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A modern paradigm to virtually teach a manufacturing processes course using finite element analysis

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ABSTRACT: Finite element analysis (FEA) is a very well-known method in most engineering fields. Its use and application have been widely recognised as a tool in the constantly evolving world of modern engineering. The FEA is commonly utilised to understand different process variables that can mimic the laboratory environment. Computer-aided engineering, design and manufacturing software that utilise FEA are crucial for understanding, estimating and planning manufacturing process parameters. The authors of this article articulate the use of FEA as a teaching method for a manufacturing processes course delivered to third-year mechanical engineering students, and depicts the experience and feedback students had utilising this tool. During the pandemic times, the potentials of computer simulations as a teaching tool are introduced; its effectiveness for on-line learning models is also discussed.

INTRODUCTION

Manufacturing is both the figurative and literal bedrock of most engineering practices and in turn, the various processes it entails are of great importance to engineering students. It is well established that manufacturing has a significant role in leading the current industrial revolution and recent technological innovations. Manufacturing contributes hugely to the world economics nowadays [1]. Aside from the economic feats, manufacturing is an integral component in any engineering process and its importance to students pursuing degrees in engineering is irrefutable.

With the constant evolution of scientific and technological advances in the modern world, the need to regularly change engineering curricula for the better has become regular procedure for most renowned educational institutions, and this has introduced a virtual engineering curriculum [2]. Recently, a handful of programmes have started to incorporate the teaching of computer-aided engineering (CAE) in their curricula to give students a more detailed and industry-oriented learning experience.

Traditionally, courses in manufacturing processes have offered a fundamental and practical approach in terms of teaching. Whereas the introduction of CAE and FEA software offers a very in-depth experience and help guide students through more details of different manufacturing topics [3]. This will facilitate designing on-line classroom-based simulations for a manufacturing processes course [4]. Several manufacturing, engineering design and rapid prototyping courses lack the balance between fundamentals and practical skills [5]. Therefore, the aim of integrating FEA into the teaching method of undergraduate engineering courses, like manufacturing processes, is an attempt to fill this perceived gap and offer students a more effective and vast facility to link all the skills acquired through this initiative.

SIMULATION-BASED EDUCATION

According to Campos et al, simulation software allows students to learn complicated concepts better and make them feel more involved in what they are doing [6]. The interest in using simulation software as teaching tools is rising as course instructors are seeing them as a potential way to help students gain more hands-on experience and make them more familiar with how tasks are done in the real world. Due to the rapid technological developments, computer simulation capabilities are getting larger and more ambitious than ever, and simulation games and software have shown their effectiveness in teaching students in the engineering field as it allowed them to improve their critical thinking, decision making and many other cognitive skills.

A simulation is a representation of the real world and the closer the simulated world is to reality, the better the learning experience. For example, students can learn about supply chain management and logistics through simulation software, which can help them gain lots of hands-on experience and be better prepared for a job in that field once they graduate.

The use of innovative technologies and computer-aided approaches in teaching engineering students is currently a necessity, as laboratories are not as accessible as before [7].

Simulations for Teaching Engineering Courses

According to Hauge and Riedel, serious games can help students learn hard and soft skills [8]. For example, they can help them understand complex systems, such as a production network, which is a hard skill, and also can help them learn how to communicate within a team. One of the first simulation games that was created for the engineering-based learning environment was the beer distribution game developed in 1985. Such games are built on the principles of constructivism. Although these games are based on constructivism and the student gains experience by playing the game, they can also enhance the student's cognitive abilities as the student is asked to take certain decisions in the simulated world of the game to achieve a certain goal. That can improve the student's decision-making skills in the real world, because the student will know how to deal with situations similar to those experienced in the simulated game.

However, the currently available teaching tools and approaches are not suitable for students to learn about new product development (NPD) effectively, because they cannot learn about it through the usual theoretical lectures, group projects and assignments only. They must learn how to do it in an interactive way that makes them involved in the process and a simulation game, such as COSIGA, is effective for NPD learning. The game allows students to participate in product development and makes them work in a group of five. The students can use phones, video calls and other forms of communication with each other and each one of them is given a specific role. They can choose out of five roles, which are project manager, designer, marketing manager, production manager and purchasing manager to simulate a real-life product development scenario.

BEWARE is also another interesting simulation game, but this one was designed to help engineering students understand the risks in enterprises and it can enhance their risk management skills. The game puts the student in a simulated world where the student has to deal with risks in production networks. The game takes the student into different levels of risk management starting with risk management in a single organisation environment, and then it goes a step further by simulating an inter-organisational risk management scenario to help in enhancing the student's understanding of organisational co-operation to manage risks [9].

Computer Simulations as a Teaching Tool during Pandemic Times

The Covid-19 pandemic has brought lots of challenges to the education sector, since at its beginning, the whole sector was forced to transform to the on-line learning model and suspend the classic face-to-face learning model. Manufacturing Process is a course in which face-to-face interaction between the student and the instructor significantly contributes to the learning experience by increasing student engagement and enjoyment. Therefore, faculty staff had to think of new models and ways to make sure the learning experience is as much interactive and exciting for the students as possible, especially in the absence of face-to-face learning.

In the spring semester of 2019 at Abu Dhabi University, mechanical engineering students, taking the Manufacturing Processes course, were assigned to analyse and simulate manufacturing processes using Ansys software as part of the course project. The goal of this project was to familiarise students with FEA software and to illustrate the usefulness it represents in manufacturing. In this article, the authors discuss these newer approaches to teaching manufacturing courses and their role in shaping the engineers of the future.

COVID-19 AND THE SHIFT TO ON-LINE LEARNING

The digitalisation of education is not an easy task and for the success of on-line learning, proper transition to technological means of education is important. The concepts of learning techniques, academics, delivery, should be positioned in a virtual zone that is offered with all types of innovation opportunities. A new route to investigate potential problems has to emerge. It should be acknowledged that innovation would be confronted with training challenges emerging from the pandemic-induced circumstances.

It is critical to position the educational model on the educational requirements of students, and educational institutions have to be responsible for the preparation of digital means for learning and be more willing to finance the technological means required for satisfactory quality outcomes. Essential aspects of the learning process depend on factors, such as accessibility, and learning and teaching models. For example, in terms of accessibility, it is important to ensure that there is a proper and solid connection to the Internet network to provide a solid learning experience.

In addition, changes to the learning and teaching models have to be adapted to new on-line learning systems. Various theories concerned with distance learning, consistently stress that the student is the main component in any educational system. The instructor is an additional important component and, ultimately, the assets available to facilitate the learning mode and provide enough technological advancement are also another important factor [10]. In on-line learning, the utilisation of the newest communication technologies is crucial. In this space, the educational community can gain access to the virtual campus and initiate communication to classmates and instructors.

Chinese universities have been one of the leading universities in the world in terms of on-line education, as they already have a solid infrastructure for on-line learning. Along with the swift growth of massive open on-line courses, the sum of which have surpassed 500 in China, the number of people enrolled in those curses has increased exponentially to at least 3 million people. Peking University, a leading Chinese university in on-line learning has provided approximately 100 on-line courses. Following the spread of Covid-19, the university had to fully shift to on-line learning and cancel face-to-face classes.

It is a major change to shift all current courses to on-line in a couple of days. An entire on-line course demands a detailed lecture plan layout, various teaching resources, like audio and video content in addition to technology support groups. Because of the unexpected Covid-19 pandemic, everything had to happen quickly. Many instructors are encountering difficulties, such as lack of experience in using on-line teaching tools or lack of assistance from educational technology groups. Besides the difficulties that faculty staff are facing, students are also suffering because of the inability to adapt to the new on-line learning as they do not have appropriate learning resources or appropriate learning conditions when they are at home.

Based on Peking University findings, Bao suggests some instructional methods to enhance the student's learning focus, as well as more active participation to accomplish an effortless shift to on-line education [11]. In addition, strengthening students' active learning ability outside of class is very important, as there will be more emphasis on their ability to learn independently on-line with less face-to-face connections with the course instructor. This can make some students more prone to laziness or carelessness which can be challenging. Also, combining on-line learning and self-learning effectively can prove difficult. Instructors must consider two phases of learning, the off-line self-teaching phase, as well as the on-line learning phase.

Regarding the off-line self-teaching phase, students are expected to review the course-specific material and hand in minor reports based on their reading of key literature prior to the class. Instructors must offer feedback to students on the tasks and identify the students' learning level. That would enable instructors to modify learning material prior to the class. Regarding the on-line teaching phase, instructors must utilise a discussion board for students to share their understanding of the key literature. Therefore, students will not be taught vague, disjointed, and shallow information, but will be confronted with deep knowledge throughout the discussion.

FEA IN MANUFACTURING

Finite element analysis is a mathematical technique that employs a theory of dividing a body into finite elements and numerically analysing these elements cumulatively, to better understand the behaviour and properties of the whole body [12]. The FEA can be used to solve countless problems and design applications, making it a very flexible and invaluable tool at the disposal of an engineer. However, this method was, and still is, far ahead of its time. Due to its nature, the only way to increase the yielded accuracy is by increasing the number of elements, resulting in an extremely arduous and lengthy process. It was only very recently, since the birth of computers, that FEA has become more prominent in industries such as, for example, aerospace, mechanical, civil and biomedical engineering.

Computer-aided FEA programs, like Ansys, function by dividing a part into an extensive number of finite elements, like small cubes for example. The program would then sum up each element's independent characteristic equations to create a pattern that helps predict the behaviour of the part, whether it be as a whole or localised by problem areas.

Many schools deem FEA, as a course, unnecessary to include in their core syllabus for a mechanical engineering degree, with some even reluctant to offer it as an elective course [13]. Abu Dhabi University, however, has not only made it a compulsory credited course, but has also tailored its curriculum to include the use of FEA programs, primarily Ansys, in many of the major courses, such as manufacturing processes [14].

Ansys is a heavy-duty program that combines computer-aided design (CAD) and FEA software. This type of program proves useful in multiple ways, especially in terms of teaching engineering [15]. Even in more elementary engineering courses, where students may not be fully aware of FEA and its applications, the CAD component helps students visualise many key elements, while giving them the experience in handling an engineering-based program, many of which are instrumental in most industrial projects. Ansys has a very extensive in-built library of materials that students can select to experiment around different environments, conditions, and constraints, as demonstrated further in this article.

COURSE DESCRIPTION

Manufacturing Processes is a junior level course offered in the spring term of the mechanical engineering curriculum at Abu Dhabi University. This course serves as an introduction to manufacturing engineering. It presents students with various traditional processes, as well as many analytical approaches in dealing with manufacturing processes, such as casting, welding, metal cutting and metal forming, as shown in Figure 1. A general skill gained from this course is to appropriately select and synthesise the most viable set of options, from various manufacturing processes, for any specific task [16].

Table 1: Manufacturing Processes weekly course breakdown [16].

Week	Topic	Readings (Textbook [17])	Assessment tool(s)*
1	Properties of ferrous alloys, definitions and classifications, and some uses of ferrous alloys including: carbon steels, alloy steels, stainless steels and cast irons	Chapters 0, 4, 5	
2	Nonferrous metals and alloys	Chapters 5 and 6	
3	Fundamentals of machining, cutting-tool materials and cutting fluids	Chapters 21 and 22	Assignment 1 Test 1
4	Machining processes: turning and hole making, milling, broaching, sawing	Chapters 23 and 24	
5	Filing and gear manufacturing, machining centres, machine-tool structures and machining economics	Chapters 24 and 25	Test 2
6	Fusion-welding processes, solid-state welding processes, brazing	Chapters 30 and 31	Assignment 2
7	Soldering, adhesive-bonding and mechanical-fastening processes	Chapters 31 and 32	Test 3
8	Fundamentals of metal casting, metal-casting processes and equipment	Chapters 10 and 11	Assignment 3
9	Metal casting: design, materials and economics	Chapters 11 and 12	Test 4
10	Metal-rolling processes and equipment	Chapters 13 and 14	
11	Metal extrusion and drawing processes and equipment	Chapter 15	Test 5
12	Powder-metal processing and equipment, advanced machining processes, joining processes	Chapter 17	Project submission
13			Final examination

The course complies with ABET's criteria for student outcomes 1, 4 and 6 [18].

ABET Criteria for Student Outcomes

1. *An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics*
2. *An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors*
3. *An ability to communicate effectively with a range of audiences*
4. *An ability to recognise ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts*
5. *An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives*
6. *An ability to develop and conduct appropriate experimentation, analyse, and interpret data, and use engineering judgment to draw conclusions*
7. *An ability to acquire and apply new knowledge as needed, using appropriate learning strategies* [18].

The student outcomes established by ABET …*describe what students are expected to know and be able to do by the time of graduation. These relate to the knowledge, skills, and behaviors that students acquire as they progress through the program* [18].

Delivery Mechanisms in Teaching Manufacturing Processes

As with many engineering courses, in teaching manufacturing processes, there is a need to satisfy traditional teaching practices to suitably deliver the course outcomes. These methods include lectures, tutorials, laboratories and textbook resources. It is the course instructor's role to appropriately choose the accurate combination of methods to aptly convey the learning material to students [19].

However, with the need to cater to the attention-span deficient newer generations, there is a need to employ more contemporary teaching methods [20]. These methods can include:

- Visual representations of the material, such as educational videos, interactive lecture slides, on-line access to textbooks and resource journals.
- Interactive computer-based tools, like CAD and CAE software, coded equipment operators and on-line assignment submittals and reviews.
- Visits of industrial sites; for example, students were taken to National Petroleum Construction Company (NPCC), in Abu Dhabi, United Arab Emirates, a regional engineering, procurement and construction company.

Project Framework

As aforementioned, the Manufacturing Processes course in Abu Dhabi University integrated the use of CAE within its curriculum. This yielded a great success in helping the students accomplish a better understanding of the course, as well as achieving the student learning outcomes set by the course instructor.

A project for the Manufacturing Processes course was constructed to provide students with hands on experience in traditional manufacturing processes. It has also encouraged them to engage in self-learning through studying contemporary issues in manufacturing, as well as providing them with an idea of industrial opportunities within the region and throughout the globe [21]. The student should be able to utilise the 3D CAD/CAE in product design using discussed manufacturing tools [22].

The project's goal statement was to use Ansys to model and simulate one of the following manufacturing processes:

- Metal cutting
- Deep drawing
- Pipe bending
- Additive manufacturing

Students were to utilise the CAD feature of Ansys, SpaceClaim, to model the process, as well as solve it, using the in-built Explicit Dynamics solver, to determine kinematic analyses and simulate the process. The project timeframe spanned throughout the semester, as it was assigned in the first two weeks and was due during the last week of classes. Students were expected to combine their own innovative capacity with the materials covered in the lectures to accordingly simulate and analyse the given processes. The main aim of this project was to expose students to industrial problems, manageable within their capacity, through an illustrious application, while offering the chance to gain skills and experience in handling a broadly valuable engineering tool.

Student Deliverables

Metal Cutting

Metal cutting processes work by using a cutting tool to remove the surface of a workpiece, in turn creating macroscopic chips [23]. Some common processes include turning, milling and drilling. For this topic, most of the students opted to choose the orthogonal metal cutting process. They employed the Explicit Dynamics component of Ansys to model and simulate the deformation as shown in Figure 1.

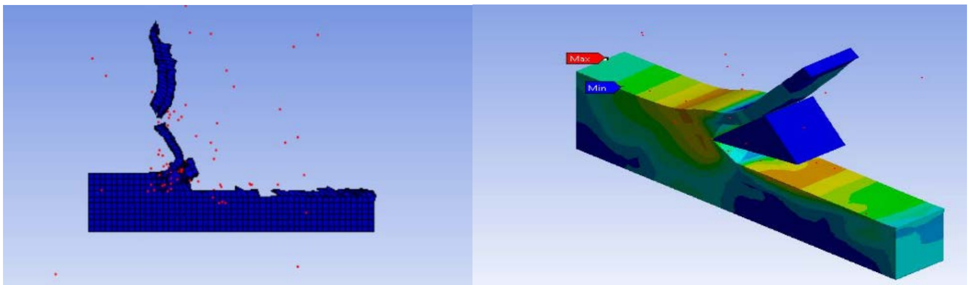

Figure 1: Metal cutting simulations in Ansys.

The students' feedback portrayed their newfound understanding of the significance of seemingly minute details played into design, analysis and simulation. Students were able to comprehend the metal cutting parameters and their effect on material removal rates, roughing and finishing cutting cycles. The produced material chips were also studied. Students were able to validate metal cutting characteristics and the orthogonal cutting model. Other studied parameters included cutting forces, effect of cutting angles and cutting velocities. The dependent and independent parameters of the cutting process have been correlated to power requirements of the cutting process.

Deep Drawing

The drawing process deals in changing the cross section of a work piece by pulling it through a die, called a draw die. Deep drawing is a process that involves the pushing of a metal sheet into a die cavity. This process is commonly used to make various kinds of kitchen appliances, food containers and automotive fuel tanks [17].

Students were able to study and model the deep drawing process in Ansys, as shown in Figure 2. The effect of different drawing ratios on the resulting part is further investigated. The result required punch force is crosschecked with analytical models. Students have shown that stress concentration areas are relevant to force and stress distributions on the part's surface. The resulted thickness distribution has been investigated.

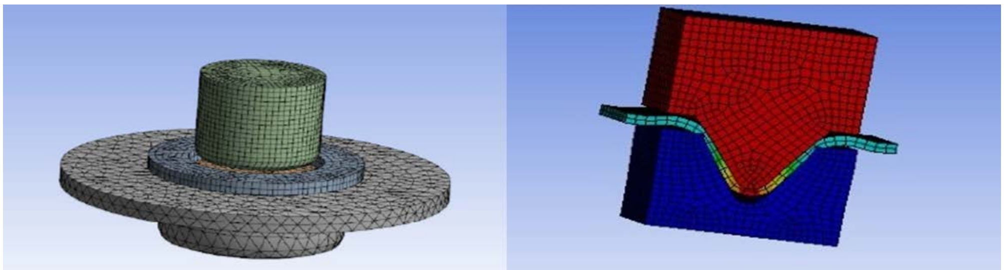

Figure 2: Metal deep drawing process simulations in Ansys.

Pipe Bending

The bending process is one of the most common forming operations, as made obvious by the widespread use of its products. It yields excellent results for applications where a high stiffness to weight ratio is required [17]. The chosen system parameters were set to study the effect of pipe radius and bend radius of required pending forces. Students were able to study different results including stresses and bent pipe characteristics, as demonstrated in Figure 3.

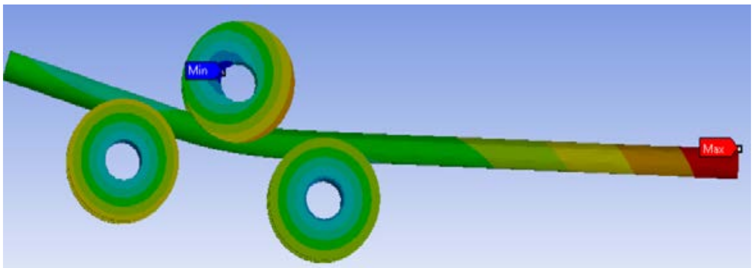

Figure 3: Simulation of pipe bending process.

Additive Manufacturing

Students were able to learn about the additive manufacturing process work by building separate layers and then stacking these layers together [17]. The additive manufacturing process can create many objects, with various complex shapes, using a wide range of materials and allows for many freedoms in design [24].

The students assigned with this topic chose to go with the three-dimensional printing additive process in Ansys and showed initiative not only in their creative modelling, but also in running two different analysis solvers in conjunction: Transient Thermal and Static Structural, results are shown in Figure 4.

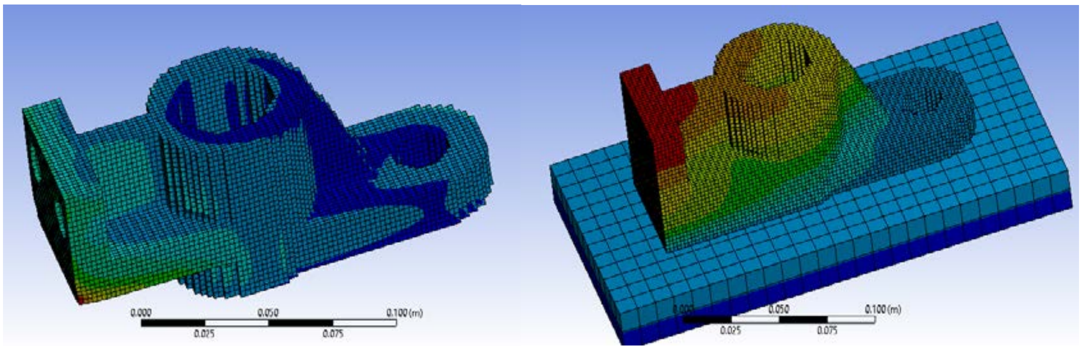

Figure 4: Additive manufacturing of a 3D product in Ansys.

STUDENT SATISFACTION STUDY

The study was conducted by asking students a set of questions that were designed to measure the overall student satisfaction with the decision to implement FEA analysis tools, such as Ansys in the Manufacturing Processes course. A sample of 38 students out of the population of third- and fourth-year Mechanical Engineering students at Abu Dhabi University who took the Manufacturing Processes course accepted to be part of this study.

The first question was designed to measure the students' level of understanding when using an FEA software, such as Ansys introduced into the course. Their answers can be summarised as follows: 84% of the participants acknowledged that Ansys indeed improved their understanding of manufacturing processes, while 16% did not find that Ansys benefited them in terms of these processes.

For the second question, the students were asked to read a set of statements and decide out of five options, which were: strongly agree, agree, neutral, disagree, strongly disagree. This question was designed to check which specific manufacturing processes students felt they could better understand by using FEA; and whether FEA tools really helped them improve their imagination and perception when modelling and testing their designs on an FEA tool, Ansys or another tool. Also, the last statement measured the students' agreeableness on the importance of learning how to use FEA tools in their future career. Table 2 shows the detailed results of the second question.

Table 2: Second question results.

Survey statement	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
FEA tools, such as Ansys, are helpful tools for learning about additive manufacturing	10.5%	0%	23.7%	34.2%	31.6%
FEA tools, such as Ansys, helped me learn about manufacturing processes, such as machining	10.5%	2.6%	28.9%	34.2%	23.7%
FEA tools, such as Ansys, enhance my imagination and perception through modelling manufacturing processes and testing them	7.9%	2.6%	10.5%	52.6%	26.3%
FEA tools, such as Ansys, are important tools in the manufacturing industry, and learning how to use them in the Manufacturing Processes course give me an advantage in the job market	7.9%	2.6%	28.9%	34.2%	26.3%

According to the results presented in Table 2, most of the students agree with the fact that FEA is a helpful tool for enhancing their learning of manufacturing processes and prepare them for their future career. Also, the students were asked to rate the overall FEA experience of the Manufacturing Processes course in the third question, and they gave it an average approval rating of 77.8%, which means that most of them were generally satisfied with the experience. In the fourth question, they were asked about the improvements that they would like to see in future FEA implementations in the Manufacturing Processes course, and most of them suggested more focus on FEA tools training by extra lessons fitted into the regular manufacturing processes lecture time to get more experience in using them for manufacturing processes modelling and analysis.

CONCLUSIONS

During the current challenging times, engineering education is facing several challenges to provide students with the required practical experience necessary to acquire engineering skills. To bridge this gap and enhance the attainment of course learning outcomes, this study proposes the use of finite element analysis in modelling manufacturing processes and evaluate its effect. Students were able to achieve the learning outcomes of the Manufacturing Processes course through studying the results of process parameters and constraints. Examples included in the article include metal cutting, additive manufacturing, pipe bending and deep drawing. The students' feedback showed adequate satisfaction of learning outcomes when using FEA in studying manufacturing processes.

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