The evolution of the Finite Element Analysis course: Steps towards human-centric engineering

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ABSTRACT

In this work, I, the chair of the Software Engineering program at the W Booth School of Engineering Practice and Technology at McMaster University, reflect on the evolution that has happened through an undergraduate engineering course, Finite Element Analysis, over the past 10 years at the W Booth School of Engineering Practice and Technology at McMaster University. I present a chronological sequence of transformations in this course based on internal and external influences. First, I outline the initial focus of the course on applied software skills training, which was advocated by industry partners and aligned with a college partnership, to ensure that students were employable in the automotive and aerospace industry almost immediately upon graduation. I then describe and reflect on two periods of significant change: (a) the enhancement of theoretical content to meet the accreditation and licensing requirements of Professional Engineers Ontario and to prepare students for graduate studies and (b) a recent push to graduate human-centric engineers capable of undertaking engineering work that considers technical, as well as social, human, and environmental issues. I also share my vision for future improvements to ensure that graduates have all the desired competencies. This reflection would serve as a good reference for anyone who wants to undertake such transformations in their course.

KEYWORDS

curriculum evolution, human-centric engineering, ethics, sustainability, social responsibility, pedagogical techniques

The Finite Element Analysis (FEA) course has been taught at the W Booth School of Engineering Practice and Technology in the Faculty of Engineering at McMaster University since 2010. The school is focused on engineering practice, and the students enrolling in our programs have a natural inclination toward applied learning. As a result, most of the courses (including the FEA course) have a significant experiential component offered through lab sessions where students apply the concepts learned in the classroom to solve engineering problems. The school started offering the Automotive and Vehicle Engineering Technology program, developed in partnership with Mohawk College, in 2008, which leads to a Bachelor of Technology degree. In this program, the course on Finite Element Analysis first offered in 2010 has become mandatory for degree completion and currently has an enrolment of about 70–75 students split between two sections. Through this course, the program trains students to have competence in applying FEA to study problems in structural and thermal analysis. Thus, it allows our students to master a computational technique to study problems in the realm of automotive and vehicle engineering.

Finite element analysis is a numerical technique that is used to study a variety of problems in the areas of energy and mass transport, structural analysis, and electromagnetic potential. While initial formulations and applications of FEA were developed to address problems in civil and aeronautical engineering in the 1940s (Courant, 1943; Hrennikoff, 1941), a serious application of FEA to solve engineering and technology problems started in the 1960s (Hinton & Irons, 1968). Today, FEA is used in a variety of industries (e.g., automotive, aeronautical, biomechanics, etc.) since it offers an inexpensive method to quickly investigate a variety of problems with modest computational resources.

Over the past decade, this course has undergone significant transformations. Specifically, from the initial years emphasizing the mastery of the software, we have progressed to an advanced version of this offering that emphasizes equal competence in the technical background, software handling, and the application of principles of ethics, sustainability, and social responsibility to ensure that students' designs and solutions are conscious of the environment and help advance our society.

In this chapter, I showcase the evolution of our Finite Element Analysis course over the past decade by presenting three phases of the evolution: Phase 1 emphasized skill training to ensure that the students are employable in the automotive and aerospace industry almost immediately upon graduation. Phase 2 marked an emphasis on engineering practice that required students to (a) have a sound technical background as prescribed by Professional Engineers Ontario (PEO), the licensing and regulating body for professional engineering in the province, and (b) be adept in using software to design and develop solutions for real-world engineering problems across the automotive and aerospace sectors. Finally, Phase 3 marks the beginning of training human-centric engineers wherein, in addition to the competencies in Phase 2, I train them to incorporate principles of ethics in their design considerations and keep the environment and society in mind while prescribing solutions. I end this reflective piece by sharing a short note on my outlook for the future.

PHASE 1: SKILL TRAINING

Course objectives and design

During this phase, the program and syllabus were largely aimed at skill development. As a result, the overall rigour in the curriculum was not very strong. Assessments of student learning were primarily based on the usage of two specific pieces of software with minimal emphasis on theoretical foundations. The underlying rationale behind this course design was that the objective of the program was to train students to be deployed as technologists in the industries where these software packages are ubiquitous. The curriculum was largely aimed at ensuring competencies for the industry and was developed in consultation with industry experts. Specifically, we have a Program Advisory Committee that is a panel of industry members in the field of automotive engineering with whom faculty members meet annually to get their opinion on the current state of the curriculum, and, based on their feedback, improve or modify the curriculum to meet current industry needs.

With respect to pedagogical techniques, while the traditional lecture setting was the norm to teach theoretical principles in engineering, problem-based learning (Centea & Srinivasan, 2016, 2017, 2019, 2021; Dochy et al., 2003; Gijbels et al., 2005) was employed to teach the use of software and some basic theory, with instructors demonstrating the use of the software and imparting key steps and ideas by solving a problem. Students were subsequently required to solve a problem as part of a lab exercise and submit a detailed lab report.

In the offerings around the 2010s, students were introduced to basic theoretical concepts as well as the use of software to study engineering problems. The syllabus contained foundational concepts of math, stress, strain, and heat transfer and introduced the terminology used in two-dimensional and three-dimensional finite element analysis. Subsequently, the course showcased the use of the theory to solve problems in solid mechanics and heat transfer.

Overall, a special emphasis was on training students to use two software packages (i.e., Catia and Ansys), which are simulation and three-dimensional design software used to study complex engineering problems with the principles of FEA. Pedagogies were straightforward; students were introduced to examples and undertook nine lab exercises to solve problems using the software. A brief description of the labs along with some sample exercises are presented in Appendix 1.

Assessments

As summarized in Table 1, students went through several assessments in the course. The first term test evaluated the students on Catia software, and the second term test assessed them on Ansys and a short and basic theoretical question. Each test was 2 hours, computer-based, and conducted in a computer lab where students could access the software. Students were given two questions to solve using the software and submitted a short report compiling their results. The final exam was comprehensive, computer-based, and had two questions: one requiring the use of Ansys and the other a relatively simple theoretical question that asked students to use FEA equations to solve an engineering problem and present the solution.

Table 1. Assessments and corresponding weights for Phase 1: Skill development

COMPONENT	WEIGHT (%)
Assignments using Catia and Ansys software	20
Term test 1	15
Term test 2	30

Final exam (comprehensive)	35

Reflection

The Automotive and Vehicle Engineering Technology program was developed in partnership with Mohawk College, so the emphasis was more on skill training. As a result, in this phase, we simply trained students to use two software packages and analyze the results produced by them. Just basic theory was taught in the classes to put things in perspective. This was largely guided by the Program Advisory Committee which viewed these software as very important tools in an engineering company. While software training is valuable, the lack of emphasis on the detailed derivation of the theoretical concepts that are used by these software packages meant that we were graduating students with a poor understanding of the principles of the subject. This knowledge gap in turn is an insurmountable barrier for students who want to undertake, for example, graduate studies or find employment in companies that develop such software. It was clear that this college-level skill training had to be surpassed to steer this course to a university level.

PHASE 2: THE ADVENT OF ENGINEERING PRACTICE

Course objectives and design

By 2015, the W Booth School of Engineering Practice and Technology had a very strong financial position, and its programs had also become very well established. As a university entity, it was natural for the school to start exploring the development of graduate programs. To avoid competition with the other departments in the Faculty of Engineering that offer Master of Applied Science (MASc) and PhD degrees, we were contemplating the formulation of graduate programs offering MEng degrees. There was also a growing aspiration among our students to achieve the professional engineer designation upon graduation from the provincial licensing and regulatory body, which is mandatory for career progression to managerial levels in industry or government. Besides, without such advanced training and certification, graduates are not able to undertake engineering practice (i.e., professional engineering services such as consultation, planning and development, research, etc.) in the public or private sector. With growing enrolment numbers, we had a bulging subset of students who were very aspirational about their future careers. Several others wanted to pursue graduate studies. These factors had a significant impact on the evolution of the undergraduate curriculum as the theoretical rigour had to be improved to meet the standards of the accreditation body, Professional Engineers Ontario (PEO), and also set up the students to succeed in graduate programs.

It was around this time that I inherited and started teaching the Finite Element Analysis course. With the above objectives in mind, I significantly enhanced the quality and complexity of the engineering applications in the lab exercises. For example, instead of studying temperature distribution in a metal plate, a very simple exercise, I introduced the temperature distribution on the fuselage of a space shuttle at the time of re-entry. Such lab exercises not only bring the students closer to an industry environment but also stimulate their learning as they are immersed in solving almost real events and scenarios. In my interactions with students, several of them have expressed thoroughly enjoying the labs because of the specific applications explored that gave them good exposure to what real-world engineering problem-solving requires. Similarly, I placed a significant emphasis on understanding the theory of FEA. The midterm and final exams had 4–5 theoretical questions instead of questions on Ansys or Catia. To answer these questions, students are required to present detailed theoretical and numerical calculations. Thus, students were exposed to understanding how the software works, not only how to use it. I also started emphasizing how this knowledge of theory was setting them up to successfully obtain the professional engineer license for which they may have to take a theory exam in FEA.

The pedagogical technique used in the classroom also varied through the years. As part of the major overhaul of the course, I evaluated possible pedagogical techniques by reading about them, testing them inside the classroom, and discussing with the students. Specifically, I considered problem-based learning (Centea & Srinivasan, 2016, 2017, 2019; Dochy et al., 2003; Gijbels et al., 2005; Rajabzadeh et al., 2022; Sidhu et al., 2017; Srinivasan & Centea, 2021), active learning (Beichner et al., 2007; Buck & Wage, 2005; Cummings et al., 1999; Prince, 2004; Sidhu & Srinivasan, 2018; Srinivasan & Centea, 2015, 2019; Wage et al., 2005), research-based learning (Bogoslowski et al., 2021; Deslauriers et al., 2011; Geng et al., 2022; Srinivasan et al., 2020), project-based learning (Guo et al., 2020), inquiry-based learning (Lewis & Lewis, 2005), problem-solving-based approach (Muhammad & Srinivasan, 2020), and co-operative and small-group learning (Buck & Wage, 2005; Wage et al., 2005). I adopted an active learning environment based on the principles of constructivist learning theory (Dunham et al., 2002; Jonassen, 1994; Srinivasan & Muhammad, 2020) because its facilitation of a hands-on mode of learning is consistent with the pedagogical priority of the school. In this pedagogy, during the problem-solving sessions, students collaborated with peers and consulted with me, and the classroom environment was set to help them reflect on their understanding of the concepts and their applications, generating a greater contextual understanding of the course content. Classroom participation and engagement in problem-solving sessions provided an enriching educational experience as students learned from their individual experiences as well as those of their peers, which helped them with the mental construction of concepts. The internal surveys with students and their performance in the course clearly indicated this to be a good education strategy.

Overall, the classroom proceedings were significantly changed. The classroom sessions focused more on theoretical formulations and solutions to expose students to the principles of FEA. To be successful in the course, students were now required to have a good understanding of the foundational concepts, be able to formulate and calculate problems using theoretical techniques, understand the calculations that a FEA software package such as Ansys performs, and design and solve problems using the software.

Labs continued to use Ansys but the complexity of lab problems was significantly raised. For example, in understanding thermal analysis, students were required to simulate the thermal analysis pertaining to the Columbia Space Shuttle disaster (see Figure 1). Other lab exercises included the design of aircraft panels, crash testing, and the evaluation of two designs of reinforced armour plates used in United States army humvees to withstand the detonation of improvised explosive devices. A total of seven to eight labs were included in the curriculum to train students in using FEA software (i.e., Ansys and Catia).

Figure 1. Heat transfer analysis of the Columbia Space Shuttle using Ansys

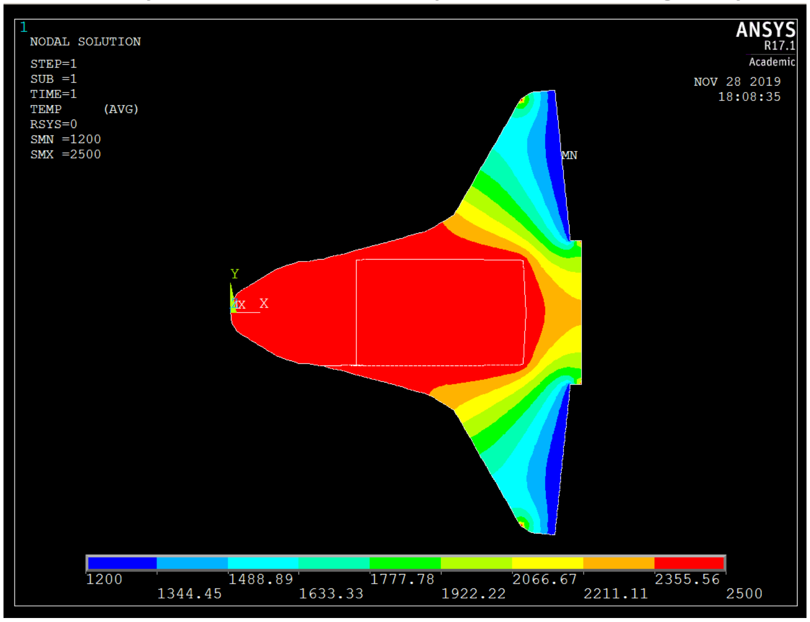

Figure generated by the author and taken from the course content. Figure demonstrates the use of Ansys software to teach thermal analysis. The distribution of the temperature in the body of the space shuttle is red, indicating a very high temperature. The wings are cooler indicated by yellow, green, and blue colours.

Assessments

As summarized in Table 2, students went through several assessments in the course, similar to the first phase. Students were not assessed on their ability to use the software. Instead, they were given only theoretical questions. They were typically asked to solve two or three FEA problems using theoretical technique and present a detailed theoretical and numerical solution of their analysis. The computer-based tests were typically 2 hours long, and the final exam was for a duration of 2.5 hours, also conducted in a computer lab.

Table 2. Assessments and corresponding weights for Phase 2: Engineering practice

COMPONENT	WEIGHT (%)
Labs	10
Term test 1	15
Term test 2	30
Final exam (comprehensive)	45

Reflection

When I took over the course in 2014, it was clear to me that I had to introduce sweeping changes to elevate it to the level of university education. In Phase 2, I introduced theoretical principles and asked students to do numerical calculations. These are far more challenging than simply learning to operate a software package. As a result, there was a stiff resistance from the students, especially because they were informed by their seniors that the course was much easier for them. I had very low teaching evaluations initially and, on one occasion, I had to submit a report to the dean's office explaining the evaluations and the plan to enhance student satisfaction. The program chair was supportive, though, and it took me nearly 3 years to overcome student resistance. I achieved this by doing the following: every year I would start the course with an opening remark, "This is not an Ansys/Catia training course. This is a course on finite element analysis, which is primarily a topic of mathematics." Throughout the term, I would also engage in discussions with students and give explanations on why learning the theory was important and how it would be useful for them in their careers. Nevertheless, I continued to have a couple of students who would feel that simply learning Ansys or Catia was good enough. Over the years, the sweeping changes in the rigour of the curriculum has helped me prepare students for the PEO subject exams. Unfortunately, students only realize the benefit of the curriculum after they graduate and are applying for this license. Their success in these exams would not have been possible with just the competencies delivered in Phase 1. The program chair continued to be appreciative of my efforts to raise the level of this course, and this served as a great impetus to continue with such reforms.

PHASE 3: HUMAN-CENTRIC ENGINEERS

Course objectives and design

The Phase 2 format of the course was very sound. Specifically, it offered a rigorous curriculum from the technical perspective, and the lab exercises on solving real-world problems imparted adequate training on popular industry software. These components set students up to succeed in an industrial setting as well as in graduate studies and PEO licensing exams. However, modern engineering is not just about design, calculations, and development; engineers are also required to consider complex social, human, and environmental issues along with technical ones. Today, at their workplace, an engineer is required to understand ethical problems, appreciate value conflicts, understand and empathize with different perspectives and constraints, identify relevant socio-technical systems, and eventually determine plans and actions based on consensus (Sidhu & Srinivasan, 2022). Thus, an ethical, human-centric engineer must have good critical-thinking and reasoning skills to play a constructive role in advancing society. These necessary attributes inspired me to integrate concepts of ethics, sustainability, and social responsibility into the course starting in 2018. While these additional aspects were added into the curriculum, I kept the technical curriculum as well as the assessment components identical to Phase 2.

While most educational institutions offer courses on ethics, sustainability, and social responsibility, these are often stand-alone courses without proper integration into technical courses (Li & Fu, 2012; Newberry, 2004). Following Bucciarelli's (2008) propositions, I opted to integrate these concepts into the course to effectively deliver these ancillary requirements within an engineering degree. A literature survey shows that engineering ethics can be taught through numerous approaches such as case studies, group discussions, presentations, codes of ethics, collaborative and challenge games and role-plays, videos and simulations, and debates (Hamad et al., 2013). I adopted the case-study approach in which scenarios were added as an extension of the existing lab exercises. This not only gives students an opportunity to engage in some thoughtful deliberations but is also a welcome variation from the routine of technical problem-solving.

For the ethics cases, hypothetical scenarios were created in which students had to arrive at a decision after making careful considerations and discussing with their peers. The group discussions during the class also provided an opportunity for them to understand alternative views and be well armed with facts and perspectives before arriving at a position. Two sample ethics questions are as follows:

> *Aircraft panel design:* How would you respond to the following scenario to design aircraft panels? Case A is an overall cheaper solution. In this case, in a discarded aircraft, 30% of the door panel material can be reused and the remaining 70% is waste that takes about 60 years to biodegrade. Case B is a 12% more expensive solution than Case A. In this case, in a discarded aircraft, 45% of the door panel material can be reused and the remaining 55% is waste that takes about 70 years to biodegrade. As a design engineer, which solution would you recommend to your manager and why?
>
> *Crash testing:* Assume that you are an engineer who is following Isaac Asimov's laws for designing self-driving vehicles. How would you program a situation where a car has to make a manoeuvre and has the following choices: (a) go straight but hit two children crossing the road (collision impact of approximately 30km/hr), (b) veer left and hit multiple pedestrians on a pavement (collision impact of approximately 25km/hr), or (c) veer right and crash right into a restaurant (collision impact of approximately 60km/hr). Justify your choice since, as the design engineer, you will have to defend the algorithm if such an incident ever occurs.

Following group discussions on the cases, students provided a commentary on the ethics questions in their lab reports.

The integration of the case studies focusing on concepts relating to ethics, sustainability, and social responsibility immensely helped the students evolve their moral imagination, as well as their reasoning and judgment skills (Sidhu & Srinivasan, 2022). Their enthusiasm and keen interest in improving this dimension of engineering was evident in the rich interactions that helped them hone their negotiation and public-speaking skills and ability to present evidence. Overall, students actively engaged with their peers, empathized with views and opinions, and ultimately reached a consensus on each of these open-ended problems. These observations point to the effectiveness of a constructivist setting that helps students develop better arguments and arrive at more informed conclusions and positions (Carew & Mitchell, 2008; Ferreira et al., 2006; Segalàs et al., 2010). They also affirm how ethics can be taught by letting students experience situations and interact with others to understand each other's views and opinions (Bauer & Adams, 2005; Stappenbelt, 2013; Steneck, 1999). It is safe to conclude that integrating the principles of ethics, sustainability, and social responsibility within the technical curriculum can help students understand the impact that an engineer can have on society and their responsibility to fulfill their professional duties. In summary, I am confident that with the addition of such case studies along with a well-established, rigorous curriculum, I am offering a very good all-round training to students.

By Fall 2021, I was able to move all Ansys labs to a self-tutored mode, promoting and transferring some responsibility of education to the students. The classroom lecturing is now kept to a minimum and students do a lot of self-learning. These changes have enabled the classroom environment to be more discussion based and the overall education process is an enjoyable experience in a course that is otherwise very challenging and one of the most difficult ones in the program. This positive learning environment is adequately reflected in my teaching evaluations.

Reflection

To the best of my knowledge, this is now a unique course in engineering that offers a variety of technical competencies and trains the students on engineering practice. Usually, FEA is taught as a purely technical subject. In fact, at McMaster, even in the Manufacturing Engineering Technology program at the W Booth School and in the Department of Mechanical Engineering, FEA is taught only from a technical perspective. Similarly, ethics is often taught as a separate course in most engineering curricula (Sidhu & Srinivasan, 2022).

While each course is unique, instructors planning drastic changes to their curriculum should consider involving student partnership. I believe that with the involvement of students in designing the curriculum, they will be able to better understand the need for such an evolution and feel comfortable with the changes. Further, evolutions emanating from such partnerships will be impactful and work better for our students. During the evolution in my course, I missed this immense opportunity, largely because I was unaware of the positive dividends of collaborative course development, and, as a result, faced stiff resistance from students in embracing change. Despite presenting a detailed justification with a thorough execution plan for their success with a revised curriculum, there was skepticism and a feeling that I was experimenting with their education.

STEPS FOR THE FUTURE

In its current format, the FEA course is very comprehensive. The rigorous curriculum offers a strong technical foundation, rich exposure to real-world engineering problems, and adequate training in topical software used in the industry and inculcates human-centric engineering principles by introducing case studies that require the consideration of ethics, sustainability, and social responsibility. However, there is still room for improvement, especially in the ethics portion.

The ethics case studies have thus far been largely on micro-ethics.[1] While they have increased awareness among students and nudged them to critically think about how engineering practices impact society, going forward, I would like to introduce explicit macro-ethics[2] cases with emphasis on environmental sustainability. Case studies could be introduced to debate and discuss policy decisions and present novel policy frameworks for key issues in their field. This will immensely help our students position themselves as human-centric engineers who not only have a sound understanding of the technical principles of the subject but are also conscious of how their engineering actions must be in harmony with environment and sustainable practices that will positively impact human life.

Finally, I believe that courses with such high standards can easily be cross-listed to enable students from other departments to take our courses and vice versa. This will strengthen the horizontal integration within the Faculty of Engineering between the Booth School and the other departments. Further, with such evolutions, the programs of the Booth School are continuously elevating themselves to higher standards, and this will ultimately enhance the school's reputation and contribute to furthering the brand of the Faculty of Engineering at McMaster.

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NOTES

1. Micro-ethics focuses on individual behaviour and decision-making in specific situations.
2. Macro-ethics focuses on large-scale issues, generally in relation to principles and rules to guide appropriate actions.

NOTE ON CONTRIBUTOR

Seshasai Srinivasan *is the chair of the Software Engineering Technology program at McMaster University's W Booth School of Engineering Practice and Technology. His pedagogical research interests include cognitive psychology in teaching and learning, active learning, problem-based learning, enhanced learning tools and methodologies, micro-instructors in social media, and curriculum development.*

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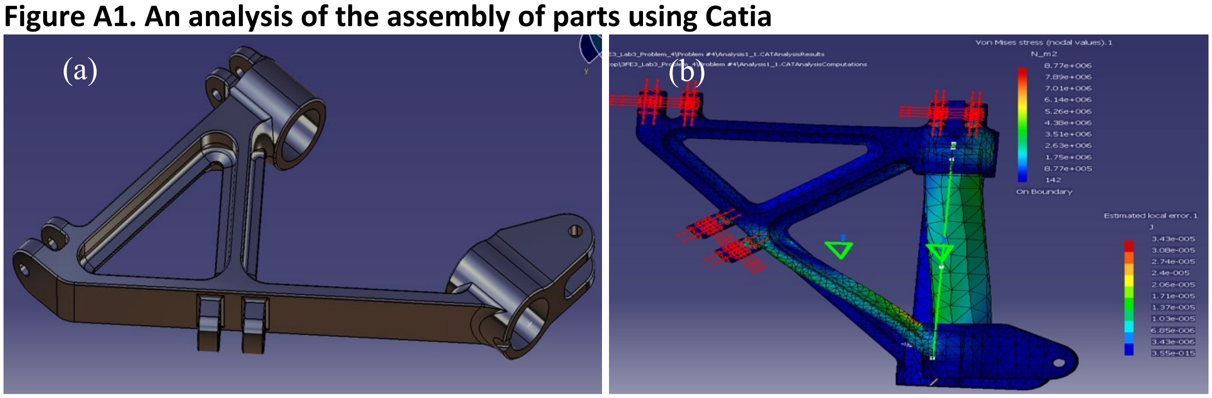
APPENDIX A

Catia analysis was taught in the first two labs of Phase 1 of the curriculum to train students to analyze an automotive part and an assembly of parts. The seven subsequent labs trained students on Ansys to analyze truss, beams, frames, heat transfer (1-D, 2-D, and 3-D), and solid mechanics (2-D and 3-D). 1-D refers to one dimension, 2-D is two dimensions, and 3-D is three dimensions. The heat can flow in one direction, i.e., along x axis (1-D), or two directions, i.e., along x and y axis (2-D) or in all three directions, i.e., along x, y, and z directions (3-D). Typical examples of Catia and Ansys analysis are shown in Figures A1 and A2, respectively.

Figure A1. An analysis of the assembly of parts using Catia



Figures generated by the author and taken from the course content. Figure (a) shows the part of a mechanical assembly drawn using the Catia software. Figure (b) shows the stress distribution of the part depicted in image (a) drawn using Catia software. Blue colour means low stress whereas red colour means a high stress.

Figure A2. 3-D heat transfer analysis of a part using Ansys

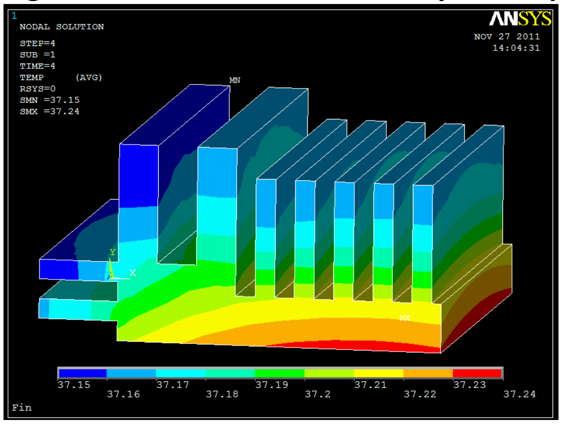


Figure generated by the author and taken from the course content. The figure shows the temperature distribution on a mechanical part drawn using Ansys software. Blue colour represents low temperature. Red colour represents high temperature.