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HOLISTIC SYNTHESIS OF THEORY AND PRACTICE IN CAE EDUCATION FOR ENGINEERS

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ABSTRACT

In recent years, the landscape of engineering and design education has witnessed substantial changes owing to the heightened utilization of Computer-Aided Engineering (CAE) tools. This shift has necessitated a further development in educational approaches, emphasizing the seamless integration of theoretical knowledge with the practical application of CAE tools. This trend is reflected in university curricula that aim to teach the use of CAE tools.

Crafting effective courses in this context is a multifaceted challenge, demanding the simultaneous delivery of theoretical foundations and the application of CAE tools to real-world problems. Notably, many courses tend to focus on a singular CAE tool, neglecting the diverse array available in the market. Recognizing this limitation, an innovative teaching concept was designed for a CAE course, with a specific emphasis on multibody simulation (MBS), at Graz University of Technology.

This paper provides an overview of the teaching concept's structure, resulting from insights collected from diverse CAE courses and the integration of various didactic measures and methods. The primary objective was to enhance the overall learning experience for students, ensuring adaptability and alignment with rigorous academic requirements.

The validation of the teaching concept is based on evaluation results, indicating increased satisfaction of students over the past years. Beyond the specific use case of the CAE courses, the transferability of the teaching concept to other disciplines that combine theoretical knowledge and practical software application is evident. In conclusion, continuous evaluation of the teaching concept and monitoring of students' learning progress remain essential for constant improvement.

Keywords: Teaching concept, MBS, machine dynamics, CAD, CAE, finite element analysis

1 INTRODUCTION

In recent years, the working environment for engineers has undergone a significant transformation, with traditional tools such as calculators, pens, and notebooks being replaced by computers equipped with advanced CAE tools [1], [2] [3] [4] [5]. This shift has impacted engineering education, leading to an increased focus on integrating courses that emphasize the practical application of CAE tools. In the 1960s, using CAE tools for finite element analysis (FEA) simulations in education was considered exceptional and confined to research applications. However, nowadays, it is firmly established and included in almost every curriculum at technical universities. [5]

The scenario differs when it comes to simulations in the field of machine dynamics. Even today, only a few universities have incorporated their application into their curricula [4].

The CAE course at Graz University of Technology strives to enhance traditional Finite Element Analysis (FEA) education in mechanical engineering by integrating Multibody Simulation (MBS). This integration is imperative, considering the increasing significance of MBS as a simulation methodology in contemporary engineering practices. This presents a challenge that extends beyond only imparting software usage: it requires establishing a connection between practical application and the underlying theoretical principles. In addition to fostering a thorough understanding, the course places special emphasis on imparting practical applicability and familiarity with various modelling approaches. An innovative approach has been developed to delve deeper into this aspect.

In contrast to many CAE courses that focus on a single tool, the TU Graz course adopts the use of three different CAE tools in the field of MBS. This approach intends not only to teach students the use of various software tools but also to cultivate an awareness of the diversity of modelling approaches in the MBS domain (see section 3.1 for details).

The objective is to make students more sensitized to selecting a suitable tool and its specific capabilities. This, in turn, equips them with the ability to differentiate variances in both structure and results when utilizing different CAE tools. From the authors' perspective, this is a crucial factor in today's era, where an increasing number of diverse CAE tools are available and some of them, according to the developer's descriptions, encompass the same range of functions and capabilities.

Drawing insights from other CAE courses and synthesizing various didactic measures and methods (*Figure **1***), an innovative teaching concept has been developed, combining all these aspects. This concept not only aligns with the content requirements but also considers the students' needs. Adjustments have been made to optimize the course for the students and thus improve their learning success, which is monitored via annual evaluations.

2 STATE OF THE ART – DIFFERENT CONCEPTS OF CAE COURSES

The following chapter presents the current situation at other universities, outlining the approach in CAE education and introducing various didactic measures and methods. The design of courses focusing on the use of CAE tools can vary in terms of the scope of teaching materials, as well as didactic measures and methods employed. In the selection of literature, courses were chosen which use several cad tools or also deal with multi-body simulation.

Cavacece, Pennestrì, and Sinatra discuss an approach from the early 2000s in [4]. In this case, multibody simulations and numerical methods were conveyed through traditional lectures. Due to licensing costs and limited resources at the time, practical sessions were not feasible, restricting the application of simulations to homework assignments.

[5] present an educational concept that integrates multibody simulation within a project-based learning approach. This approach strongly emphasizes practical implementation and application but requires a foundation in theoretical knowledge.

In addition to separate presentations of theory and practical implementation, as seen in the previous examples, there are concepts that propose a combination of both. Examples include [1], [6] and [7]. These concepts commence with traditional lectures to impart theoretical fundamentals, succeeded by a practical section where students acquaint themselves with the simulation software.

Beyond the shared structure of theory input and practical application, [1], [6] and [8] present the combination of various teaching methods. Common learning approaches include project-based learning and group work. An observable trend is shifting away from a rigid separation between theory and practice to a more integrated approach, placing particular emphasis on project-based learning concepts that foster experimentation and exploration. [5] and [9] demonstrate that engineering students, in particular, benefit significantly from receiving educational content through different learning layers, adhering to the motto: "Tell me, and I forget; teach me, and I remember; involve me, and I learn" [10]. [4], [10] and [8] emphasize that, in addition to using simulation programs/CAE tools, group work and project-based learning serve to critically discuss modeling approaches and evaluate results. Learning how to effectively model these systems and analyse results correctly is an objective that cannot be achieved with traditional instruction alone [5].

3 TEACHING CONCEPT

In this chapter, the CAE teaching concept of the Institute Logistics Engineering from Graz University of Technology is presented. The structure of the course was derived from insights gained from the state-of-the-art section and the combination of various didactic measures and methods. After the concept was developed, industrial partners were involved. This involved identifying the skills that industrial partners expect from graduates in this field. Accordingly, the content was shaped to meet these requirements, aiming to enable students to independently develop solutions for given problems and interpret the results accordingly. This emphasis is particularly evident in Section 3.5 Exams, where the focus is placed, and the performance assessment is adjusted accordingly. Figure 1 attempts to clearly show the various components of the course.

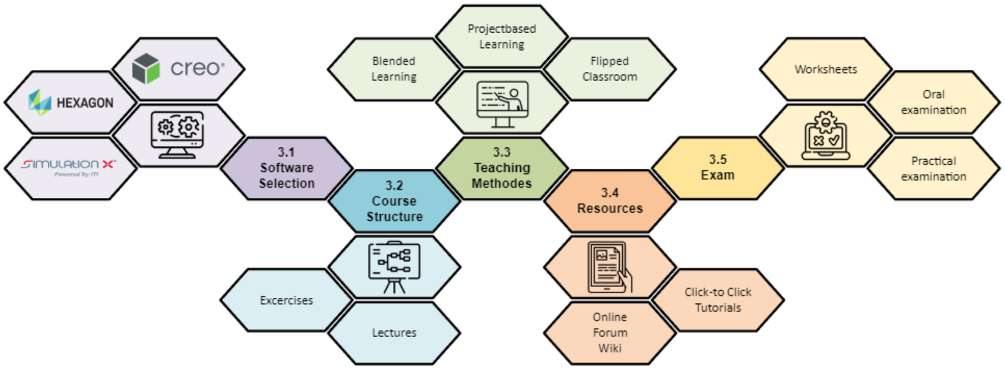

Figure 1. Structure of the CAE Teaching Concept

3.1 Software Selection

An innovative approach pursued by the authors is not only to use a single simulation software for teaching MBS but to incorporate three different software solutions. This approach aims to convey to students that not every problem is solvable with any software and that different levels of abstraction are required. It also illustrates that both the model development and the quality of results can vary significantly.

The first software solution[1] is Creo by PTC, serving as a comprehensive software that provides not only an MBS environment (Creo Simulate), but also features for FEA and geometry generation (Creo Parametrics). This kind of software suite can accompany almost the complete design process. The implemented multidirectional associativity allows the user to always edit the same model, regardless of the program component in which the changes are made. This means that changes made to the geometry of a component are also applied directly to the MBS model, which can help to reduce development time. But this advantages also entail drawbacks: the multi-body simulation (MBS) capabilities are reduced in comparison to dedicated MBS tools like Hexagon Adams. For instance, as outlined in the product descriptions, both tools support the utilization of 3D contacts[2], but MBS in PTC Simulate is only capable of mapping a 3D contact between special geometry pairs.

The second software is SimulationX by ITI Software, functioning as MBS software that enables simulations at various levels of abstraction. Mechanical models can be abstracted using simplified signal flow-oriented modelling up to physically object-oriented modelling. A notable aspect of this simulation software is the multiphysics approach, allowing the expansion of mechanical models into different domains such as electrical engineering, hydraulics, or pneumatics, thereby enabling the representation of interactions within entire systems and control loops. Even though this tool has extensive capabilities for mapping three-dimensional multi-body systems, there are no options for mapping a 3D contact, to stay with the example of the 3D contact.

The third software, Adams by Hexagon, positions itself as a high-end MBS software. For example, Hexagon Adams offers the most advanced implementation of a 3D contact and the ability to create sub models automatically. In addition to these functionalities, this software offers a wide range of options for intervening in the solving process of the multibody system, from the selection and configuration of the solver used to deep interventions in the solving process itself, which make it possible to change the behaviour of the model during the calculation or to reduce the calculation time by selectively deactivating irrelevant constraints. While the modelling and solving capabilities of MBS systems exhibit notable strengths, the MBS software suffers drawbacks in other areas. In Hexagon Adams, the functionalities for geometry generation are limited, adopting a basic approach. This constraint is offset to a certain amount by the system's ability to import a diverse array of supported geometry formats but also shows room for improvement.

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[1] The program components listed only include those that are necessary for the CAE course. PTC Creo, ESI SimulationX and Hexagon Adams also include other program components, but these are not relevant here.

[2] A 3D contact is a kinetic constraint that is only activated when a geometry collision occurs between two components. If a geometry collision is detected, the reaction force is calculated using a non-linear spring-damper system and friction.

The information presented in this section is not intended to pass judgment or endorse any specific software. Its purpose is to highlight the distinctions among them, which may not always be immediately apparent, and thereby raise students' awareness. This awareness is crucial not only in the decision-making process when choosing among these three tools but also in a more holistic context to assist students in selecting a suitable CAE tool for a specific simulation task in general.

3.2 Course Structure

The course structure unfolds in three distinct blocks, each focused on a particular simulation software. To set the stage for the entire course, an initial theoretical session provides a comprehensive overview of MBS modelling. This session delves into the foundational concepts and principles applicable to MBS. Following this general theoretical session, the course progresses into software-specific theory sessions tailored for each simulation software. These sessions are meticulously designed to highlight the unique features, capabilities, and methodologies associated with modelling in the respective software platforms. Emphasis is placed on elucidating the fundamental distinctions between the software options, ensuring students develop a nuanced understanding of the intricacies involved.

3.3 Teaching Method

The pedagogical framework of the CAE course's teaching concept is woven around the principles of blended learning, aiming to synergize the advantages of both online and in-person instructional methods. Central to this approach is the simultaneous recording and transmission of lectures, providing students the flexibility to engage with course content both remotely and in traditional classroom settings.

A wealth of instructional videos complements the theoretical aspects, which have been adapted to the lecture content, meticulously guiding students through the intricacies of practical exercises. These videos, offering detailed insights into the usage processes of the tools, serve as valuable resources for independent learning. To foster a dynamic learning environment and ensure personalized support, weekly open tutorial sessions are conducted, allowing direct interaction between students and instructors.

Within these tutorial sessions, a flipped classroom methodology is employed to deliver course content. Students independently engage with learning materials, including worksheets and videos, prior to the tutorial sessions. During these interactive sessions, the instructors provide in-depth explanations, clarify doubts, and facilitate discussions, promoting a deeper understanding of the subject matter.

3.4 Resources

This section introduces an array of resources and tools meticulously developed to enhance the learning experience for students. The strategic development of these tools was a central focus in shaping the teaching concept, considering that the CAE course attracts students from diverse backgrounds, including mechanical engineering and biomedical engineering[3]. The inherent challenge is to bridge the gap in prior knowledge among students, fostering a shared understanding that accommodates the diversity of their academic backgrounds.

All foundational theory lectures on essential topics are recorded and made readily accessible to students. Complementing these lectures, a series of video tutorials is provided, addressing problem scenarios to those encountered in the worksheets. These video resources serve as valuable supplements to support self-study initiatives.

Beyond videos, practice examples are presented wherein complete solutions are withheld, offering hints and results instead. This intentional approach encourages students to independently review and refine their problem-solving skills. Furthermore, detailed click-to-click guides are available to elucidate the operational intricacies of each software, providing step-by-step instructions for efficient software utilization.

To foster meaningful interaction among students and between students and instructors, a dedicated online forum has been established. This platform serves as a hub for addressing and discussing queries.

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[3] The Program in Biomedical Engineering provides a comprehensive foundational education encompassing technology, medicine, and the natural sciences. This program's uniqueness lies in the combination of engineering and natural sciences, a fundamental understanding of biology and medicine, and essential computer science principles. The curriculum also covers an introduction to safety aspects and necessary regulations in the field of medical technology. Details can be found under the following URL: https://www.tugraz.at/en/studying-and-teaching/degree-and-certificate-programmes/bachelors-degree-programmes/biomedical-engineering

Additionally, a weekly Q&A session is conducted, offering a direct opportunity to collaboratively tackle specific problem scenarios. As an extra resource, a comprehensive wiki has been curated, documenting problem scenarios from previous years. This serves as an initial reference point, capturing recurring issues and their solutions.

3.5 Exam

The assessment framework for this course is structured into three pivotal domains, providing a comprehensive evaluation of students' capabilities. Firstly, the semester is punctuated with seven worksheets, strategically spaced throughout the term, each subject to independent assessment. These worksheets present students with small projects[4] aligned with specific focal points, deliberately designed to be open-ended. The intentional flexibility of these assignments aims to stimulate creativity and hone problem-solving skills, fostering a dynamic learning environment. Emphasis is placed not only on the solution but also on the interpretation of results, as this is deemed a significant key competency, alongside proficiency in software modelling and operation.

In the culmination of the semester, a practical examination unfolds, challenging students to solve specific problems in a real-time, on-site setting. Tasks include, for example, the analysis of the driving dynamics of a car axle or the vibration behaviour of an overhead crane. The application example and the desired output variables are provided. The modelling must be chosen accordingly by the students to derive the required results from the modelling. Following the practical examination, a structured oral examination is conducted, delving into students' comprehension of the underlying theoretical principles and their adeptness in tackling practical tasks. There are questions regarding the modelling, and students must justify how they arrived at their choices. Subsequently, the interpretation of the results is also examined. It is not sufficient to only generate results; an important aspect of the examination is also the interpretation of these results. This oral assessment component completes the evaluation cycle, providing a well-rounded measure of both practical skills and theoretical understanding.

By incorporating diverse assessment methods, ranging from open-ended projects to on-site problem-solving and theoretical comprehension checks, the evaluation process ensures a nuanced and thorough understanding of each student's proficiency. Ultimately, this multifaceted approach aims to foster a well-rounded set of skills and knowledge, preparing students for the challenges and demands of real-world applications in the field of computer-aided engineering.

4 RESULTS AND CONCLUSION

The CAE teaching concept, introduced and implemented at Graz University of Technology, has undergone significant success in recent years. The thoughtfully designed resources and teaching format have demonstrated their efficacy, successfully bridging the knowledge gap for students with diverse backgrounds, bringing them to a common and proficient level.

Recent evaluation[5] results over the past six years bear testament to the positive impact of the program. Approximately 60% out of 153 students expressed a very high level of satisfaction with the course, indicating the effectiveness of the teaching methodologies and the overall learning experience. Moreover, a substantial 75% of these students found the workload to be reasonable, suggesting a well-balanced and manageable academic environment that accommodates the varied needs of the student body. This evaluation is based on qualitative factors and reflects student satisfaction. Quantitative factors such as grades are not considered, as they cannot be used as indicators of good teaching quality. The noteworthy achievement of the CAE teaching concept is further underscored by its nomination for the “Prize for Excellence in Teaching”[6] in 2021. This recognition not only confirms the positive feedback from students, but the learning concept is also examined and assessed by external experts. The nomination is proof of the commitment and innovation of the teaching approach.

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[4] The projects in the worksheets, for example, address the modeling and analysis of the dynamic behavior of a single-cylinder engine under given operating conditions or the vibration analysis of drive shafts.

[5] Cumulative result of the course evaluations provided at TU Graz, carried out electronically, by the CAMPUSonline system. Details can be found under the following URL: https://mibla-archiv.tugraz.at/09_10/Stk_1/Lehrveranstaltungs_Evaluierung.pdf

[6] The "Prize for Excellence in Teaching" is an award recognizing outstanding teaching at Graz University of Technology, with nominations being made by the students themselves. Details can be found under the following URL: https://tu4u.tugraz.at/en/students/our-tu-graz/teaching/prize-for-excellence-in-teaching

On a technical level, students have demonstrated through the completion of worksheets and exams that they possess the necessary knowledge and skills in handling CAE tools upon completion of the course. It is particularly encouraging that many students, after completing the course, go on to write bachelor's and master's theses in relevant areas at the Institute of Logistics Engineering by using CAE. This suggests that the course has inspired students for these topics.

Another significant point is that students, after the course, are capable of navigating in three different simulation domains. It is noteworthy that earning the title of an expert in using a specific software would require years of practical experience. Therefore, the authors consider it more beneficial to develop a broad understanding of the world of simulation programs rather than limiting oneself to a single software.

In conclusion, this teaching concept can serve as a template for various instructional formats that require the integration of theoretical knowledge with the practical application of simulation programs. The diversity of tools employed, along with the approach of providing different strategies through various software solutions, can serve as inspiring models for future teaching concepts.

Despite the success of the teaching concept, there was a fluctuation in the evaluation results after the year 2021. This is attributed to the fact that, following the COVID-19 years, fewer Q&A sessions were offered, and students expressed a desire for more support. This feedback needs to be incorporated into a continuous improvement process. Alongside student feedback, this optimization process should consistently align with the current suggestions and needs of students while reflecting the technological state of the art. The integration of modern teaching and learning methods, as well as the regular update of course content in accordance with the latest developments in CAE technology, is essential. Through surveys, evaluations, and close collaboration with students and subject matter experts, successful evolution and adaptation of the teaching concept can be ensured.

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REFERENCES

[1] Tang C. P., Xue Z. and Wang Y. *Innovative Approaches and Lesson Learned in Teaching CAD/CAE Applications Course*, 2010.

[2] Chunxia Z., Tiying W. and Mingwei X. The Application of CAD/CAE Technology in the Teaching of vehicle Engineering Specialty. *J. Phys.: Conf. Ser.*, vol. 1345, no. 2, p. 22046, 2019, doi: 10.1088/1742-6596/1345/2/022046.

[3] Sirotenko A. N. and Partko S. A. CAD/CAE/CAM when teaching the discipline “Fundamentals of machine design”. *J. Phys.: Conf. Ser.*, vol. 1691, no. 1, p. 12026, 2020, doi: 10.1088/1742-6596/1691/1/012026.

[4] Vita L. and Pennestri E. *Multibody dynamics in advanced education*, 2002.

[5] Lipinski K., Docquier N., Samin J. C. and Fisette P. Mechanical engineering education via projects in multibody dynamics. *Comp Applic in Engineering*, vol. 20, no. 3, pp. 529–539, 2012, doi: 10.1002/cae.20421.

[6] Ru-xiong L. and Jiaov S. Teaching Technique Innovation on CAD/CAM/CAE of Mold Course. *IERI Procedia*, vol. 2, pp. 137–141, 2012, doi: 10.1016/j.ieri.2012.06.064.

[7] Kuna P., Hašková A., Palaj M., Skačan M. and Záhorec J. How to Teach CAD/CAE Systems, *Int. J. Eng. Ped.*, vol. 8, no. 1, p. 148, 2018, doi: 10.3991/ijep.v8i1.8185.

[8] Fernandes F. A. O., Fuchter N. Júnior, Daleffe A., Fritzen D. and Alves de Sousa R. J. Integrating CAD/CAE/CAM in Engineering Curricula: A Project-Based Learning Approach. *Education Sciences*, vol. 10, no. 5, p. 125, 2020, doi: 10.3390/educsci10050125.

[9] Kröpfl P. R., Kröpfl P., Probst A. and Landschützer C. Integration of simulation into product development at Austrian secondary and tertiary technical education. doi: 10.35199/EPDE.2023.5.

[10] Abdullah Umair Bajwa, Ed., *Closed-loop mechanical engineering design teaching to electrical and computer engineering students using CAD, CAE and 3D printing*, American Society for Engineering Education, 2023.