26TH INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
5-6 SEPTEMBER 2024, ASTON UNIVERSITY, BIRMINGHAM, UNITED KINGDOM

# ENHANCING STUDENT COMPREHENSION THROUGH APPLIED SCENARIOS: FROM PRACTICE TO THEORY

**Edward CAUSTON**
Nottingham Trent University, United Kingdom

## ABSTRACT
Engineering students frequently encounter difficulties with numerical and analytical techniques, perceiving them as unengaging or overly theoretical and failing to see the relevance to engineering contexts or their future careers. The issue may be exacerbated by the use of traditional didactic teaching methods that often emphasize recall and computational rigor over comprehension and the capacity to adapt and apply the methods learnt to new contexts.

This paper details the approach taken to teaching a third-year module 'Performance Engineering' at Nottingham Trent University. By structuring learning around practical scenarios and introducing technical methods in the context of solving applied problems, students are better able to contextualize their knowledge. Flipped and active learning techniques are used to enhance conceptual comprehension and ensure students are able to apply the methods learnt beyond the contexts presented.

*Keywords: Practical application, flipped and active learning, analytical and numerical techniques*

## 1 INTRODUCTION & BACKGROUND

A core skill to be cultivated in engineering students is the ability to apply analytical and numerical methods to solve practical problems. Techniques drawn from mathematics and statistics are ubiquitous across engineering disciplines, requiring students to develop confidence when utilising mathematical language and approaches to describe real-world scenarios, to analyse them and to effectively communicate with others in the profession and beyond [1, 2, 3].

Simultaneously, it is apparent that engineering students frequently struggle with more mathematical topics, perceiving these as overly abstract, disconnected from practical applications and hard to understand [4]. This may lead to a negative perception of mathematics as "a gatekeeper, denying entry to otherwise talented would-be engineers" [5]. The consequent reduction in motivation may contribute to student disengagement leading to poor attendance or drop-out [1, 4, 6].

To counter this, it is critical that students see the purpose of techniques learnt, that these are contextualised, and their meaning and application made explicit. This is particularly true for engineering students for whom maths is a tool for posing, presenting and solving problems not the object of study itself [6]. Instruction in mathematical and related techniques may be better suited to the dispositions of students and to the demands of the discipline where it is structured around their application as opposed to formal introductions in abstract terms. This may be facilitated through effective use of applied engineering scenarios to enable students to see the relevance of methods learnt and to provide a concrete context in which conceptual connections are made explicit and readily apparent [1, 2, 3, 4, 6]. [1] In doing so, theory and practice are integrated, and the student may better appreciate the value of techniques learnt. Furthermore, by asking students to engage in solving applied problems themselves, teaching moves from a 'transmissionist' to a 'connectionist' model focussed on developing understanding of *why* they are using a technique as opposed to merely following a pre-defined procedure [2].

To achieve this may require the collaboration of engineers with mathematicians, when the latter are tasked with teaching engineering students, to enable the generation of appropriate applied examples [1, 2, 10]. When engineers themselves are engaged in teaching mathematical topics, it is commonplace to

[1] A thorough elucidation of the importance of making the connections between concepts explicit can be found in the works of the philosopher Robert Brandom [7] as applied to mathematics and science education [8, 9].

provide practical examples elucidating the relevance of techniques learnt to practical engineering scenarios. Anecdotally, these examples may be introduced only in passing or only after instruction in an abstract context, that is, the practice follows from the theory. It is contended in this paper that students may benefit from reversing this progression, instead beginning from an applied problem scenario and introducing techniques in this context. As such, the practical scenario acts as a scaffold for developing students' understanding from which techniques learnt may be subsequently developed and abstracted for future use. Beginning instruction from applied examples may act as an initial source of motivation, clearly setting out the relevance and use-value of techniques while clarifying the meaning of concepts and quantitative features to assist comprehension. Doing so may more effectively orient the student before they have had an opportunity to become lost in abstract details.

This paper considers a 3rd year engineering module at Nottingham Trent University (NTU). It illustrates an approach to teaching in which applied examples are used both as a starting point for instruction to be subsequently used as a scaffold for learning techniques, and as a means of extending student comprehension once basic conceptual comprehension is achieved. Feedback from students is considered and conclusions drawn regarding how the approach may be adapted to other contexts.

# 2 PERFORMANCE ENGINEERING

## 2.1 Overview of Module

Performance Engineering is a 3rd year core module taught to all students in the Department of Engineering at Nottingham Trent University. In the academic year 2023/24, the cohort consisted of approximately 150 students across four engineering disciplines: mechanical engineering, electronic & electrical engineering, biomedical engineering, and sport engineering. Teaching took place across one term and consisted of two lectures and one seminar each week as well as an optional drop-in session.

The module aims to develop students' understanding and application of methods for setting, measuring, improving, and monitoring performance of engineering processes. In practice, much of the module is devoted to instruction in statistical, mathematical and other analytical techniques to be applied in an engineering context. Topics leant include discrete and continuous probability distributions, sampling and estimators, the central limit theorem, capability analysis, correlation and regression, hypothesis tests and ANOVA, factorial analysis, statistical process control and reliability engineering. Learning outcomes are assessed through a 2-hour in-person examination and an individual coursework assignment. The exam contains both calculation questions, in which students apply techniques learnt to data provided, and questions requiring students to explain the methods used, their limitations and application. For the coursework assessment, students are given a hypothetical engineering scenario and data relating to this. They choose appropriate methods from the module to analyse the data and draw practical conclusions, delivering their findings through a pre-recorded PowerPoint presentation and supporting Excel calculations.

## 2.2 Approach to Teaching

Given the technical nature of the module, many students may be intimidated by the mathematical detail required. Furthermore, the range of engineering disciplines represented means that the background knowledge of students may not be equivalent. Teaching time-constraints make it difficult to introduce all required content within taught sessions at a pace all students will be able to follow. To address these issues, the module is taught through a mix of synchronous and asynchronous learning, with a partially flipped approach to instruction [11, 12, 13]. Each week introduces a new topic. Students make use of online resources consisting of a series of short 5-10 minutes videos [12, 14] interleaved with multiple-choice questions for regular formative assessment. At the end of the week, students complete an extended problem set reviewing the week's content. These resources are intended as the primary source of content knowledge. Learning is automatically differentiated as students may work through resources at their own pace.

*Table 1. Module content and structure for Performance Engineering*

| Week / Topic(s) | Asynchronous Learning | Lecture 1 | Lecture 2 | Seminar |
|---|---|---|---|---|
| 1. Quality, Performance and Statistics | Quality, performance and statistics. Populations and samples. Displaying & interpreting data. | Introduction to module including details of assessments. | Applied scenario (starting a pizza company): Previewing topics. | Excel for data analysis and problem sets testing use. |

| | | | | |
|---|---|---|---|---|
| 2. Introductory Statistics | Measures of average & spread. Discrete and continuous probability distributions. Sampling, estimators and the Central limit theorem. | Case Study 1.1: Quality characteristics and descriptive statistics. | Applied scenario (bike manufacturer): Reviewing prior week, introducing probability distributions, sampling and estimators. | Problem set on descriptive statistics, probability distributions, sampling, estimators and the central limit theorem. |
| 3. Analysing Processes | Measuring processes. Process capability. Cause and effect analysis. | Case Study 2.1: Binomial and normal distributions. | Applied scenario (phone case testing): Introducing capability and Ishikawa diagrams. | Problem set linking capability analysis and probability distributions. |
| 4. Testing Relationships | Correlation. Regression. Confidence intervals. Hypothesis tests. | Case Studies 1.2 and 2.2: Probability distributions and capability analysis. | Applied scenario (testing biomolecules): Introducing correlation, regression and hypothesis tests. | Problem set on confidence intervals and hypothesis tests. |
| 5. Further Testing Relationships | Multiple and non-linear regression. Paired t-test. Chi-square test. | Case Studies 1.3 and 2.3: Hypothesis tests | Applied scenario (paint manufacturer): Hypothesis tests, multiple and non-linear regression. | Problem set on multiple and non-linear regression, paired t-tests and chi-square tests. |
| 6. Design of Experiments | Factorial experiments and factor effects. Mid-module review questions. | Review of topics learnt including further applied examples. | Applied scenario (hot chocolate recipe): Introducing factorial experiments. | Problem set on factorial experiments, factor and interaction effects. |
| 7. Analysis of Variance | Analysis of Variance (ANOVA). | Case Studies 1.4 and 2.4: Planning factorial experiments. | Applied scenario (drug's manufacturer): Hypothesis tests and ANOVA. | Problem set on the analysis of variance. |
| 8. Controlling Processes | The need for control. Control limits. Establishing control limits. Out-of-control processes. Relation to capability. | Case Studies 1.5 and 2.5: Application and interpretation of ANOVA. | Applied scenario (Christmas bauble manufacturer): Reviewing capability and introducing control. | Problem set on statistical process control. |
| 9. Reliability | Reliability vs quality. Determining failure rates. 'Bathtub' curve. Exponential and Weibull distributions. Reliability block diagrams. | Mock exam on introductory statistics and analysing processes. | Applied scenario (light bulb manufacturer): Introducing reliability engineering. | Problem set on reliability engineering. |
| 10. Further Topics (not examined) | Pre-recorded video from industry speaker on a real-world quality engineering scenario. | Mock exam on factorial analysis and ANOVA. | Quality, sustainability, environmental performance, ISO standards. | Problem set applying techniques to monitor environmental performance. |
| 11. Revision | Practice exams. | Mock exam on reliability. | Mock exam on process control. | Reviewing and critiquing sample answers to an exam. |

Synchronous learning consists of two weekly lectures and a seminar. During the first lecture, a case-study scenario is introduced, and students work in small groups to apply techniques from prior weeks to analyse data and draw conclusions. This serves to revise content and deepen understanding while simultaneously preparing students for their coursework (more details on case-studies will be provided below). During the second lecture, the current topic(s) are introduced through an applied scenario. The lecturer poses a series of questions for discussion first in small groups and then with the whole cohort. New techniques addressing the issues raised are then introduced and students are provided with short questions testing their understanding of these. Towards the end of the week, students attend a seminar. The more challenging parts of the current topic(s) are reviewed, adapting content to the students present and their current level of understanding. Students are then set a series of problems to complete either individually or in small groups. The lecturer assists and answers are reviewed at the end.

Clear instructions are given to the students throughout the module as to the expectations with regards to engaging with both online materials and on-campus taught sessions. The need to complete online materials and activities in advance of seminars is emphasised as is the importance of using these to adequately prepare for assessments. Simultaneously, it is made clear to students that attending lectures and seminars is crucial for understanding how to apply the techniques learnt and pass assessments. The module content and structure are shown in **Table 1** above.

## 2.3 Selected Examples

Throughout the module, extensive use is made of applied examples to introduce relevant concepts and techniques and to deepen student comprehension and their ability to apply the techniques learnt.

### *2.3.1 'Cell2U' - Phone Case Analysis*

This example was used in a lecture to introduce capability analysis while linking to previous learning on probability distributions. After a brief introduction to the company including an overview of the injection moulding process used for manufacturing phone cases, students discussed how the company should investigate reports of cases falling outside specified dimension tolerances. This initial discussion provided context for the problem scenario and challenged students to apply their knowledge of previously introduced techniques in conjunction with practical reasoning to devise a strategy for investigating the root cause of issues. Subsequently, students were informed that the temperature of a polymer mix may have had an effect. Sample measurements were provided for analysis as well as a specified range of allowable values. While all sample measurements were within specification limits, some students noted that this was no guarantee that temperature would not fluctuate outside these if further measurements were taken. During discussion, students were led to recognise that the temperature could be modelled as a normal distribution with mean and standard deviation derived from the sample. From this it would be possible to estimate the probability of fluctuations outside specification limits. MS Excel was then used to analyse sample values, produce a histogram and estimate this probability. In this context, capability indices were introduced as a means of standardising analysis.

This example illustrates how an applied scenario may be used to scaffold student learning. Students are provided with a concrete situation and a practical problem to solve. In this context, the relevance of previous learning of statistical concepts is made explicit. Use of software helps link the theoretical discussion of the problem to numerical data that can be visualised and interpreted. Finally, the new concepts (capability and capability indices) are introduced. Introducing these through this applied scenario may assist in maintaining engagement, emphasising conceptual links, and making limitations apparent, such as the assumption of a normal distribution.

### *2.3.2 'SwitchedOn' – Light bulb reliability*

In this example, techniques were introduced to assess the reliability of light bulbs. The company was introduced, and students were asked how to assess the proportion of bulbs likely to fail within 1 year from data collected over a shorter timeframe. After discussion, students suggested subjecting bulbs to more stressful conditions than those encountered in normal use to increase the failure rate (accelerated testing). Example data was then presented, an appropriate lifetime distribution used to model data and the model scaled-back to normal operating conditions. From the model derived, the proportion of bulbs expected to fail in 1 year was calculated.

Reliability engineering can be a challenging topic for many engineering students, requiring use of a range of mathematical tools and models that may be perceived as overly abstract and incomprehensible. Starting from an applied scenario aims to make apparent from the start the purpose of the techniques learnt. The mathematical links between concepts such as *failure rates*, *lifetime distributions*, and *reliability* can subsequently be explained within this context after the concepts themselves have been introduced. As with the previous example, the use of software to analyse concrete numerical data may help students link abstract models to physical quantities, potentially illuminating the conceptual structure and illustrating practical application.

### *2.3.3 'The Cheesy Company' and 'Roped-Up' – Extended case studies*

Across multiple lectures, two extended case-studies were used to review and apply techniques learnt and to extend student comprehension building upon prior learning. The first revolved around a cheese manufacturing company and their attempts to optimise the quality of their cheese and improve efficiency. The second centred on a manufacturer of ropes for use in rock climbing and ensuring quality and safety after a change to manufacturing processes. Each week during lectures, students were provided with relevant data for one or both case studies. Working in small groups, they analysed the data using techniques learnt in previous weeks to form conclusions and make practical recommendations.

As well as reviewing prior content, the use of these extended case studies across multiple weeks linked together the methods learnt, elucidating conceptual links between, for example, factor effects, hypothesis testing, probability distributions and capability. In this way, students were provided with an opportunity to practice techniques and their application with the aim of consolidating knowledge and preparing for assessments.

## 3 DISCUSSION & EVALUATION

The module described demonstrates how practical scenarios may be used to scaffold learning. These scenarios aim to assist students in constructing conceptual understanding of numerical and analytical techniques drawn from mathematics and statistics. Simultaneously, students may be better enabled to apply the techniques learnt in real-world contexts. This is consistent with recommendations from the literature to utilise problem-based learning focussing on mathematics applied to real-world problems [1] and upon learning mathematical concepts in the context of engineering applications [6].

A further advantage of this approach is its potential to engage students. To assess this, student feedback was gathered by two means. The first was a survey targeted at evaluating the effectiveness of an extended case study activity used in lectures. Responses were collected pseudo-anonymously from 43 students. These generally indicated a favourable attitude, with most students indicating that they enjoyed the activity (84%), that it helped them to engage (81%) and to understand the topic (86%). Of the remaining respondents the majority were neutral in their responses. Respondents commented that they found "the opportunity to work collaboratively… [helped them] understand the application of techniques", that it "helped put the topics into practice", and that it cemented their knowledge and reassured them regarding their use of techniques. Others stated that it was a useful preparation for assessments and the opportunity to explain topics to their peers helped them to understand content themselves. The main criticism was that the time provided to complete tasks was limited and that they would have preferred the opportunity to explore the scenarios in more depth. The second method of gathering feedback was through a standard module survey issued to evaluate all modules at Nottingham Trent University. In this, 97% of respondents indicated their overall satisfaction with the module. Students commented that they "understood how these methods can be applied in real life", that they "really like the consistent use of examples", and that the module "gave [them] the chance to actually use this knowledge in real-world-like scenarios". Others suggested that case studies could be made more relevant to manufacturing or engineering processes in their discipline.

This approach does present its own challenges, not least of all the difficulties conceiving suitable applied scenarios that make use of the appropriate methods to be learnt. This may necessitate the use of simplified 'toy-model' examples to enable students to access the problem-scenario and extensive scaffolding. Few real-world engineering scenarios are sufficiently symmetric to yield to a basic analysis at a level suitable for a first introduction to the area. Simplicity is essential to ensure students can access the relevant concepts and are not distracted by irrelevant features or noise in data. As competence and confidence grows, further detail may be added and scenarios evolved toward something more realistic.

Equally, the range of students to be taught must be considered to ensure the scenarios themselves do not present difficulties for students from a diverse range of backgrounds. This may require time in taught sessions ensuring the scenario has been clearly conveyed. The use of images to illustrate can assist as can the choice of examples or contexts with which students are familiar.

Finally, mastery may require students to subsequently practice techniques in isolation to ensure they are sufficiently ingrained and procedural knowledge is consolidated. Once basic conceptual comprehension is attained, not all practice need be in the context of a practical scenario as this may slow learning and distract from developing technical competence. However, it is recommended that practical scenarios continue to be frequently used to ensure the link to practice is maintained.

## 4 CONCLUSIONS

In this paper, an approach to teaching technical content has been illustrated in which instruction begins from practical applied examples. The use of practical scenarios helps students to construct relevant conceptual frameworks, orientating them toward content appropriately from the outset and laying out the context clearly. The background assumptions feeding into concepts are made apparent by providing a concrete starting point and linking abstract concepts to measurable quantities underlying them. The basic comprehension thus developed may subsequently be used as a scaffold to further develop concepts. As students continue to practice the techniques learnt, further use may be made of practical scenarios to build confidence, consolidate conceptual understanding, and appreciate real-world application.

This approach cannot be automatically translated to the teaching of other technical content but will require some effort to generate suitable scenarios which are accessible to students while effectively capturing the concepts and techniques to be learnt. However, it is hoped that the above analysis demonstrates how an approach centred on practical scenarios as the basis for learning may be achieved and will provide motivation for other educators.

## REFERENCES


[1] Flegg J., Mallet D. and Lupton M. (2012). Students' perceptions of the relevance of mathematics in engineering. *International Journal of Mathematical Education in Science and Technology, 43*(6), 717-732.

[2] Harris D., Black L., Hernandez-Martinez P., Pepin B. and Williams J. (2015). Mathematics and its value for engineering students: what are the implications for teaching? *International Journal of Mathematical Education in Science and Technology, 46*(3), 321-336.

[3] Sazhin S. S. (1998). Teaching mathematics to engineering students. *International Journal of Engineering Education, 14*(2), 145-152.

[4] Rooch A., Junker P., Härterich J. and Hackl K. (2016). Linking mathematics with engineering applications at an early stage–implementation, experimental set-up and evaluation of a pilot project. *European Journal of Engineering Education, 41*(2), 172-191.

[5] Winkelman P. (2009). Perceptions of mathematics in engineering. *European Journal of Engineering Education, 34*(4), 305-316.

[6] López-Díaz M. T. and Peña M. (2021). Mathematics training in engineering degrees: An intervention from teaching staff to students. *Mathematics, 9*(13), 1475.

[7] Brandom R. (1994). *Making it explicit: Reasoning, representing, and discursive commitment*. Harvard University Press.

[8] Derry J. (2017). An introduction to inferentialism in mathematics education. *Mathematics Education Research Journal, 29*, 403-418.

[9] Causton E. (2019). Bringing inferentialism to science education. *Science & Education, 28*(1-2), 25-43.

[10] Scanlan J. O. (1985). The role of mathematics in engineering education: an engineer's view. *International Journal of Mathematical Education in Science and Technology, 16*(3), 445-451.

[11] Karabulut-Ilgu A., Jaramillo Cherrez N. and Jahren C. T. (2018). A systematic review of research on the flipped learning method in engineering education. *British Journal of Educational Technology, 49*(3), 398-411.

[12] Banu E. A. and Kuusinen C. M. (2019). Measuring the Effectiveness of Videos for Concept Understanding in a Flipped Engineering Class. In *2019 ASEE Annual Conference & Exposition*.

[13] Kerr B. (2015). The flipped classroom in engineering education: A survey of the research. In *2015 International Conference on Interactive Collaborative Learning (ICL)* (pp. 815-818). IEEE.

[14] Zaneldin E. and Ahmed W. (2018). Assessing the impact of using educational videos in teaching engineering courses. In *ASME International Mechanical Engineering Congress and Exposition* (Vol. 52064, p. V005T07A022). American Society of Mechanical Engineers.