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Teaching Aerospace Structures and Materials to the world – Analysis of the edX MOOC Introduction to Aerospace Structures and Materials

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Although aerospace traditionally has always had a multidisciplinary approach to engineering and design, the increasing complexity of aircraft and spacecraft and the rapid digitization within the aerospace industry has led to a large number of related engineering and scientific disciplines such as electrical engineers, computer scientist to work much more directly within the aerospace domain than before. Next to that there is a shortage of highly trained engineers worldwide to meet demand. As a result, there is a clear need to provide basic knowledge to non-aerospace engineers working in the field and to motivate and attract more people to engineering and aerospace in particular. This paper details how the creation of a Massive Open Online Course (MOOC) at an introductory level in Aerospace Structures and Materials provides an efficient and fit-for-purpose tool to achieve both aims. The paper will discuss the course design, the course set up, the course evaluation and how the course fits within the online learning philosophy of Delft University of Technology. It will use learning analytics to analyze our learners and their needs.

I. Introduction

For many years Aerospace Engineers considered themselves to be part of a single-themed multidisciplinary field. In order to design aircraft and spacecraft a multitude of different fields of science came together, all geared towards creating that safe, optimal, yet affordable design. Within this multidisciplinary culture there is an inherent understanding of design philosophy, risk aversion, safety awareness and certification. However, with the rapid digitization of the aerospace industry and the resulting increasing dependency of aerospace on computerized systems, aerospace engineers are having to rely on and work more closely together with other fields, such as computer science, from the start of the design and in virtually every aerospace subdiscipline. As a result, a need has arisen to ensure that there is a sufficient knowledge and awareness present among these new collaborators to ensure that the high standards in aerospace are maintained.

At the same time, this rapid growth in the use of technology in the wider society, has also led to a growing demand to train more engineers. In order to do so, more young people must be attracted to engineering as a career. This has already led to many initiatives to promote STEM education among young people but the increase in the number of students in STEM disciplines such as engineering is still lagging far behind demand.

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Engineering universities are increasingly looked at to play an ever-greater part than before in providing solutions for both issues, without being given significant extra funding to do so. To meet this challenge in the field of Aerospace Structures and Materials, Delft University of Technology in the Netherlands (TU Delft) decided to create a massive open online course (MOOC): Introduction to Aerospace Structures and Materials. The course is aimed at those working in this field in the aerospace industry, coming from a different background as well as (young) people wanting to learn more about aircraft and spacecraft design. This paper will discuss the course design, the course set up, the course evaluation and how the course fits within the online learning philosophy of Delft University of Technology. It will use learning analytics to analyze our learners and their needs and discuss the lessons learned.

A. What is a MOOC?

Although distance learning has already been in existence for centuries, the wide availability of Internet and the development of online video capabilities saw this industry transformed and overtaken by traditional universities embarking on offering their campus education online to a worldwide audience. The first attempts to offer free online university education stemmed from the OpenCourseWare initiative as started by amongst others MIT and TU Delft in 2007. However, in 2012 a rapid emergence of specific platforms occurred, such as Coursera, edX and Udacity, offering online campus education, open and free for all, and the era of MOOCs had begun.

The term MOOC or Massive Open Online Course was first coined by Dave Cormier in 2008. Generally, the term MOOC is used to refer to large (> 1,000) online university courses whose content is free (open) for anyone. This was definitely the case for the first few years of MOOC Development, but currently there are many different variations on MOOCs that no longer meet this strict definition. What is true is that the introduction of MOOCs has made education and more importantly the opportunity to gain knowledge more available and affordable to a much wider audience through its online anytime, anyplace offering.

As large engineering universities were involved in the creation of MOOC platforms, engineering and computer science courses are well represented, although the offerings for aerospace related courses is still relatively limited.

B. Online Learning at Delft University of Technology

In 2012 Delft University of Technology wanted to take their commitment to OpenCourseWare to a new level and started to develop an online education program with the mission “To Educate the World”. This program initially started by developing online variants of existing on-campus MSc courses in Aerospace and Civil Engineering and Technology, Policy and Management [1], but this was rapidly accompanied by the development of MOOCs. The first MOOCs were in Solar Energy, Drinking Water Treatment and Aeronautical Engineering.

To deliver the MOOCs Delft chose to become a partner in the edX platform, founded by MIT and Harvard, as its non-profit basis of operations was in line with that of a government funded institution such as Delft University of Technology. Next to that TU Delft had successfully worked with MIT in the OpenCourseWare Consortium in the preceding years.

In 2014 TU Delft brought all these initiatives together in the Open and Online Education programme. To support this endeavor, the TU Delft Extension School was started which extensively supported the academic teaching staff in the development and marketing of their course. This included e-learning developers, video production support, copyright support as well as marketeers. In line with TU Delft’s commitment to OpenCourseWare all MOOCs and the know-how on how to create and run online courses were made available as OpenCourseWare also.

At the time of writing TU Delft has served over 2.5 million online learners worldwide; created over 100 MOOCs, 25 online academic courses; 44 professional education courses; 14 short programs taught by some 260 dedicated instructors. A full overview of all online offerings of TU Delft can be found on online-learning.tudelft.nl.

II. Why Create a MOOC Introduction to Aerospace Structures and Materials?

In 2013 the first online MSc courses in Aerospace Structures and Materials were created [2] aimed at industry professionals. These courses were developed further and currently TU Delft offers several paid online courses for professionals in the Aerospace Structures and Materials field, which have attracted many industry professionals [2], [3]:

- Aeroelasticity
- Air Safety Investigation
- Fatigue
- Introduction to Lightweight Structures
- Linear Modelling

- Non-Linear Modelling
- Smart Structures

The first MOOC on aerospace engineering, Introduction to Aeronautical Engineering, was launched by TU Delft on edX in 2014. This MOOC, which has attracted over 120,000 learners to date, was aimed at a wider audience than industry professionals. Shortly after, MIT launched aerospace related courses also: Introduction to Aerodynamics [4], Flight Vehicle Aerodynamics and Introduction to Aerospace Engineering: Astronautics and Human Spaceflight, and Engineering the Space Shuttle.

However, although the TU Delft MOOC Introduction to Aeronautical Engineering briefly addresses the topic of structures and materials, it was clear that there was a gap in online offerings in the area of Aerospace Structures and Materials. No one as yet had created an introductory course. Based on their now well-established experience in creating online courses, 5 staff members of the Aerospace Structures and Materials Department, took the joint initiative to fill this void.

III. Fit in On-Campus TU Delft Curriculum

Rather than reinventing the wheel, we looked at the existing on-campus introductory course in Introduction to Aerospace Structures and Materials. This course is part of the AE1110 Introduction to Aerospace Engineering Module which is taught in the first semester of the first year of our bachelor degree in Aerospace Engineering at TU Delft. This course, taught by the fifth author, has in some form or the other been part of the aerospace curriculum since the late 1940s and was suitable in level and size to be transformed to an online course. An added advantage of using an existing course was that there was an archive of assignments and homework that could be drawn upon for the creation of this MOOC. The course also conveniently already had its own set of lecture notes, written by the fifth author, Alderliesten, meaning that these could also be made available to our online learners without the learners having to incur additional cost. It was also felt that it would be a great opportunity to update the course and the lecture notes to include the latest developments and design the MOOC such that the material developed would also benefit our on-campus students.

IV. Course Design

Based on the original on-campus course, which was a 7-week, 2h lecture per week course, we set out and designed the MOOC. As the course and the online lecture notes need to meet the highest standards for viewability and accessibility, and in order to meet the stringent copyright standards associated with the Creative Commons standard adopted as part of TU Delft's MOOC policy, all slides were redesigned for optimal visibility and the lecture notes were upgraded to an OpenTextbook under a CC-BY-SA license using the PressBooks platform [5].

A. Learning Objectives & Content

The learning objectives of the MOOC Introduction into Aerospace Structures and Materials were kept the same as for the on-campus course. At the end of this course, learners will be able to:

- Explain how aerospace structures are designed, and why particular choices are made
- Which materials are used, and why?
- Explain the loads and stresses aerospace structures must withstand
- Explain how aircraft and spacecraft are manufactured
- Understand the safety philosophies used in aerospace structural design, and how they affect design choices
- Create preliminary design solutions for structural design problems and material choices

Based on the seven-week format, the course was divided into 7 topical modules and one wrap up module (See Fig. 1). Each week is supported by one or two chapters of further reading from the e-book [5]. The content of each topical module is explained in more detail below.

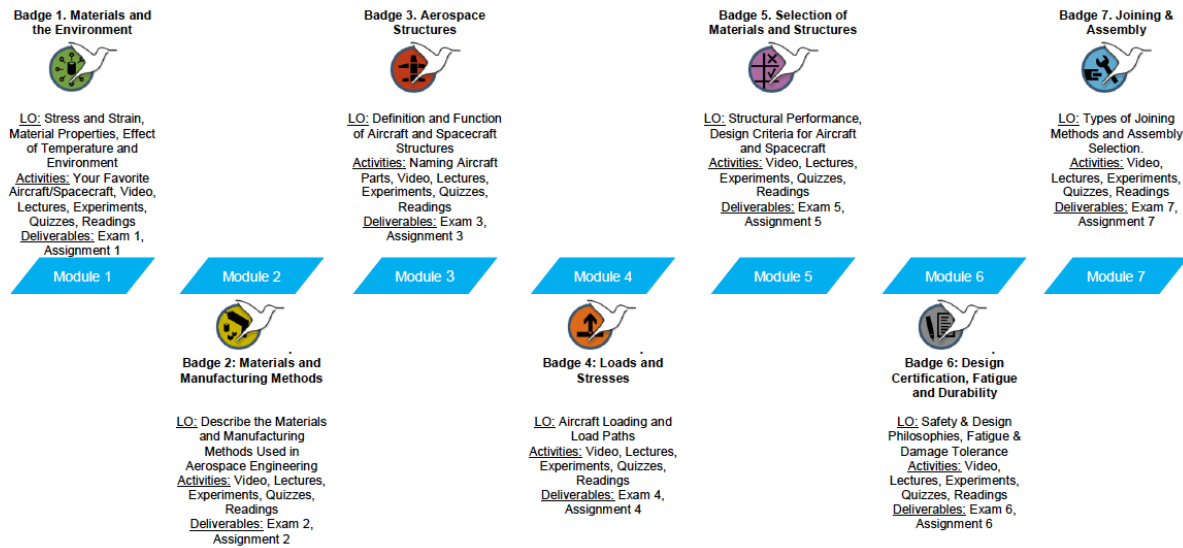


Fig. 1 Course Badges and Module Overview.

1. Course Introduction and Materials and the Environment

In this module learners are taken through the basic concepts of material properties and the phenomena of stress and strain, by starting to talk about the simple spring experiment measuring the extension of a spring under load. Concepts such as elasticity, toughness, brittleness and ductility are demonstrated and discussed. The learners are then slowly introduced to the notion that you can manufacture materials with desired properties and the principles of isotropy and anisotropy are introduced followed by the explanation of composite material starting from creating a single ply consisting of fiber and matrix material slowly building up to stacking plies to create the desired material properties.

Next, the learners are confronted with the environment the materials are being used in and how material characteristics such as yield stress and ultimate stress are influenced by temperature. We also discuss the actual operating environment and their effect on performance, discussing the effect of moisture and the use of chemical in light of corrosion processes and well as the effects of radiation and degassing.

2. Materials and Manufacturing Methods

Material properties and manufacturing methods are closely related. Often, this is also visible in the design of components and structures. In this module, starting with an overview of typical parts and products, learners are made aware of the relationship between materials, design, and manufacturing processes.

First, for different groups of materials the relevance and their applications are outlined. For aerospace applications we tend to look at the materials' performance and weight. Based on this overview, the module is focused on metal alloys and fiber reinforced composites.

The relationship between materials and manufacturing is explained by showing that metal alloys show plastic behavior and can be liquefied. Plastic behavior may result in all kinds of forming and cutting processes, where the ease of each process is highly dependent on a few material properties like yield stress and failure strain. The casting processes are based on the feature that metal alloys become liquid at high temperatures. When liquid, the metal is poured into die cavities, assisted by gravity and subsequently cooled to solidify.

The other main group of aerospace materials are composite materials: materials composed of different constituents. Since the ingredients can be manipulated, the properties can be tailored towards a specific application. Both low weight and this anisotropic behavior are key for their application in the aerospace domain. One constituent, the fiber, cannot be deformed permanently, and therefore specific processes are required for composite parts and structures, putting the fibers in the right positions. Which process is suitable, depends on two choices: fiber length and the choice of the second constituent in most composites: the polymer. The polymer can be a thermoset or a thermoplastic, each having distinctive properties during processing. The resin properties result in processes like infusion, filament winding, press forming and alike.

The different sections of this module are presented in such a way, that the students learn the basic facts and numbers, see and understand the relationships between materials and production processes, and can easily follow the logic of the story.

3. *Aerospace Structures*

In this module, we introduced learners to the structural components of aircraft and spacecraft, starting by naming and explaining the main structural elements of aircraft and spacecraft, and by dividing the structural parts in to primary and secondary load carrying elements. We then link these elements to the function they have within the aircraft and why certain structural choices are made. The concept of load carrying sheet material is introduced, evolving to stiffened shell structures. Finally, the individual structural design elements of aircraft fuselage and wings are discussed including the function of each element and the same is also done for space structures, focusing on both the spacecraft and the launch vehicle.

4. *Loads and Stresses*

In this module, loads that act on the different structural aircraft parts are studied and the paths these loads travel through a structure are discussed. We explain how to apply that knowledge to the design of the load introduction for a wing-fuselage connection. We then discuss how the loads and load paths affect design choices and how they introduce stresses and strains in the structure. The students learn how to calculate stresses and strains for two load cases on a fuselage structure: pressurization and torsion. This leads to the understanding of what the consequences are for having a pressurized fuselage for aircraft design and how to use these calculations for basic scaling of the fuselage skin thickness. Also bending of wing spars is looked at in detail and what that means for wing design. Based on this load case, the students will understand the function of the spar elements in the wing and how they transfer loads and stresses in the structure.

5. *Selection of Materials and Structures*

Within this module, learners are introduced to the differences between design and analysis. Prior to this module, learners focus on conceptual understanding and engineering analysis where there is only one correct and expected answer. This module breaks this paradigm by addressing the reality that many solutions are possible, and that engineers need to make informed decisions to guide them to a “good” solution. This is all done in the context of the selection of a material and a basic structural concept for a given engineering structural problem. Learners are walked through understanding the functional purpose of a structure and that excessive deformation and material failure are the typical functional limits for structures. Various tools for weighing design choices, such as looking at specific strength and specific stiffness for material selection, are presented and discussed in a manner that reinforces to the learners that these tools simply provide insight for the engineer to make a judgement call in their design decision which may be influenced by other factors including cost, manufacturability, etc. beyond the strength-stiffness perspective considered by the analysis tools. The module is anchored by looking at the application of the design perspective to the preliminary design of a launch vehicle. This application introduces a new variation of the stiffness perspective where the vibrational behavior of the launch vehicle is a critical driving parameter. After walking the learners through a design case, they are tasked with designing their own space structure.

6. *Design Certification, Fatigue, and Durability*

In module 6, we teach learners how structural safety is a joint responsibility of airworthiness authorities, aircraft manufacturers and operators, and how it is defined and measured against different units based on the characteristics and usage of structure and component. Learners discover how, during the design process, many possibilities for failure are already eliminated, through adoption of design philosophies developed based on experience through in-service accidents and incidents. We discuss lessons learned from various accidents, and how throughout time these lessons led to the development of three major design philosophies, incorporating aspects like fatigue and damage tolerance to different extents.

Learners then get acquainted with fatigue as damage and failure phenomena, and how these first of all relate to structural discontinuities characterized by stress concentrations. As a first introduction, students are exposed to elementary fatigue life assessment through the use of fatigue life curves.

Finally, we discuss how damage tolerance incorporates fracture mechanics concepts like the stress intensity factor to evaluate the presence of cracks in structures, for which the concept of stress concentrations has little meaning. Through the definition of fracture toughness, students learn how residual strength can be assessed in case of fatigue damage, and how critical that is when monitoring and improving the durability of aircraft and spacecraft.

7. *Joining and Assembly*

In this final module, we will look at how aircraft and spacecraft are assembled, and what joining methods are used and why. We do not just discuss the nuts and bolts, but we will also look at riveting, welding and bonding. As the

analysis of these joints can become quite complex and above the intended level of the course, this module focuses on understanding the key pros and cons to the most common joining methods used within the aerospace industry. These relate not only to performance, but also to manufacturability as well as limitations with respect to different material types. Building upon the design viewpoint in Module 5, this module is concluded with an exercise where the students need to select a joining method for a particular structural application, and motivate the suitability of their choice through considering all of the structural analysis and design concepts learned throughout the entire course. This exercise also anchors the important reality that engineers do not only have to conceive designs, but they need to be able to convince others of their merits, particularly given that there can be multiple possible design solution.

B. Set up

In online learning, it is important to keep students motivated. As a general whole there is no social pressure to attend classes and learners' online presence is asynchronous, however research has shown that learning is primarily driven by intrinsic motivation and self-determination [6]. Barak et al. identified 5 types of MOOC learners who complete MOOCs: problem-solvers, networkers, benefactors, innovation-seekers, and complementary-learners [6]. It is important that within a MOOC the needs of each of these are addressed.

The course in its design was similar in set up so that a clear structure was in place for learners. However, to avoid boredom and disengagement a variety of activities was included in the set-up of the course, such as different self-assessment activities, linking activities to the learner's favorite aircraft or spacecraft, and ensuring that the videos themselves were sufficiently engaging and entertaining, including far more engaging footage than that of a voice-over-slides recording or classroom recordings. By having both closed and open-ended problems and allowing room for discussion on our discussion forums we tried to address the needs of all learners and also allowed them to engage with each other. We also wanted to encourage students' academic curiosity and provided links to other sources of knowledge through our e-book [5] and a collection of links to further knowledge. What became very clear was that like the course team themselves, students really liked to engage with the topic of aerospace and kept up with developments and asked many critical questions on the discussion boards on current events and developments. We as staff even learned a thing or two still, which was an added bonus for us. Finally, we also really wanted to create the experience a learner would have if they were attending a face-to-face engineering course, experiments, which we will highlight in the next section.

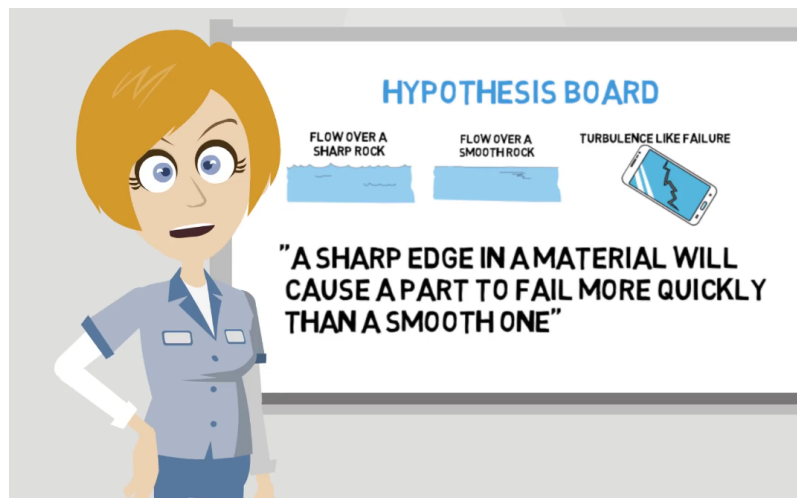


Fig. 2 Hannah Hypothesis at her hypothesis board.

Experiments

A key element that the course team wanted to nurture within the course is the natural creativity, curiosity, and critical thinking skills that are rooted in most students drawn to engineering related courses. These traits are at the root of scientific inquiry and are necessary skills to develop further alongside technical skills. To address this, the course team decided to embed an experimental element within the course that would, as much as possible, allow learners to conduct an experiment themselves at home. This was achieved through the creation of a virtual teacher, known as

Hannah Hypothesis (see Fig. 2), who would teach learners how to use the Scientific Method as a structured approach to scientific enquiry. Each of the Hannah Hypothesis videos would guide learners through the following process:

1. Identifying a question based on curiosity, experience, and/or observations of the world around us
2. Formulation of a hypothesis as a possible answer to this question
3. Designing of an experiment to test the hypothesis
4. Gathering observable data from the experiments
5. Weighing the hypothesis against the gathered data to form conclusions

In creating the series of experiments, care was taken to provide instructions for learners so that they could replicate the experiment at home with household materials. Care was also taken to show that in some cases developed hypotheses would fail to be demonstrated by the experimental results. This was done to reinforce the importance of critical reflection on experimental results and the acceptability of having tests result in failed hypotheses.

C. Assessment

With any distant learning course, the assessment is the tricky part. During any course you want to retain learner motivation, give them feedback and monitor their progress. This is hard enough in our on-campus courses of 300+ students, but achieving this for over 8,000 students is an even larger challenge. To keep learners engaged, a small self-assessment quiz was given at the end of each submodule. Boud and Falchikov [7] define self-assessment as: the involvement of learners in making judgements about their achievements and the outcomes of their learning. They also feel that self-assessment is a necessary skill that supports student learning both now and in the future professional development as it allows the learner to develop their capacity to be assessors of learning. This is one of the primary reasons it is often employed in online learning. Learners had unlimited attempts at these questions, received automated feedback on their answers and could see if their knowledge and understanding of the material was sufficient or whether they perhaps needed to revise more.

To appeal to a learner's motivation to earn rewards and take part in the gaining of an official course certificate, a badge system was introduced. Badges are a proven, common online motivation tool [8]. With the help of the graphical designer of the Extension School a badge was created, specific for each Module. Upon successful completion of a module the learner would gain the accompanying badge. In Fig. 1. you can see the badges of each module as well as the module overview.

Each module is concluded by an exam and an assignment. To earn the badge for a module, learners need to score 60% or higher on both. Each exam consists of 10 questions using a variety of question types, from multiple choice questions to numerical answers. The assignment would often be a more design-based question, either based on their favorite aircraft or spacecraft, a real aircraft or spacecraft, and always be based on a realistic issue. In module 2 for instance we asked the learner to create a simple structural and materials design for a combined firewall and bulkhead of a small 2-seater aircraft (See Fig. 3). With the help of a rubric learners score themselves on the assignment, which as many experiments with this have shown in the past [9], they do diligently and very honestly and even harshly with some actually failing themselves when we would have given them a pass!

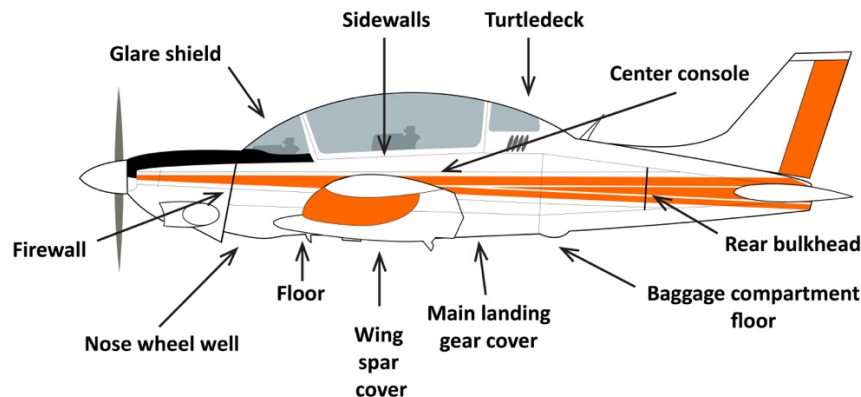


Fig. 3 Example of Assignment: Design a Bulkhead/Firewall.

rate of 75% which is a high response rate for online questionnaires. This is indicative for the commitment of learners to the course in aiding to make the course better.

The overall average grade given to the course by the learners was 8.69/10, S.D. = 0.19 which is a very high score within TU Delft for a MOOC. When asked about their course experience, students felt the course was about right, however, some students felt the course was too short, despite a 7-week course already being longer than the recommended 4-6 weeks by edX (See Fig. 5)

Students felt the course was ...

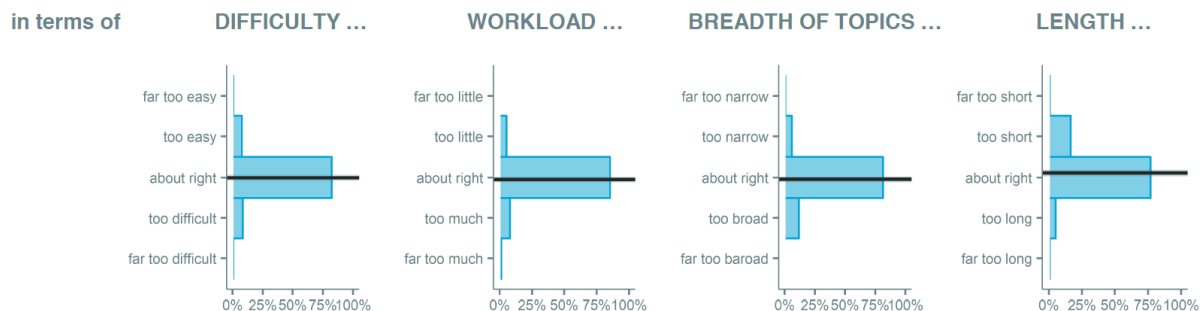


Fig. 5 Student's Post Course Evaluation of Difficulty, Workload, Breadth and Length

When it came to which elements were perceived to have the highest importance, value and satisfaction, videos were rated the highest followed closely by reading materials and exercises. When asked about the biggest challenge for completing the course students overwhelmingly listed time availability in both the pre- and post-course survey, scoring 66% and 65% respectively (N = 1107 and N = 137).

When asked about improvements to be made to the course, learners would like to receive more in-depth explanations of numerical assignments and more numerical assignments.

Based on the evaluations we extended the number of videos to include more experiments and created a few videos to explain the numerical problems. We also extended the feedback on many of the quizzes, exams and assignments to further assist our learners. Many of the learners also provided detailed errata on our e-book which we gratefully used to update the e-book.

VI. Conclusion and Future Developments

After completing the first run we can conclude that the course has been a great success. With much higher ratings than the average DelftX MOOC and despite having a relatively high passing grade requirement the average amount of students completed the MOOC. It was also interesting to see that our course did not only attract industry professionals but is also attracting a large percentage (29%) of high school students taking the course in relation to their current or prospective studies. Hopefully, this course will also assist in making aerospace engineering a more attractive field for young people.

After its maiden run as an instructor paced course, the course was updated based on the outcomes of the evaluations and is now a semi-permanent feature on the edX platform as a self-paced course, running 11 months per year, starting in March and ending in January. The current run that is open until early February 2020, with the next run already scheduled to start in March 2020. The current run is again very popular and has already attracted more than 9,000 learners at the time of writing.

It is felt by the course team that they more than achieved their objectives to fill the gap in introductory knowledge in Aerospace Structures and Materials as well as in creating an active and attractive course that will encourage more young people in STEM in general and in aerospace in particular.

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helped us out whenever we wanted push things to the limits of the platform. Finally, a very special thank you to our Aerospace Online Coordinator, Renée van de Watering. Thank you for being there at every step of the way, supporting us through this process and marketing the course when it was ready to launch. Without you there would have been no MOOC!

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