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Mathematics delivering the advantage: the role of mathematicians in manufacturing and beyond

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Much has been written about the benefits that mathematics can bring to the UK economy and the manufacturing sector in particular, but less on the value of mathematicians and a mathematical training. This article, written from an industry perspective, considers the value of mathematicians to the UK's industrial base and the importance to the UK economy of encouraging young people in the UK to choose to study mathematics at school as a gateway to a wide range of careers. The points are illustrated using examples from the author's 20 years' experience in the security and intelligence and manufacturing sectors.

1. Introduction

As someone who has spent almost 20 years in industry, being asked to share an industry perspective on the role of mathematics in manufacturing has led me to reflect not only on the value of mathematics itself but also on the value of mathematicians across industry. My reflections are not only based on personal experience in the security and intelligence and manufacturing sectors but also on the experience of the numerous mathematicians I have worked with over the years, largely outside of formal mathematics research or analysis roles.

Having shared my anecdotal evidence of the contribution mathematicians make, I move on to discuss some recent research that highlights why too few young people in the UK are choosing to study mathematics and other science, technology, engineering and mathematics (STEM) subjects at school and the actions that need to be taken to address this.

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2. Background

Before I start I want to share my background in order to provide some perspective on the examples I refer to later.

I am currently the Chief Operating Officer for BAE Systems Submarines where I am responsible for more than 5000 people building nuclear submarines, unquestionably the most complex engineering project currently underway in the UK. Prior to submarines, most of my career has been spent in the security and intelligence sector, starting out at a small defence intelligence consultancy which following a period of rapid growth and acquisition is now BAE Systems Applied Intelligence. Despite working across very different industry sectors, the common thread in my career is driving change and delivering results in complex data-rich environments.

But, I am at heart a mathematician. I studied for a D.Phil. at the Oxford Centre for Industrial and Applied Mathematics (OCIAM) where my adventures in complex ray theory and their application to stealth technology taught me how to create simple models out of seemingly impossibly difficult situations and importantly to engage in a common language with the many visiting industry representatives.

Since then, I have been involved in the application of different forms of mathematics to a wide range of challenges from optimizing aircraft landing separation distances through to identifying VAT carousel fraud and tackling cyber-crime. An example of the value of mathematics from my earlier career but which is relevant to manufacturing is illustrated below.

3. Illustrations of the value of mathematics: cyber-security

With the average cost of a data breach in the UK exceeding £2.5 million [1] and 89% of data breaches having a financial or espionage motive [2], it is not surprising that cyber-security features highly on most companies' risk registers and particularly those within the defence manufacturing sector. But before we explore how mathematics contributes to cyber-security it is worth pointing out that cyber-security is not really about technology but about dealing with humans deliberating subverting computer systems for their own ends. Mathematics plays a number of important roles in this domain including finding deviant human behaviour hidden in large volumes of computer-generated data—finding 'needles in haystacks'—and supporting the army of security analysts investigating cyber-related incidents—'augmenting human behaviour'.

(a) Finding 'needles in haystacks'

Perpetrators of cyber-crime are usually keen to avoid detection so they do their best to hide their activity in amongst the noise in a large volume of typically computer-generated data points. This activity is difficult to detect as it can be difficult to know what you are looking for until you find it and even then the behaviour will keep changing deliberately to avoid detection. A range of mathematical techniques can be deployed including:

— Anomaly detection: This can be used where enough is understood about the behaviour to understand what the data will look like if the behaviour occurs. This can be achieved by using a rules-based approach to detect the tell-tale signs. The challenge then is to find ways of detecting behaviours that are only seen in suspicious circumstances and not in everyday traffic. This can be achieved by statistically analysing large volumes of historical data.

— Machine learning: This technique can be deployed when very little is understood about the behaviour the suspicious activity exhibits. In this case, a rules-based approach cannot be applied as there is insufficient understanding of what to write rules about, let alone the rules themselves. In this case, statistical analysis is also futile as we do not know which

> statistics are relevant. Machine-learning techniques enable us to systematically search through all of the possible ways of cutting the data to find the ones that are strongly and uniquely associated with suspicious behaviours and are very powerful in the detection of cyber-crime. Self-organising maps, championed by Kohonen [3], is one such technique that underpins much of the fraud and cyber-security solutions that I was involved in during my time at BAE Systems Applied Intelligence.

Similar machine learning and statistical techniques are also being applied to manufacturing, analysing huge volumes of data to provide better predictive accuracy to every phase of production. One common feature between both domains is that the mathematical algorithms involved improve in accuracy the more data they have access to—hence the increase in focus on 'big data' technologies in this domain, as in so many other domains where machine learning is being applied.

(b) Augmenting human behaviour

Cyber-security is still a surprisingly manual process and while mathematical techniques are used to detect possible subversions the job of reviewing, investigating and taking action are all done manually today. The digitalization of more and more key business processes, exposing them to cyber-security risks, has led to a global shortage of these skills. There are over 1 million vacancies in the world today for cyber-security analysts. In general, shortage of high-skilled talent is one of the major concerns of manufacturing companies—the McKinsey Global Institute projects a potential shortage of more than 40 million high-skill workers by 2020 [4].

As a result mathematics is also starting to play a major role in finding ways of automating and augmenting humans in these roles, determining from the data which tasks and processes are amenable to automation, finding ways of automatically carrying out some of the investigative steps that humans do today and so on.

4. The value of mathematicians

There are numerous examples of how mathematics supports manufacturing from optimizing production schedules through to simulating the performance of manufactured components. However, in this paper, I share a perspective on the value of mathematicians and a mathematical training using my personal experience and that of other mathematicians with senior roles in industry. I have distilled the reflections into three key points.

(1) Mathematicians' ability to create simplicity out of complexity.
(2) The importance of understanding and challenging computer-based models.
(3) The role of industrial mathematicians in creating value through collaboration.

(a) Creating simplicity out of complexity

How often are you confronted with huge quantities of data and expected to make a rapid decision? This is part of daily life in the manufacture of submarines which is no surprise when you consider that the latest class of nuclear submarine requires 347 km of cabling, 42.5 km of pipes and more than 13 000 electrical installations and is able to simulate day and night as well as generate its own oxygen and water. However, the trick is being able to create simple models that provide insight and enable informed decisions.

As Helen Haworth explains in her article on the application of mathematics to finance [5], simple models are often the most powerful and this is equally true in manufacturing as it is in

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finance. In my experience, a mathematical training supports in the creation of simple, insightful models with mathematicians bringing a number of key qualities:

— not being daunted by the huge volumes of data and avoiding the temptation to dive straight into the detail;
— being able to stand back and identify the potential key parameters or drivers in a given situation and using these to develop and test simple models against the data; and
— being able to communicate the results with others.

In submarine manufacturing, these skills are put into daily use by those analysing the thousands of production metrics that are produced weekly enabling production issues to be identified and rectified early and investment to be targeted where it is likely to yield the greatest return. From a personal perspective, my mathematical experience was a key factor in enabling me to transition between leadership roles in two fundamentally different but equally data-rich industry sectors, from security and intelligence to complex manufacturing.

(b) Challenging the computer

In common with many other fields, manufacturing industry relies heavily on computer-based modelling to inform both engineering decisions and those relating to productivity and efficiency. As a result, there is a tendency for managers to make decisions without sufficient understanding of the strengths and weaknesses of the underpinning models or to place undue confidence in the model outputs. In the complex manufacturing industry some of the potential pitfalls can be illustrated by looking at techniques used to predict how long it is going to take to design, build and test a new highly engineered product. This is a key question, particularly in my current role where it can take more than 10 years to build a submarine.

One of the techniques commonly used to predict the duration of engineering and construction projects is a stochastic technique called Monte Carlo simulation [6]. This technique is designed to forecast the likely schedule out-turn based on judgements of the maximum and minimum durations of individual tasks and an assessment of the risks that could beset the project. A model is then created that links and sequences the tasks and risk impacts. This model is then run tens of thousands of times using randomly selected values usually based on a normal distribution around the mostly likely durations and risk impacts. The output from a Monte Carlo simulation is then a curve that equates a probability to a particular schedule duration, for example there is a 70% probability that the project duration will not exceed 43 months. Output from this analysis is then used to determine delivery dates and risk provisions which on major projects can extend to tens of millions of pounds.

However, Monte Carlo simulation has a number of flaws which are often not appreciated by those who use it. Firstly the output is only as good as the input data. It is not uncommon for results of Monte Carlo simulations to be quoted to several decimal places when an inspection of the model inputs reveals a very cursory or over-optimistic assessment of the risks. Poor quantification of risk can lead to results which are meaningless and certainly should be treated with caution. In addition, the use of normal distributions to generate the simulation data makes the assumption that the manufacturing and construction industry is normally distributed with individual tasks equally likely to be early as they are late. Real life tells us this is not true. Care, therefore, needs to be taken to select appropriate probability distributions that reflect experience in manufacturing performance and also challenge optimism bias in the data. Doing this effectively requires the mathematical understanding and confidence to challenge both the models and the experts providing input.

This is just one example from manufacturing industry where a mathematical training adds real value both within the project teams and as a senior leader interpreting and challenging the results—there are many others.

(c) Creating value through collaboration

The final point I would like to make is the value of mathematicians, particularly applied mathematicians in driving cross-functional working. My personal experience of studying at OCIAM taught me the power of bringing together different disciplines, some academic, others not, to tackle problems in manufacturing and a range of other fields. My DPhil on complex ray theory was inspired by challenges that Colin Sillence from BAE Systems was facing in the positioning of sensitive antennae on stealthy aircraft and gave me first-hand experience of the value of bringing together mathematics with manufacture of state-of-the-art technology.

I also learnt a considerable amount from participating in study groups with industry which would typically involve problem solvers getting together to look at novel problems outside any of their specific areas of expertise which resulted in a rich tapestry of ideas, some of which could then be pursued along more conventional lines. For example, I remember in the early 1990s being part of a study group in Cambridge looking at the effects of tall buildings on mobile phone signals. At that time mobile phones were the size of a brick and few and far between and I doubt anyone realized what a phenomenon they would become.

This collaborative problem-solving approach has stayed with me throughout my career and has proved invaluable on many occasions partly as I have transitioned into new domains, as I did when I moved from security and intelligence into submarine manufacturing.

5. Building a talent pool of mathematicians in the UK

The value of mathematical science research to the UK economy was estimated by Deloitte in 2010 [7,8] to be worth approximately 2.8 million in employment terms and around £208 billion in terms of gross value added (GVA) to the UK economy (approx. 16% of total UK GVA). I would argue that when you include the value mathematicians and a mathematical training to the UK economy, the value of mathematics would be even higher.

However, the UK is failing to encourage enough young people to choose to study mathematics and other STEM subjects at school and then into higher education with the Campaign for Science and Engineering suggesting that the shortfall of STEM workers in the UK could be as high as 40 000 each year [9]. Yet only one in four at English secondary schools choose more than one STEM subject at A level (compared with half of French 16–18 years old studying a science-orientated Baccalaureate [10]. This is not only a serious issue for employers like BAE Systems which is set to recruit over 200 graduates (mostly from STEM subjects) in 2017 and for the manufacturing sector as reported by BCG [11] but for the UK as a whole given the value mathematics and broader science is demonstrated to bring to the UK economy.

We, like a number of other major employers of mathematics and science graduates in the UK, support the Your Life campaign (www.yourlife.org.uk) designed to ensure the UK has the mathematics and physics skills it needs to success in today's competitive global economy. The Your Life campaign focuses on enabling young people to make informed subject choices post 16 and inspiring them to study mathematics and physics as a gateway to wide-ranging careers.

Research sponsored by Your Life [10] drawing on two extensive academic research programmes (ASPIRES from King's College London [12] and UPMAP from University College London) has identified a number of root causes for young people opting out of science at 16 including:

- losing interest as mathematics and physics lessons become more practical;
- hearing messages from teachers, parents and peers that mathematics and physics are only for the ultra-bright; and
- teachers and parents pushing students to prioritize good grades and as a result steering them away from STEM (in which, as historical evidence suggests, it can be more difficult to achieve high grades).

However, the overriding messages is that young people have an alarming lack of knowledge of the many career paths dependent on mathematics and science, despite employers calling for these skills. As a result the Your Life campaign, of which I am a supporter, has focused on using social media to broaden 14–16 year old's awareness of how mathematics and physics supports a wide range of careers from graphic designers through to data scientists. For me this is why appreciating and promoting the value of mathematicians as well as mathematical research is important.

6. Conclusion

The value of mathematics to manufacturing industry and beyond is broader than the application of mathematical research and extends to the value those with mathematical training bring to the workplace. As well as being undaunted by the vast quantities of data that characterize our world today, the ability of mathematicians to think logically, break down complex problems and importantly to challenge is invaluable.

However, despite substantial evidence of the value mathematics brings to the UK economy, we are failing to encourage enough young people to study mathematics and physics at A level. Research suggests that one of the main reasons is a lack of understanding by students, parents and teachers of the wide range of careers open to those studying mathematics and physics. Addressing this gap should be a priority for us all.

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