creative solutions to problems did improve. This increase in confidence was sustained by the teachers' use of models or thinking routines such as SCAMPER (see Section 6.4 and Case Study C) which supported learners through the process of coming up with new ideas and helped them realise that creativity skills can be learnt:

"…children like to be right, they don't like to be wrong, and therefore by having a 'have you done the S [Substitute] bit' they're quite happy that they're doing it right, because they're thinking of things to do with S. And therefore they're more likely to come up with ideas because they know they're following the right process. I think the open-endedness of the other [approach] was 'we don't know if we're doing it right." **(Head of science, secondary school, TLaE)**

Learners also improved their ability to work in teams. Teachers reported that collaboration skills increased and that learners showed greater respect for, and built on, each other's ideas. Collaborative group work was a key feature of the activity created within the TTRP schools:

"Open ended problem solving has been the main way of introducing the EHoM, for example, giving the children six dowelling rods and a sheet of sugar paper, then asking them to work out the shape needed from the sugar paper to cover a tipi…they found this really challenging,. Only when all the children have had a really good go is any further instruction or helpful hints given – they really need to try their own problem solving." **(Teacher, primary school, TTRP)**

When teachers cultivated creative problem solving through learner collaboration they also generated an environment in which peer learning flourished and this in turn supported an increase in learners' confidence to contribute their ideas:

"When peer support is encouraged and the correct classroom climate is created, which I feel I achieved, learners show respect and trust towards peers and feel they can take more risks with their ideas and questions without feeling embarrassed." **(Primary Engineer teacher)**

Sometimes instances of voluntary peer mentoring within a group were noticed. One FE teacher thought this desire to help others might have been prompted by the mentoring student himself having had to struggle to learn:

"Some of them have started seeing themselves as a mentor for other students. They'd go around asking, 'Do you need my help?' …I think they're the ones that actually struggled before. The reason why they get it was because they have put in the work before. They know that it's difficult, but because they work really hard throughout the year, they kind of caught up to that point." **(Engineering lecturer, FE college)**

Primary learners made more of an effort to support their peers with special educational needs (SEN), behaviour which was observed less frequently before the EHoM intervention. Furthermore, those children with an SEN appeared to be more engaged when working on STEM tasks.

Learners also began to realise that if they shared ideas when working in groups, this process would help them arrive at a better answer, possibly more quickly, than other groups.

This appealed to their competitive spirit, especially with boys.

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. 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:

"Two pupils in particular who have difficulty with concentration and focus stuck with the task for a whole afternoon until they eventually found a solution which was satisfactory to them." **(Primary Engineer teacher)**

Teachers noticed a greater willingness on the part of some learners to acknowledge that there was room for improvement in their performance when reviewing their work. The teachers attributed this change in disposition to the altered climate in the class:

"Because it's okay to make mistakes, then I think they feel quite happy with that within themselves. I think there's an honesty there as well." **(Year teacher, primary school, TLaE)**

Problem-finding –checking and 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 6, learners increased their capability in this area. Initially, in D&T and STEM classes, teachers often reported that learners wanted to move quickly through the design stages since they were too eager to reach the making stage. However, during the interventions, teachers noted that learners' confidence to ask questions improved and they appeared to become more curious about the phenomena they were investigating:

"The Year 9 pupils were able to apply EHoM to their designs to improve accessibility for people of all ages and disabilities. In particular the pupils benefitted from the opportunity to 'Problem Find' as it forced them to critique their own designs" **(D&T teacher, secondary school, TTRP)**

Learners also became more resourceful and demonstrated an increased ability to engage in independent learning. Students did their own research to augment the resources provided by the teacher when they were engaged in learning, whether in the classroom or in an after-school club:

"I observed that over the course of the club the children learnt how to problem find and try to fix their problems rather than ask for adult help." **(Primary Engineer teacher)**

Adapting – critical thinking and deliberate practising

One learning disposition that underpins critical thinking is reflection, particularly when associated with self-evaluation. 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 link theoretical and practical knowledge. When asked to explain the reasons for their proposals, learners who had been given thinking routines to help them develop their critical thinking skills were able to draw more readily on principles relevant to the subject and articulate their justification for their choices. So, for example, the learners who were using the SCAMPER tool:

"…were getting good at coming up with every possibility and then eliminating them, and using science to eliminate the ones that were not scientific." **(Head of science, secondary school, TLaE)**

This was an improvement on the situation before interventions, where, for example, a teacher reported that although high achievers in Year 7 might be familiar with the theory behind metal expansion they were unable to explain the connection between this theory and the need to leave a gap for the metal to expand in the design of railway tracks.

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 learners lacked:

"When I asked students about their greatest experience in sketching, half the class 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 DT or art. They said – these are Year 10s – at no point had anyone actually sat down and gone through some methods [of sketching]. One student said it was 'go and draw x, y or z', and they'd never really been given direction in school, or techniques." **(Mathematics teacher, secondary school, TLaE)**

Systems thinking – connecting and pattern-making

Systems thinking was the most under-developed EHoM evidenced during our study; perhaps because it was the one that teachers were least able to recognise from prior experience, or perhaps because to fully appreciate its significance, they had to adopt a more radical change to their teaching such as using the EDP. In those schools where the EDP was used, teachers saw an improvement in learners' ability to connect ideas and see patterns emerging from their data. This suggests that it might be easier to cultivate systems thinking in conjunction with using the engineering design process, where it can provide context for engineering problems.

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. Children transferred their use of mind mapping (Section 6.4) from one subject into others. Others were able to apply EHoM, particularly improving, learnt in STEM sessions to literacy and were able to reason why they had done something in a particular way. Teachers found that they could change learners' perception of how to tackle mathematics questions by reminding learners of the occasions when they had been working on engineering problems:

"[...by saying] 'let's think about it as a gSTEM problem' changed children's mindsets of how they were thinking... that was a way of just triggering that thought process, [that] enabled them to tackle it in a different way." **(Year teacher, primary school, TLaE)**

Teachers began to see EHoM as an integrative factor that could link school subjects together. Learning conversations were taking place across the school that used the same language to make connections:

"...they might have to tailor that to what they were doing, but in a sense it became a common language that they understood and could sort or engage with." **(English team leader, secondary school, TLaE)**

7.2 Evidence of developing engineering growth mindsets

In Section 5 we made the explicit connection between Carol Dweck's research into the development of growth mindset and the way in which this is central to the engineering design mind. In many cases, before the EHoM interventions, teachers said learners lacked resilience, perseverance and self-efficacy and were easily discouraged by failure, thus showing evidence of a closed rather than a growth mindset.

But as the project progressed, they reported that learners got better at using the EHoM the more they practised them and that they demonstrated an increased growth mindset more generally:

"They were so enthusiastic about trying out new ideas and because they had got that resilience and independence, just because they're that bit older, they really wanted to tackle head-on new concepts and ideas and have that independence and opportunities to actually research to find out the answers themselves." **(Year teacher, secondary school, TLaE)**

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 and commented that, "we have also seen students willing to take risks and try and accomplish something without an answer." Teachers also reported a positive attitude beginning to be seen from less-focused pupils:

"Less able children have been more resilient and taken an active lead during engineering tasks. I have also seen a huge difference in the way my class relate to each other, not just in these sessions. They have become better communicators, more able to listen to the opinions of others and better able to manage conflict within social groups both within and outside of the classroom." **(Teacher, primary school, TTRP)**

Even with limited exposure to EHoM, teachers reported that they observed improvements in their learners' willingness to think more creatively and in their confidence to talk about their ideas (Case Study I Camelsdale Primary School).

7.3 Impact on literacy, numeracy and oracy

While we did not specifically aim to investigate the impact of cultivating EHoM on attainment in literacy and numeracy, some primary teachers noticed improvements in these subjects. Within literacy classes during the intervention period, 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:

"Pupils' reasoning skills in Maths have particularly improved. The 'tinkering' ethos has shown benefits in the

CASE STUDY I:
Camelsdale Primary School, Haslemere, West Sussex (www.camelsdale.w-sussex.sch.uk)

Themes: Learner outcomes – enhanced creative problem solving, problem finding, curiosity and self-confidence, EHoM self-report survey, thinking routines

Camelsdale Primary School is an average size primary school of around 220 children aged 4 to 11. It is a member of the Forest School group and has participated in Building Learning Power. The school also participates in the Green Power Goblin Racing Car Challenge.

One teacher embedded EHoM in her Year 2 class and encouraged students become more creative problem solvers by generating their own ideas and solutions in creative writing tasks or open ended mathematics investigations. She used a number of different thinking routines, including Talking Partners, Talk to the Hand and Thunks. A climate of acceptance was encouraged, with 'no wrong answers'.

At the start and end of her EHoM intervention the children completed a questionnaire to assess their own ability in the engineering habits of mind. In the following year, this teacher guided her colleagues to introduce EHoM during a school-wide Science Week. The teachers used questioning techniques to support problem finding and problem solving, they taught mind-mapping techniques to encourage visualisation, and generally encouraged a regime of improving and adapting. One teacher used the LEGO® Therapy system with Year 1 children with SEN who found it difficult to work with other children.

All teachers reported that using EHoM in Science Week had encouraged children to demonstrate greater perseverance, resilience, confidence and a willingness to expand their thinking. They also noticed how the children transferred techniques learnt in one subject, for example mind-mapping, to other subjects. When commenting on their own behaviour, the teachers noted how they had increased their confidence in 'standing back' and allowing the children to take the lead in learning. They also realised that something not going to plan in the classroom could provide a powerful learning experience and opportunity to model EHoM.

Image courtesy of Camelsdale Primary School

"children's acceptance of 'marvellous mistakes' and this has in turn impacted on their ability to apply their skills to a range of contexts." **(Primary Engineer teacher)**

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). Teachers reported that learners demonstrated an increased fluency in expressing ideas or opinions:

"Their use of language also developed. Rather than providing one word answers they produced a lengthy explanation and justified their knowledge and understanding or developed their questioning skills to show they were creative problem solvers."**(Primary Engineer teacher)**

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. In one UTC specialising in engineering, this applied particularly to students who had experienced less prior schooling before entering the UTC in Year 10 rather than Year 12:

"Year 10s are more on board with skills needed by employers than Year 12s. They can ask relevant questions of employers, make eye contact and network with them. Year 12s have come from 5 years of schooling elsewhere and seem less receptive than younger students to engage with the UTC ethos." **(Director of STEM, secondary school, TLaE)**

7.4 Self-managed learners and impact on classroom management

In general, teachers reported that children were enthusiastic and motivated and displayed very little challenging behaviour during the EHoM sessions. In one secondary school attitudes towards learning had improved and behaviour was notably influenced:

"The groups were deliberately chosen because of their lack of engagement, behavioural issues etc., there has been an improvement across a host of measures, slightly better homework, more conscientious, less aggressive towards each other - they plan much better and are now more willing to accept the value of a sketch or model prior to producing a final outcome." **(Teacher, secondary school, TTRP)**

In schools where the focus for EHoM was within the 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 at their own level. However, 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:

"I have found that children have become stewards of their own learning throughout this project as they have taken more pride in their work, persevered and produced iterative products/end results as a final outcome. For some pupils this has been a stark contrast from what we would have expected previously." **(Teacher, primary school, TTRP)**

7.5 Impact on learners' understanding of engineering

The need for young people to gain a realistic view of the labour market is vital in maximising their chances of obtaining employment, so contacts with engineers were invaluable in enhancing learners' perceptions of engineering and in motivating them to aspire to it 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, as teachers continually stressed:

"So saying 'this is what actual engineers and people in the workplace actually use', then I think it makes them see the relevance of why they're doing STEM lessons." **(Head of STEM, secondary school, TLaE)**

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 or was it because he was a different face and the children wanted to find out information from him? They certainly asked more 'deep' questions to the engineer and they used far more expressive language when asking him a question. This gave me food for thought." **(Primary Engineer teacher)**

The impact of cultivating EHoM on primary learners' awareness of what engineers do is demonstrated in Case Study J Barmulloch Primary School, in Glasgow.

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:

"The students, really without knowing it's part of the interview, were actually more successful because they were utilising some of those EHoM and sort of the language and the buzz words." **(English team leader, secondary school, TLaE)**

Visits to employers by students led to better understanding of the range of jobs available in engineering. Learners and their parents began to understand that engineering is more than fixing cars. If sustained contact with employers is maintained by the school, the later employment benefits for learners can be significant, but single one-off visits, however interesting in the short term, do not seem to provide much benefit in the longer term (Jones *et al.*, 2016).

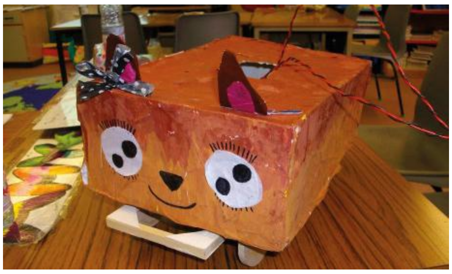
CASE STUDY J: Barmulloch Primary School, Glasgow

Themes: Learner outcomes – enhanced understanding of engineering through engagement with engineers, project-based learning, extra-curricular club

Barmulloch Primary is a small school with around 95 children. It is located in one of the most deprived areas of Glasgow. The two teachers who participated in Primary Engineer's year-long Professional Recognition course Engineering STEM Learning were keen to learn how they could accommodate engineering in their classes.

The teachers identified key EHoM they wished to develop and interviewed practising engineers to establish their perceptions of EHoM. Both teachers decided to frame their classroom interventions around creative problem solving, as the engineers they interviewed had ranked this skill in the top three most important EHoM. One teacher worked with P7 learners aged 10 to 11 years to produce a working electrical model of a moving vehicle. The children were expected to design and produce a fully functioning model that could travel on different surfaces and ramps. The second teacher worked with younger P6/5 learners through an after-school club that had a 'shoe-box car' design project which featured open-end tasks with limited teacher-led intervention to facilitate collaborative creative problem solving.

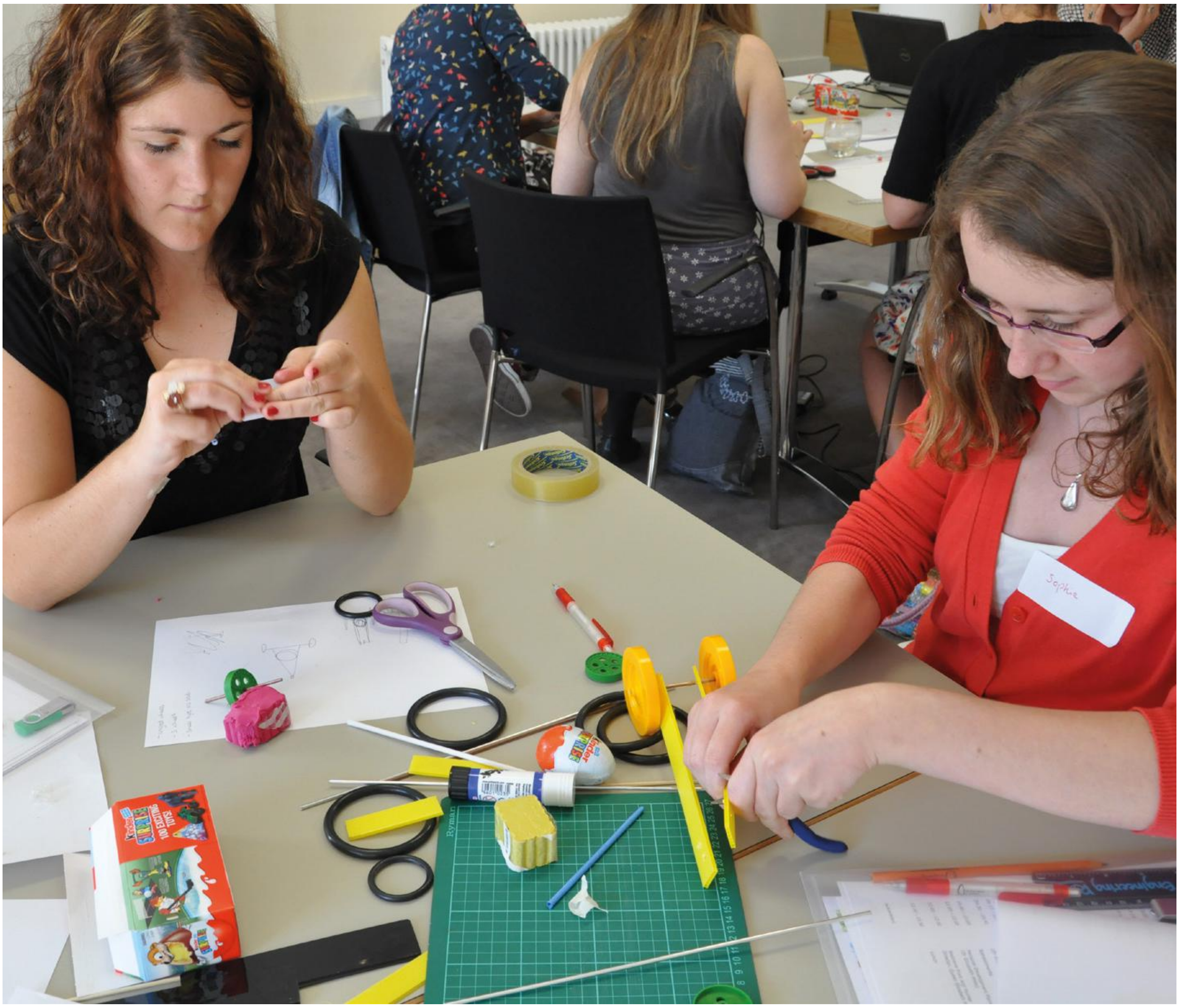
Engineers supported both teachers and talked with children about what engineers did. Both teachers used facilitation techniques more frequently to enable children to take the lead in project-based learning. They found that by relinquishing their 'control' EHoM flourished and the children developed an increased awareness of engineering and the role it plays in the wider world. For example, before the intervention, one child described what an engineer does as 'makes things work' but after the intervention he could give more specific examples such as 'designs buildings and useful things, cuts wood, works with chemicals'. Similarly, when asked before the intervention what skills an engineer uses, the response was 'needs to be good at everything, uses technology', but after the intervention the child's vocabulary was much more specific, as 'creating, construction, electronics, analysing, woodwork, teamwork'.



Images courtesy of Barmulloch Primary School

7.6 Summary of outcomes for learners

Learners at all levels of education appeared to engage with EHoM and acquired more confidence and capability in the target habits, notably creative problem solving, improving critical thinking and curiosity. Teachers noticed significant improvements in terms of learners' mindset (perseverance, learning from mistakes, playful experimentation) and noted improved confidence as independent learners and team-workers. Although we did not set out to measure attainment in core literacy and numeracy, teachers reported some interesting gains in these subjects. There were also significant improvements in learners' understanding of engineers and engineering.



8. 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. It was significant that despite the very considerable pressures on schools, teachers were able to commit to being involved in the research and see it through for between one and two years, so we were interested in understanding the degree to which teachers were or were not able to alter their methods within this period and what those changes meant to them.

8.1 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)**

Both small and large habit changes took place during the interventions. One teacher, in the early stages of changing the way feedback was given, said it was difficult initially to remember to write something like: "You've tried hard" on a learner's book rather than "Great mark!". Despite the fact that a generalised effort-focused comment like "You've tried hard" has less value to the learner because it lacks specific information about what was good about their performance or how it could be improved, and therefore does little to move the learner forward (Black and Wiliam, 1998), small steps like these are the building blocks of habit change for teachers.

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. Teachers realised that they must not restrict creative problem solving by closing down discussion of ideas that contained errors in thinking and had to be more accepting of all the ideas that students generated; nothing was considered a wrong answer if it was contributed as part of the design process:

"…that's almost the hardest thing, because we, by our own nature, will have eliminated their suggestions based on what we already know, and that's the one thing we can't do." **(Head of science, secondary school, TLaE)**

They began to justify this position with reference to the ways of thinking in the subject in the real world, so learners were 'thinking like a scientist, or an engineer':

"[This was] a real way of working in science, because what often happened... somebody would have an idea and somebody would take it on and adapt it and modify it and they understood that, actually, to share ideas you get to the answer quicker." **(Head of science, secondary school, TLaE)**

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. One English teacher explained:

"'I think it was probably slightly harder for the more arty subjects like English but that was quite useful, because where students didn't understand, you were able to say to them 'well, how could you find the meaning of this?'… So when they [learners] didn't understand, there were learning experiences to be gained just from unpicking it together." **(English team leader, secondary school, TLaE)**

Teachers demonstrated that they were more willing to see teaching as improvisation, or know when to allow student-teacher collaboration to emerge and when to drive interaction. They became more skilled at engaging in 'cognitive apprenticeship' style teaching techniques, such as modelling, scaffolding and coaching (Adams *et al.*, 2015). This high level of flexibility, or the ability to be an 'adaptive learning expert', is an important mindset for teachers to develop (Hattie, 2012).

Despite the EHoM framework being new to most teachers participating in the project, they found that could readily incorporate creative problem solving, improving, problem finding, adapting and visualising into their teaching. However incorporating systems thinking outside of STEM posed the greatest challenge:

"If I looked at improving, visualising, problem solving, sometimes adapting, that was all okay for us probably … [but] if it weren't an engineering lesson, most people found it a little bit difficult with systems thinking." **(English team leader, secondary school, TLaE)**

8.2 Teachers as collaborators

The value of teachers learning together in professional learning communities is recognised as leading to enhanced learner outcomes (HM Inspectorate of Education, 2009) and featured prominently in our three projects. In most cases teachers were working on their interventions in pairs, in subject or cross-disciplinary groups, or as a whole school, so there were many opportunities to learn from each other. Working on the project encouraged the teachers to collaborate with each other to learn new skills:

"I've not done any form of arts or design or DT at school, it was a very academic school; I wasn't expected to do things. So [teacher] took me to one side and gave me a model-building class, but that's the extent of it, I didn't know how to cut wood or glue it together, and so those are the limitations." **(Science teacher, secondary school, TLaE)**

Teachers also collaborated to deliver a cross-curricular experience incorporating EHoM. Cultivating EHoM brought teachers from different departments together and this supported the integration of teaching as well as learning. This integrative function of EHoM was particularly noticeable in the UTCs, where it was reported that those who taught subjects such as art, English, business and physical education, began to realise how EHoM could be embedded in their own subjects. This led to greater engagement with the overall engineering ethos of these schools as EHoM became a common language:

"Everyone was really on board with it [EHoM], particularly the art and English teachers, because suddenly they felt like they could be included in what we're trying to achieve, because they could see how all of 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. This led to them offering CPD sessions to their colleagues themselves:

"I introduced the concept engineering habits of mind and demonstrated how they could be using EHOM in many curricular areas. I also offered for others to observe an engineering lesson where I role modelled EHOM being implemented. This was very well received." **(Primary Engineer teacher)**

Primary Engineer teachers also shared their practice by giving presentations to the Scottish Association for Engineering Education annual conference and to the Engineering Skills Investment Panel, as well as at the Academy.

A example of how EHoM supported integration between departments and collaboration between teachers is described in Case Study K.

8.3 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 most evident in two areas: their increased use of facilitation techniques and the enhancement of their questioning techniques.

Teachers acknowledged that adopting a facilitative style was 'a risk' and 'very scary to deal with' but their confidence in 'standing back' or 'letting go of the reins' increased as the intervention progressed:

"From a personal development level I feel this has been hugely beneficial for me and the students it has directly affected. My skills base knowledge has been boosted, the way I now sit back more and let pupils persevere more allows children to work around a problem and ultimately feel more fulfilled at the successful outcome – more pride and less frustration." **(Teacher, primary school, TTRP)**

Nevertheless, they still recognised that facilitation as a strategy was something they needed to practise:

"I have to be a lot hands-off, because there's a message that obviously I want to go, This is wrong, you need to correct this, so I need to take a step back, I needed to be conscious about when I had to take a step back." **(Engineering lecturer, FE college)**

Teachers also became more skilled at facilitating discussion and helping learners generate ideas through good questioning, particularly at the start of a lesson:

'The question "what do you already know" was a good starting point for engaging with a systems thinking approach to problem solving.' **(Year teacher, primary school, TLaE)**

The teachers became 'better noticers' (Hattie, 2012) of their own teaching because, in addition to identifying that their facilitation skills had increased, they also acknowledged they had to be flexible and recognise when learners needed more scaffolding with learning tasks, more reminders to use a technique in support of the EHoM, or just more time to practice. This teacher who had introduced his learners to boxing realised that he still had to

CASE STUDY K: The JCB Academy, Rocester, Staffordshire (www.jcbacademy.com)

Themes: Teacher outcomes – enhanced teacher collaboration, departmental integration, EHoM icons and posters, EHoM in English

The JCB Academy was the first University Technical College to be opened in England and delivers engineering and business education to students between the ages of 14 and 19.

The school aimed to embed EHoM across the curriculum and explore how they could be made visible in in all subjects not just in engineering. Resources were prepared to promote understanding and to 'translate' EHoM into learning dispositions that non-engineering teachers could use.

Despite not being able to embed EHoM as quickly as originally intended, this in-depth consideration of the meaning of EHoM in the context of a UTC with an engineering specialism made a valuable contribution to the project.

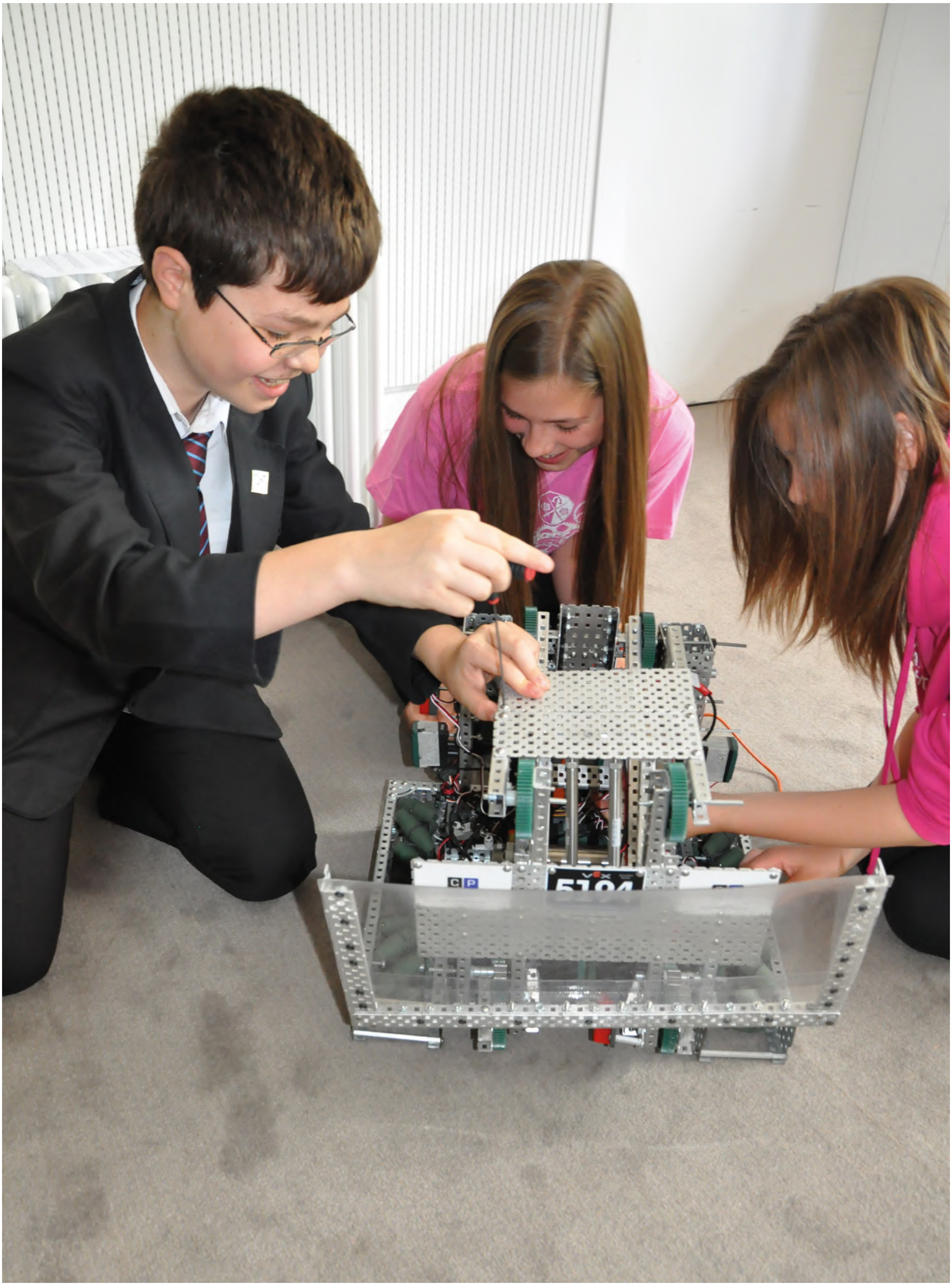
The Head of English, responsible for leading participation in TLaE, used EHoM in her own classes and found that she was able to help students transfer dispositions they used when working on engineering projects, for example improving, into their writing in English lessons.

This led to some interesting insights about the potential for EHoM to act as an integrative mechanism for the whole school since UTCs have an interesting challenge to integrate core subjects with their specialisms to create a coherent learning experience for students.

This realisation helped teachers to align EHoM with much of what they were already doing in the classroom and apply them in all subjects.

In March 2016 students from The JCB Academy were among 117 students who were presented with The Duke of York Award for Technical Education (2016).

Images courtesy of The JCB Academy



remind the students to adopt the technique during independent learning sessions:

"There was a marked increase in their ability [in boxing], but when it wasn't me directing them ... I found that actually a lot of them tended to revert back to their old habits, which I suppose is why we call them habits." **(Mathematics lecturer, secondary school, TLaE)**

The teacher came to recognise students needed time to practise the basic level of boxing before he could move on to visualising more complex geometric shapes.

In the classroom there is always a need for a balance between providing support and challenge, but teachers found that the EHoM provided them with a vehicle for doing this effectively. They were able to refer to the EHoM when encouraging children to improve on their first attempts in lessons other than the STEM lessons by using encouragement such as:

"Think about how you tackled that in the STEM lesson. What did you do? Did you give up? No, you looked for another way." **(Year teacher, primary school, TLaE)**

Essentially, the teachers recognised that learning is a process or a journey and that superior learning occurred when they resisted the pressure to tell learners how to achieve the answers and allowed them to get there for themselves:

"I recognised the importance and value of process in helping to develop pupil understanding by leading them through the different stages of designing a product rather than simply focusing on children completing a task." **(Primary Engineer teacher)**

Learning also involves emotions, and teachers recognised that not only were they enjoying the experience of cultivating EHoM, but also their colleagues began to show interest and adopt similar approaches:

"They were surprised by how much they enjoyed lessons with an engineering focus and have been keen to incorporate this in other areas of the curriculum." **(Teacher, primary school, TTRP)**

It was acknowledged that in the past some teachers had not provided enough time to recognise and celebrate learners' achievements and they saw the positive impact it had on the climate in the classroom:

"The most surprising thing that came out of this ... it wasn't really the editing and improving, because we were doing that anyway, but just that chance for the children to really get involved with each other emotionally." **(Year teacher, primary school, TLaE)**

8.4 Teachers' confidence in engaging with engineers

Knowing that EHoM are derived from research with practising engineers appeared to increase teachers' confidence about emphasising the importance of the EHoM to learners' future employability. They gained knowledge that gave them confidence to make links between the subjects and skills they were teaching and the world outside the school:

"That's something the EHOM has given us, you know, the habits of mind has informed us as practitioners that we need to create learning situations where students can experience that [EHoM]." **(Engineering lecturer, FE college)**

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 Primary Engineer teachers noted how useful it was to know about EHoM before engaging with their interviewees:

"I really enjoyed researching engineering habits of mind and it helped me reflect and evaluate my pedagogical approach. It also helped me to feel a little more confident when approaching engineers for interviews. I felt like I could engage in the conversation and not feel completely out of my depth."
(Primary Engineer teacher)

Furthermore, in schools where employer contacts for curriculum projects had initially been brokered by schools, teachers themselves now seemed more confident to initiate their own contacts:

"We're trying with the new schemes of work that we're writing, to pick an area that we think would be interesting and then find an industry partner to work with." **(Science teacher, secondary school, TLaE)**

In the UTCs, where employers are partners in the school, there was recognition that their involvement could be more coordinated to ensure that employer-led initiatives included and reinforced the EHoM cultivated by teachers.

The experience encouraged FE curriculum managers to be more direct with employers about how their involvement with the college can be mutually beneficial. The college uses a simple three-level description of engagement - 'row, steer or cheer'

"'Cheer' supports a curriculum, encourages and perhaps facilitate a tour or something like that. 'Steer' is steer a curriculum, tell us what you need, that type of thing. And then 'rowing' is actually getting involved - sponsor a unit and deliver learning to young people ... Ideally, we would look for employers to do all three." **(Faculty Manager, Engineering, FE College, TLaE)**

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)**

A synthesis of the thoughts of professional engineers on how education should change to develop future engineers has been compiled from the interviews undertaken by the Primary Engineer teachers with engineers prior to them coming into their schools. This is available on the project website.

8.5 Summary of outcomes for teachers

For the teachers themselves, using the signature pedagogies and making changes to incorporate EHoM into their teaching resulted in them gaining confidence to address new curriculum challenges, particularly in the computing curriculum. Collaboration both within the school and externally through the professional learning communities facilitated their engagement with new pedagogies. The value of working with professional engineers, for themselves and their learners, was made clear.

9. Enablers and barriers for cultivating engineering habits of mind

In this section we explore the factors that appeared to contribute to enabling or impeding teachers in their efforts to cultivate EHoM. Since our schools were a self-selecting sample, we make no claims about the replicability of their interventions or suggest that there might be causal links between what they did and the outcomes we have described in previous sections. Nevertheless, we can highlight some common enablers and barriers relating to factors such as the existing learning culture and preferred pedagogies of the school, for example.

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

9.1 A conducive school culture

EHoM can be cultivated effectively when the school culture is sensitive to the language and practice of dispositional teaching as 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. At all educational levels, from early years to further education, the EHoM framework appeared to resonate with teachers because it aligned strongly with their existing school culture in at least one of these aspects.

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 secondary schools in the TLaE project had engineering, computing or business as their existing subject specialism and, together with the FE College, had a strong interest in promoting the employability of their learners. This focus encouraged them to see in EHoM an opportunity for confirming their existing school mission and possibly offered them a way of enhancing it in the future:

"Our focus as an academy is based around developing students to be engineering and business leaders of the future…And when we looked at the idea behind the engineering habits of mind, there was a lot within that that we felt could be useful for us as an academy and things we were already doing, but also maybe some things we were looking to develop as well." **(English team leader, secondary school, TLaE)**

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, echoing the wider views of primary teachers in a national survey (CBI, 2014). However, even when faced with a culture that focused on core subjects, teachers found that the grounding of EHoM in dispositional learning, habits of mind and growth mindset provided the stimulus they needed to persuade colleagues to engage with STEM subjects and improve learners' awareness of engineering and employability.

For some schools, the opportunity to engage in the project came at a time when the school was working on increasing its focus on engineering and engagement with industry. In some cases curriculum developments were in place or in planning into which EHoM were easily embedded:

"At the time [school name] began its involvement with TLaE, the school had already been working on expanding its provision of STEM through a change programme that included designing

STEM challenges in collaboration with industry partners. These STEM challenges offered an ideal opportunity to embed EHoM within the STEM curriculum." **(Head of STEM, secondary school, TLaE)**

In the case of the FE college, there was a general desire to re-focus engagement with industry and increase collaboration over curriculum development. Furthermore, one primary school headteacher realised primary schools had an important role to play in stemming the crisis over STEM recruitment:

"I recognised that if we could narrow that gap lower down in the curriculum, in key stage one, key stage two, it might then enable more people to be inclined to choose science subjects at a post-16 level and most certainly go on to take them potentially at a degree level as well" **(Headteacher, primary school, TLaE)**

However, some schools and colleges that expressed interest in being involved in the project soon discovered that they were not able to participate as originally planned. Sometimes staff shortages or leadership changes influenced this decision. In other cases when the school itself was in its first year of operation, those leading the project found that they had other priorities to attend to and recognised that teachers can become demoralised when too many changes or initiatives are introduced at the same time.

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 to us that the major learning was less about the use of 'kit' and more about different ways of teaching as described in Section 6. 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 opportunity for teachers to be introduced to coding, programming and related electronic kit, such as microprocessors (Crumbles (Redfern Electronics), Makey Makey (JoyLabz) and Raspberry Pi (Raspberry Pi Foundation)).

For these teachers this support was needed in order to understand how to use equipment with which to engage pupils in 'making' challenges. The interest in making things 'move' and make noise within the Robot Orchestra challenge, provided stimulus and purpose for this new learning:

"Teachers noted the need for funding but they also requested ongoing training in suitable technology and lesson ideas that fit the national curriculum, as well as staff time and training on how to tinker with equipment to a very high level of difficulty in order to support high achievers." **(Teacher, primary school, TTRP)**

9.2 Alignment with schools' approaches to teaching and learning

Where there was explicit support within the school for the signature pedagogies that underpinned our approach, it was easier for teachers to engage with EHoM. More importantly, where there was a willingness to experiment with any or all of these approaches, schools were likely to be in alignment with the overall approach.

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'.

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:

"When discussing the research project within staff meetings, it was agreed that much of our practice already followed the engineering habits of mind, however teachers across key stages were keen to understand how these could be further embedded

into our school ethos and teaching."
(Headteacher, primary school, TLaE)

They readily engaged in attempts to include EHoM within their teaching, rather than teaching extra lessons or adding content. They were able to adapt their practice and be more explicit with learners about what they were doing and why. Teachers had to learn the language of EHoM, but as in many other subjects such as science and literacy, although this may be challenging initially, schools that value the precision of language that teachers use with learners found learning a 'new' language relatively straightforward.

Mapping EHoM to ways of thinking promoted in subject curricula should help with their implementation. Some encouraging examples of the use of computational thinking could be seen in the TTRP schools, specifically in those that participated in the Manchester Robot Orchestra Project in July 2016 (Case Study L).

9.3 Effective integration of EHoM into primary and secondary curricula

In Section 2.3 we noted that the revised National Curriculum and the Curriculum for Excellence offer opportunities for teachers to incorporate EHoM. In our school case studies we saw examples of EHoM integration at primary level within science, D&T, computing, literacy and numeracy, as well as health and wellbeing in Scotland.

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. One primary school taught weekly STEM sessions for each year group that integrated mathematics, literacy, science and IT lessons:

"We know that industry is struggling to recruit people with STEM subjects. So, we thought we'd be leading edge and pioneer STEM at primary level and provide an offer, but one that

CASE STUDY L: Manchester Robot Orchestra Challenge (www.robotorchestra.co.uk)

Themes: Enablers for EHoM – curriculum alignment through computational thinking and coding, robots, music

The Manchester Robot Orchestra Project is led by Professor Danielle George MBE at the University of Manchester. Participating schools were tasked with creating a robotic instrument that would play alongside members of the Halle Orchestra.

TTRP schools that participated were Christ the King Primary School, Sacred Heart Primary School and Seymour Park Primary School.

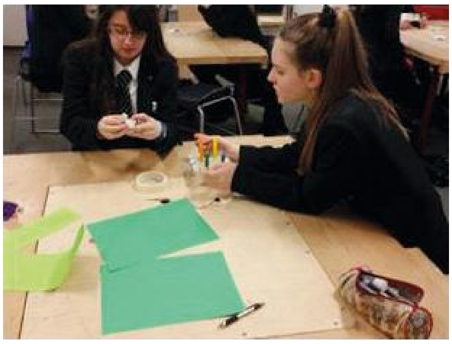
The Robot Orchestra project provided an opportunity for pupils to tackle a creative engineering challenge which drew upon computing skills and EHoM. In creating and programming their robotic instruments, pupils used a range of computational thinking concepts identified by Barefoot Computing, see Figure 4.

When designing their instruments, pupils decomposed the project during the process of creating the instruments and with the instrument itself. The robotic drummer engineered by Sacred Heart School could be decomposed into the mechanical mechanism for the arms, the drum blocks and the robot body.

Pupils wrote algorithms specifying the movement of the servo motors used to generate sound. In the case of Christ the King Primary School, the algorithm described the movement of beaters to play the xylophone keys, including the angle they must move through the time pattern of when the notes were struck. Since patterns features heavily in music, the recognition and use of patterns was key to efficient coding.

After designing their instruments, pupils created and coded their robots. They regularly tested and debugged code, again employing computational thinking skills. For example, when they decomposed code into sections, running a section at a time to pinpoint bugs, they employed a logical mindset to 'think through' the action of each block of code.

Images courtesy of Robot Orchestra Project, University of Manchester



Images courtesy of St Ambrose Barlow RC High School

CASE STUDY M:
St Ambrose Barlow RC High School , Salford (www.stambrosebarlowswinton.org)

Themes: Enablers for EHoM – curriculum alignment through design & technology and computing, tinkering, transition day, teacher collaboration

St Ambrose Barlow RC High School explored EHoM through two projects. The first supported a feeder primary school in the delivery of D&T and computing. The second evaluated the impact of EHoM on Year 9 pupils engaged in an Architectural Project.

The school was approached by Christ the King RC Primary School to support its delivery of the new Key Stage 2 curriculum in D&T and computing. It was agreed that St Ambrose Barlow would provide support through a cross-curricular project which focused on the topic 'castles'. The project involved Year 6 pupils from Christ the King designing, building and tinkering with Trebuchets. The secondary teacher visited the primary school a number of times and on one transition day 30 primary pupils visited the secondary school to build the trebuchets.

The Year 9 Architect Club pupils used EHoM to improve their Shopping Centre Designs, for which they used BIM software. The pupils focused on problem finding and creative problem solving to explore the accessibility and inclusivity of their designs.

The TTRP workshops re-energised the teacher's appreciation for tinkering. This inspired him to buy new resources and materials to allow pupils the opportunities in lesson to tinker and explore. A strong relationship with the primary school has developed. Having dedicated days to collaborate has allowed teachers to develop projects together.

For the primary pupils, the projects fostered greater confidence in their abilities in D&T. Experiencing a workshop and using the equipment helped them believe that D&T is a subject they can do. This gave them a better understanding of it and enhanced their excitement, rather than apprehension about D&T lessons in high school. The Year 9 pupils were able to apply EHoM to their designs to improve accessibility. In particular the pupils benefitted from the opportunity to 'problem find' as it forced them to critique their own designs. The projects confirmed that EHoM can be embedded in D&T lessons and projects.

wasn't tokenistic, but that had a sound pedagogy that could be embedded into the curriculum with clear progression in skills, that could be built on year by year." **(Headteacher, primary school, TLaE)**

Despite these achievements, we got an overwhelming sense of pressure on teachers, even 'fear', as one described it, caused by lack of time to cultivate EHoM when working with what they described as a 'content-led' curriculum. They recognised that habit change requires a period of time in which to flourish:

"Time was against us, especially with ingrained habits, and it's going to take years to get them out of those habits." **(Faculty manager, Engineering, FE college)**

Despite the challenges, primary teachers did find imaginative ways of carving out time to incorporate EHoM by integrating subjects:

"The constraints of a demanding new curriculum now makes trying to fit in this approach difficult, however like our project, if you combine different subjects you can steal some time from the weekly timetable to fit it in." **(Teacher, primary school, TTRP)**

At secondary level, we have examples of EHoM integrated into science, mathematics and, as in Case Study M, within D&T.

Banks and Barlex (2014) suggested that it is possible for STEM subjects to collaborate in ways that are to mutual advantage and non-disruptive of the normal timetable. It requires teachers to 'look sideways' in the curriculum so that they are aware of what has already been taught in the other STEM subjects and then teach their own subject 'in the light of STEM', requiring pupils to use this previous learning.

EHoM were also integrated into STEM enrichment programmes. One school had a whole school change programme revised to concentrate on STEM taught across Years 7 to 9 and was taught through STEM challenges devised in collaboration with engineers and employers. Similar examples can be found in Section 8.4.

Secondary teachers decided that EHoM was best introduced at Key Stage 3 and embedded as soon as learners entered the school in Year 7, "because we've got complete control over it and it's not an examined subject we can be very creative" (TLaE head of STEM). This continued in Year 8 so that they become accustomed to using the skills by the time the enter Key Stage 4, because "you would not have time to put it in there." (TLaE head of science).

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. This Primary Engineer teacher came across unexpected challenges:

"Timescales for certain activities were extended. For example, additional coats of paint had to be applied to some of the cars due to the type of cardboard used to build them which required more time to dry." **(Primary Engineer teacher)**

Before adopting a dispositional approach to teaching using EHoM, teachers and learners appeared to be driven by the need to complete work and achieve an end product. However, EHoM interventions helped the teachers realise that the time could be better spent on facilitating and that this approach generated more time to see how learners were really developing:

"By acting as a facilitator, by giving basic instructions and providing the necessary resources, it gave me more time to observe to provide more accurate assessment information." **(Primary Engineer teacher)**

Some found it a challenge to incorporate changes to their teaching which they knew worked, such as 'wait time' after asking questions, but which they thought might take up too much time:

"Three seconds does not seem too long, however when you have a whole day planned and trying to 'fit' so much into the curriculum, time can become an issue." **(Primary Engineer teacher, TLaE)**

9.4 Validation from external assessments

For teachers, the existence of an external examination provides an obvious imperative to organise curriculum accordingly. According to the teachers, preparation for externally focused assessments can take precedence over providing opportunities to develop skills, whether in Year 6, when teachers have to prepare children for SATs or in Years 9 to 11 for GCSEs:

"We've probably not done as much gSTEM as we would have liked to this year, in year six; we've done as much as we possibly can but equally, we're trying to prepare the children for what may have to come." **(Year 6 teacher, primary school, TLaE)**

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/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:

"With the movement towards a 100% exam, so this year's current Year 10, when they take their exams in 2017, will have nine hours of english exam … what would you need to do in order to make sure that that didn't impact? You would have to show how the cultivation of those engineering habits of mind would actually mean that their students will be more effective in exam performance." **(English team leader, secondary school, TLaE)**

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. This fear was expressed particularly in UTCs and FE, where it was reported that some students apply to study engineering without really understanding what it involves. They imagine that studying engineering will involve making things, but quickly become disillusioned when they find the course is split 80% and 20% between theory/practice:

"The curriculum should include more 'hands-on' experience of using tools, eg CAD CAM, to prepare students for the work place. The content knowledge learnt at school quickly becomes out of date, but the psychomotor skills remain as basic skills." **(Mathematics teacher, secondary school, TLaE)**

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. The NEA is based on a contextual challenge and requires candidates to explore one of three contexts suggested by an awarding organisation and through identifying the needs and wants of people in that context, develop their own brief for designing and making an outcome that meets these needs and wants (DfE 2015). 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. If a qualification was available for introducing engineering themes to children in Years 7, 8 and 9, it could provide substantial encouragement to study STEM subjects in later years. However, such a qualification would have to have the status of a GCSE for it to be taken seriously:

"It's complicated to find a suite of qualifications that support what they are trying to do, especially when it comes to finding a qualification that merges the two specialisms of engineering and IT." **(Vice Principal, secondary school, TLaE)**

9.5 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.

We noted in Section 6 that teachers used a range of feedback techniques associated with 'assessment for learning' (Black *et al.*, 2003) to enhance learners' performance of EHoM, but given the ever-present focus on assessment of learning, teachers were acutely aware of the need to present concrete evidence of achievement if they wished to continue their intervention.

They used observations of learners' behaviour in class or noted the evidence from learners' outputs to track progression and growth in the development of EHoM. However, they recognised that in order to persuade senior leadership teams (SLT) of the value of incorporating EHoM, they needed measurable data to show evidence of the success of their approach. Seeing more engaged and confident learners in lessons which 'is the first sign of maybe you're getting it right with how you're approaching lessons' (Head of science, TLaE) is a positive step but eventually the evidence has to be stronger than this.

Teachers thought it was important to ensure that the EHoM experiences were built on progressively each year, so that as learners move up to another class or school, the receiving teachers can build on what has been done previously. Therefore the challenge of finding an efficient system to record and track EHoM development was reported by teachers at all levels. Some schools used our EHoM self-report tool (Appendix 3) and some 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:

"I always find the baseline data quite spurious, because when they don't understand something they're often more inclined to think they know more about...what do they call it, unconscious competence, whereas when they start to learn about them they realise they don't know anything about them." **(Director of STEM, secondary school, TLaE)**

One of the key features of successful transition from primary to secondary school is when teachers share information about learners' skills and understanding (Evangelou, *et al.*, 2008), and our schools had varied experiences here. One TLaE primary head suggested that there was a gap in passing on information between her school and the secondary school because the transition forms from the secondary school only sought facts about attainment and attendance but asked for no details about the child's learning habits, so there might be little chance of continuity in a learner's development of EHoM. However, other primary schools worked on this type of progression with their feeder secondary school, either through developing EHoM tracking forms or working jointly on EHoM interventions.

Some teachers suggested that a marking scheme for each EHoM at different levels would be helpful, although they recognised that the education system is moving away from describing attainment by level. Nevertheless, they obviously wanted to use more precise language with learners not only to describe their achievements but also to suggest how they might improve. It was clear that they wanted to be able to give more finely tuned feedback to learners but that they struggled because the EHoM language was not yet sufficiently refined to enable them to do this:

"It is difficult to know, I mean, when you don't know; I don't know how to say how improved something is, I just don't know. I mean, it looks a lot better than it did when I saw it before, so..." **(Science teacher, secondary school, TLaE)**

This may suggest that teachers would welcome more ideas on how to express 'design judgement' which covers aspects of a design such as aesthetics, coherence, unpredictability, feasibility, interactivity, and novelty, as identified by Adams and her colleagues (2015).

In some schools it appeared that it might be possible to record progress in EHoM by adapting existing tracking and recording systems. Nevertheless, the lack of visibility of the EHoM in the language of the curriculum and marking schemes could be a barrier to teachers adopting them and trying to assess them, since unless the terms are clearly referenced and allocated marks, they are not going to be valued:

"Why are we valuing certain things and not valuing other things? For example, there's a full 18 marks for marketing your product in product design, which is important, but then, problem finding and adapting would barely fit in with that." **(Mathematics teacher, secondary school, TLaE)**

A few schools were using the Pupil Attitudes to Self and School (PASS) survey tool to measure learners' attitude towards themselves and school, which might offer scope for mapping EHoM. For example, improving might align with Measure 7 'confidence in learning' that 'identifies a pupil's ability to persevere when faced with a challenge' or with Measure 9 'response to curriculum demands', where the pupil 'focuses more narrowly on school-based motivation to undertake and complete curriculum based tasks' (GL Assessment, 2016).

Even if appropriate descriptions of EHoM levels or assessment criteria were available, finding a valid method to assess contributions to group work, for example, might still present a challenge due to time restraints:

"I think the portfolios on an individual basis are a very good way of monitoring how well it's been implemented. But I still don't know, if you've got 100 every year ... and however many portfolios, is that really a good way to assess it from a schools' point of view and to track it? I'm not sure." **(Director of STEM, secondary school, TLaE)**

BTEC assessment criteria were also criticised for not being 'EHoM friendly', by allocating marks only when the answer is correct, not for showing how the answer was derived:

"If they were doing A-levels, in the exam they will get awarded for working it out, they will get awarded for getting this far. But for BTEC, because it is criteria referenced, they either get the mark or they don't get a mark. So, I guess it doesn't really support the habits of mind that way."
(Engineering lecturer, FE college, TLaE)

As employers engage more closely with FE colleges and UTCs in the planning of apprenticeships, increased accountability from the providers is expected by employers, which also enhances a culture of performativity:

"There's less of this idea that 'you're the college and we'll let you get on' … I think there's more of an appetite for employers to shape what we do or to be involved in what we do. Certainly when it comes to apprenticeships, there seems to be more and more a culture of targets and SLAs, with agreements about performance and things like that, which I'm all for."
(Faculty manager-engineering, FE college, TLaE)

9.6 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. The delivery of a whole-school STEM scheme of work constantly challenged the room allocation system 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 no storage facilities for models. The cultivation of EHoM within project-based learning requires flexible, purpose-built spaces to facilitate interdisciplinary learning and these were often not readily available.

There is no shortage of organisations offering to run STEM events for schools (Morgan *et al.*, 2016). However, sometimes schools became frustrated with those only offering a few hooks designed to spark learners' initial in engineering. For schools where learners have already decided they wanted to study engineering, such as UTCs, inputs are needed that go beyond single events.

Teachers suggested that it would be very 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 Centre (2016), Tomorrow's Engineer (2016) or Born to Engineer (2016) and DATA (2016) but perhaps they need to be explored more specifically for resources supporting EHoM.

9.7 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. Each group is situated within a specific culture and each side has its own traditional organisational boundaries which have to be negotiated successfully for the partnership to flourish (Flynn *et al.*, 2016).

While national organisations exist to provide support to 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.

Not all primary schools found it easy to engage with engineering employers, with one headteacher frustrated by the reluctance of local employers to fully

engage with the engineering initiatives at her school:

"Unfortunately, my experience of industry is that they're quite narrow-minded in regards to primary education. So, there are no funding streams that I can access. When I contact the local businesses, for example, [company], who are on our doorstep, they're just not engaging, it's really frustrating." **(Headteacher, primary school, TLaE)**

It appears to be important to articulate the benefits for engineering employers to engage with all levels of education to further young people's interest in engineering. Teachers who had successful relationships with employers reported that engineering employers could benefit by getting closer to learners, enabling them to spot promising future apprentices or employees. For schools and colleges delivering apprenticeship programmes, increased collaboration can support establishing service level agreements and setting realistic performance targets for students.

As the evaluation of the Young Foresight intervention to engage industry with education through the KS3 D&T curriculum demonstrated, (Barlex, 2012) greater engagement with education can lead to important gains for the company and for the personal development of its engineers. For example, employees who deliver talks and workshops in schools develop their communication skills, while companies can demonstrate high impact corporate social responsibility (CSR) by mentoring students.

However, 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. Teachers reported that it is important to make curriculum involvement manageable for employers in terms of their time and be clear about their role. In most cases teachers found that engineers contributed effectively when they entered the classroom, but on a few occasions it was noted that they would 'sit in a corner and say nothing' (TLaE secondary teacher). Some teachers experienced new-found confidence, having successfully secured the support of an engineer:

"I asked [engineer] … to allow more thinking time. He could not believe the difference, plus the children were becoming more confident with the engineering habits of minds … They were able to say why they were doing things in a particular way and ask [engineer] questions to help develop their understanding or to confirm the answer to themselves." **(Primary Engineer teacher)**

Overall, it was encouraging to learn about the extensive involvement of engineers in engineering curriculum development and delivery to support EHoM in our three projects, and some schools saw potential for even closer alignment between the engineers' involvement and the school's curriculum outcomes. Ofsted has confirmed the importance of positive relationships for sustaining links between schools and industry to secure the best outcomes for learners from this engagement (Ofsted, 2016b) but this body has also noted that too few schools and colleges liaise with employers to fully exploit their potential input to develop a curriculum to meet Britain's skills needs (Ofsted 2016a:75).

9.8 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). For all three projects, TLaE, TTRP and Primary Engineer, this is what teachers experienced in the main, but for the ongoing embedding of EHoM, teachers had recommendations for SLTs that we explore in Section 10.2. In this section we relate some of the enablers and barriers that might be attributed to leadership and highlight the need for effective middle leaders who act as change agents during times of innovation.

We have noted how the teachers' EHoM interventions began to improve the levels of trust in the classroom, between teachers and learners and between learners and their peers. Therefore senior leaders also needed to role model the attitude and behaviours of EHoM and to show enthusiasm and willingness to experiment, innovate and be creative within the curriculum. As one teacher reflected:

"[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. The process of collaborating within professional learning communities has been acknowledged as valuable for teachers' CPD generally and, for STEM teachers, it helps them learn more about their subjects, use more research-based methods to underpin their teaching, pay more attention to students' reasoning and understanding and use more diverse modes of engaging students in problem solving (Fulton and Britton, 2011:8). So it was helpful that most headteachers in the TLaE and TTRP projects ensured that at least two members of staff were involved in the intervention, and some ensured that larger groups of staff participated. One school used its Teacher Learning Communities meetings to support the EHoM interventions, where teachers met once a month to share what they were doing in their classrooms and ask questions of each other.

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. In some of the larger institutions teachers suggested that they could have been more proactive about sharing their innovations with other departments.

Teachers who undertook an action research approach to exploring the changes taking place in their classrooms when they introduced EHoM reported that it opened up their thinking about their teaching, but this required time. It was suggested that it takes a year for teachers to try out a new idea and build it into their teaching 'toolkit'.

Beyond the individual school communities, each of the project teams offered their teachers a structured a programme of training and interaction throughout the academic year that brought them all together. Within the TTRP project, the University of Manchester offered support for teachers to develop their knowledge and skills in using specific equipment, share time with academic engineers and be involved in experiential learning activities, focus groups and dissemination events. However, this approach is noted to be unsustainable in the long term. Teachers needed to see the value of the project to their own professional needs and for that to be visible and valued by senior leaders, external bodies and have learner impact.

The presence of middle leaders in the participating schools was an enabler that contributed 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. These individuals encouraged other teachers to get involved with EHoM; they designed teaching schemes, lesson plans and resources for their colleagues, they fostered links with external agencies and responded enthusiastically to the requirements of the project teams, even when reorganisation affecting their role was happening within their institution. They reflected on their successes and learnt from their failures. One Head of Science prepared slides for other teachers to use in the initial version of her STEM Programme but this did not work as well as she had hoped:

"I made all the PowerPoints and I made it very, very prescriptive in terms of 'this is what you're supposed to be doing', so non-specialists could do it but then it just didn't… it didn't quite… and again that's maybe because the staff didn't have the ownership, they didn't have responsibility, they saw it as an additional lesson; so it's all those classic things." **(Head of science, secondary school, TLaE)**

Some schools experienced 'false starts' or did not progress as far or as fast as they would have expected during the project, but those teachers responsible for leading the project recognised that for the introduction of EHoM to be successful, teachers as well as learners needed support or scaffolding in order to learn new habits:

"You just sometimes have to be there and show people and hold their hands a little bit, because we're also trying to embed a new habit in our teachers, which is very hard as well." **(Director of STEM, secondary school, TLaE)**

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.

UTC teachers reported that despite having chosen to attend a school specialising in STEM, learners were often unaware of the true nature of engineering and became disillusioned with the curriculum on offer because there was limited time for practicals and they did not realise the extent to which mathematics is required at A level.

10. Conclusions and implications

This series of coordinated, small-scale interventions emerged from a reframing of what it is to be an engineer and research into how teaching and learning methods can best be selected to cultivate certain engineering habits of mind. This educational reframing and an accompanying shift in pedagogies were piloted across a number of schools in three different regions of the UK. Teachers undertaking these changes were given targeted support within a wider professional learning community in which there were opportunities for them to co-design new ways of teaching. In this section we draw conclusions from our evaluation of the teachers' activities and discuss implications for different stakeholders.

10.1 Conclusions

Our TofC 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. Following a re-statement of the full TofC below, we draw a number of headline conclusions with regard to this hypothesis and our research questions.

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.**

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 engineering habits of mind, (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 conclusions from our five more detailed research questions, see Section 3.1:

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. All six EHoM and their

sub-habits were useful although the least developed 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 with regard to engineering education.
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. To move forwards it will be important to understand two aspects more fully: how best to measure progression within each of the EHoM and the components for building successful engineering education professional learning communities for teachers.

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.

10.2 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 it might be helpful to focus on the generation of free resources to enable more teachers to make their own small scale changes. During the course of the study we have gathered together resources produced by the teachers that are being made available to the wider education community through a project website hosted by the Academy. The Academy has already begun to identify strategies for co-ordinating the multitude of initiatives supporting engineering in education (Morgan *et al.*, 2016), it might like to consider how the promotion of EHoM and the development of additional teaching resources could be integrated into this process. For example, it could encourage the National STEM Learning Centre to tag relevant resources that support EHoM, use its own network of STEM Teacher Coordinators to promote EHoM, or bring together an alliance of subject and engineering institutes, for example, The Design and Technology Association, The British Science Association, The Mathematical Association and the Institution of Mechanical Engineers to collaborate with a focus on pedagogy rather than on content.

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. It would be helpful if cases could include examples of progression through this subject onto engineering degree and sub-degree courses.

c) As the computing curriculum presents many opportunities to encompass EHoM, and increasing recognition is 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 10.2d. These learning communities might function with reference to a number of models of professional learning and support schools in meeting standards for teachers' professional development (DfE, 2016c). For example, one model offered by SEERIH that underpinned its work with TTRP schools is a five stage development process referred to the 'Trajectory of Professional Development' (TOPD) (Bianchi, 2016) which denotes an increasing level of ownership and autonomy a teacher can adopt regarding their personal development, and in doing so relates to the development of their identity as a leader, see Figure 8.

Alongside making the progressive nature of PD more explicit, the TOPD model emphasises the importance of 'co-create', an interactional process essential for teacher development.

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). Schools and employers each have their own culture, accountability regime and legislative requirements that are important for each side to recognise. Therefore strategic and operational issues of the partnership need to be explored and clearly understood by both parties for it to work well.

h) Engineers have the ability to bring contextualisation 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 (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) In the light of the proposal to create new Institutes of Technology, (BEIS, 2017:42) government should 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 (between Key Stage 1 and Key Stage3), 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).

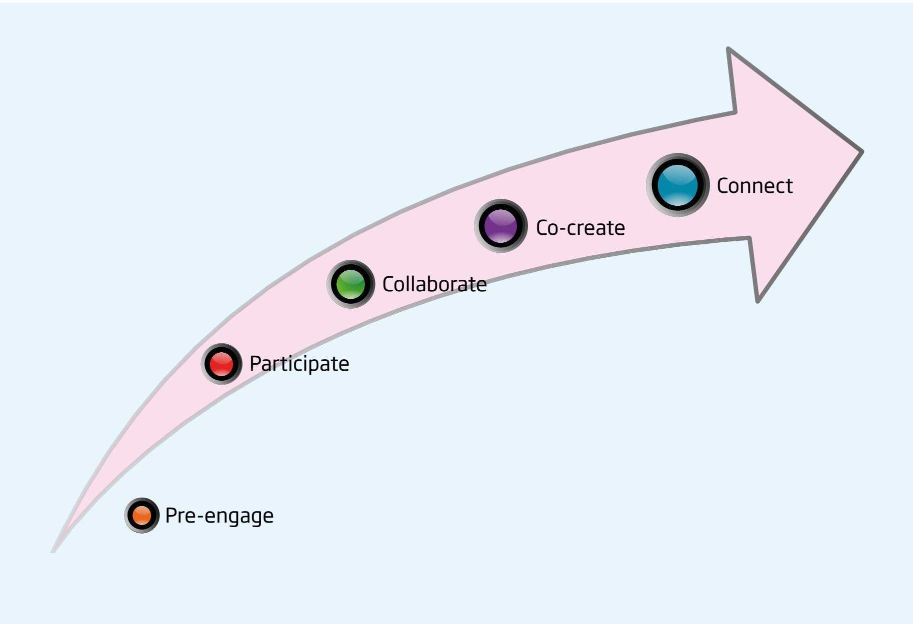


Figure 8: Trajectory of Professional Development (Bianchi, 2016:73)

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Appendix 1. Stages and ages in English and Scottish curricula

National Curriculum: England		**Curriculum for Excellence: Scotland**	
Primary Years	**National Curriculum**	**Primary Years**	**Curriculum for Excellence**
Year R (Reception) (age 4–5)	Early Years	P1 (age 4–5)	Early level
Year 1 (age 5–6)	Key stage 1	P2 (age 5–6)	First level
Year 2 (age 6–7)	Key stage 1	P3 (age 6–7)	First level
Year 3 (age 7–8)	Key stage 2	P4 (age 7–8)	First level
Year 4 (age 8–9)	Key stage 2	P5 (age 8–9)	Second level
Year 5 (age 9–10)	Key stage 2	P6 (age 9–10)	Second level
Year 6 (age 10–11)	Key stage 2	P7 (age 10–11)	Second level
Secondary Years	**National Curriculum**	**Secondary Years**	**Curriculum for Excellence**
Year 7 (age 11–12)	Key stage 3	S1 (age 11–12)	Third/Fourth level
Year 8 (age 12–13)	Key stage 3	S2 (age 12–13)	Third/Fourth level
Year 9 (age 13–14)	Key stage 3	S3 (age 13–14)	Third/Fourth level
Year 10 (age 14–15)	Key stage 4	S4 (age 14–15)	Senior phase
Year 11 (age 15–16) GCSE exams taken	Key stage 4	S5 (age 15–16)	Senior phase
		S6 (age 16–17)	Senior phase
Year 12 (age 16–17)	Key stage 5	S6 (age 17–18)	Senior phase
Year 13 (age 17–18) A-Level exams taken	Key stage 5		

Appendix 2. Participating schools and teachers

Thinking Like an Engineer (TLaE)	Teachers
Primary Schools	
Camelsdale Primary School, Haslemere, West Sussex	Sarah Palmer, Headteacher; Julie Brownbill; Veronica Carter; Hannah Enticknap; Nicky Thickpenny; Liza Caie; Dave Whillier
Gomer Junior School, Gosport	Georgina Mulhall, Headteacher; Karen Digby, Senior Teacher; Kirsty Garland; Elodie Gardner; Heather Guyett-Smith; Peter Milnes; Sharon Toone; Linda Wheal; Matthew Woolway
Secondary Schools	
Bay House School, Gosport	Carole Terry, Head of Science
Bohunt School, Liphook, Hampshire	Lindsay Davison, Head of STEM Philip Avery, Director of Education Jane Edwards, Jeremy Barber
Brune Park Community School, Gosport	Stephen Shaw, Innovation and Development Manager
Medway University Technical College, Chatham, Kent	Kieron Walsh, Vice Principal Amy Broom, Director of STEM (up to December 2016)
New Forest Academy, Holbury, Hampshire	Sharon Crowe, Head of Learning and Achievement in Science Lincoln Dugdale, Kenendy Chung
The JCB Academy, Rocester, Staffordshire	Jim Wade, Principal, Ellie Sillitoe, Director of English and Learning & Teaching
The Petersfield School, Petersfield, Hampshire	Joanna Goodship, Head of Faculty-Maths and Technology
University Technical College Reading, Reading, Berkshire	Jonathan Nicholls, Vice Principal, Engineering and Science; Sean Kearns, Mathematics teacher
FE College	
Reading College, Reading	Scott Reilly, Faculty Manager-Engineering (up to January 2017) Alex Warner, Director of Career Pathways Engineering lecturers: Ian Campbell, Martin Davies, Fraser Glass, Ben Mhishi, Jun (Joe) Wang, Noel Wood

Tinker Tailor Robot Pi (TTRP)	Teachers
Primary Schools	
Christ the King Primary School, Salford	Karen Hill, Shane Nolan, Alan O'Keefe, Nicola Potts
Crumpsall Lane Primary School	Jon Chippindall
Great Moor Infant School	Toby Tyler
Great Moor Junior School	Bob Breckwoldt, Chris Turner
Queensgate	Mike Knowles, Phil Ryan
Rode Heath Primary School	John Randall, Julie Wiskow
Seymour Park Primary School	Melissa Loughran, Lucy Spellman
St Chad's Primary School	Matthew Handley, Mark Ratchford
St John's Primary School	Sarah Zaman, Abigail Wyatt
St Mary's RC Primary School	Lisa Croston, Stuart Lloynd
St Thomas's Primary School	Claire Cartwright, Amanda Lambert
Temple Primary School	Neilam Iqbal, Jason Linney
Secondary Schools	
Abraham Moss Community School	James Kelly, Nichola Riley, Kieron Mullen
Falinge Park High School	Peter Cloran, Dan Hodgson, Rory Johnson, Simon Ward, Anna Woodhead, Aaron Ahmed, Eammon Jundi
St Ambrose Barlow High School, Salford	Bernadette Furey, Daniel McDonagh, Natalie Taylor

Primary Engineer	Teachers
Aultmore Park Primary and LCR	Deborah Taylor
Barmulloch Primary School	Lauren Fisher, Claire Thomson (Sibbald)
Galston Primary School	Sarah Bain
Hillhead Primary School	Jennifer McKenzie
Onthank Primary School	Tracey McKie
Riverside Primary	Alexis Davren
Shortlees Primary School	Emma Chalmers
St Joseph's Primary School	Caroline MacMIllan

Appendix 3. Engineering habits of mind self-report survey

EHoM questionnaire for learners

Do you think like an Engineer?

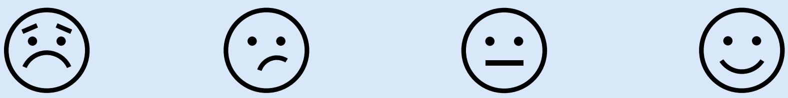
This is a quiz to find out how you see yourself when you are trying to do things that are new or difficult. There are 12 statements.

Look at each one and think how true this is of you when you are learning (now, compared to how you felt before we started the EHoM activity). This includes things you are learning for your own interest out of school, as well as in lessons. Of course we all vary, but try to choose the answer that is closest to you in general.

If you think a statement is rarely or never true of you, circle the 1. If you think it is sometimes true, circle 2. If you are quite often like that, circle 3. And if the statement is true very often or always, circle 4.

Remember:

1 = rarely (or never)	2 = sometimes	3 = quite often	4 = very often (or always)



Date ……………………………………………….

Name ……………………………………………… Class …………………………………….

1.	I like making links between things in my head	1	2	3	4
2.	I enjoy putting things together to make something new	1	2	3	4
3.	I'll check and check again until I am happy	1	2	3	4
4.	I love asking questions and having my own point of view	1	2	3	4
5.	I like thinking out loud when I am being imaginative	1	2	3	4
6.	I like making models to show my ideas	1	2	3	4
7.	I like making what I've done better	1	2	3	4
8.	I explain how well I am doing to my teacher or friends	1	2	3	4
9.	My brain comes up with lots of good and new ideas	1	2	3	4
10.	I like working in a group	1	2	3	4
11.	I stick up for what I think when talking with other people	1	2	3	4
12.	I work hard and practise to get better, even when it's tricky	1	2	3	4

ROYAL
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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.

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Make the UK the leading nation for engineering innovation

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