

SIMULATION WITH OR WITHOUT DEPTH? DIDACTIC OPPORTUNITIES AND BOUNDARIES OF FEA USE IN EARLY ENGINEERING EDUCATION

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ABSTRACT

The use of Finite Element Analysis (FEA) has long been established as a core component of engineering education. Due to the increasing availability of CAD-embedded workflows, FEA is now accessible at a significantly lower threshold, leading to its growing application even in early stages of training, often without the methodological depth required for robust dimensioning or optimisation and validation. At the same time, FEA offers high didactic potential: the visualisation of abstract quantities such as deformation, stress, or load paths on 3D models can make theoretical content more tangible and support diverse learning approaches.

This paper investigates the purposeful use of FEA in early phases of engineering education, with a focus on diversity-sensitive learning through visualisation. A survey conducted among teachers at Austrian HTLs (secondary higher vocational schools) serves as a case study to assess the current state of practice. The aim is to derive action-oriented guidelines for the responsible implementation of FEA in teaching: when does FEA provide value as a tool for visualisation and conceptual understanding, where are its limits in terms of informative validity, and how can it contribute to inclusive didactic strategies?

Findings suggest that FEA should primarily be used as a tool for visualisation and conceptual understanding in early training phases. Validation-focused simulations (e.g., for dimensioning or optimisation) are better suited to advanced stages. Furthermore, the diversity-sensitive added value of visualisation, as a bridge between various learning paths, is elaborated and illustrated through concrete examples.

Keywords: Simulation-based learning, Finite Element Analysis (FEA), Engineering education, Didactic approaches, Intuitive usability

1 INTRODUCTION

Since the proliferation of 3D modelling in the 1980s and its continuous integration from the mid-1990s onward, digital product models have become the foundation for downstream CAx applications and thus for modern virtual product development. Around 2005, CAD-embedded FEA marked a key milestone by making simulations more accessible. [1] This transition broadened access to what was previously the domain of experts. Today, users are often only a few clicks away from color-coded simulation results. [2]

While this low-threshold accessibility presents opportunities, it also carries risks. Robust simulation results are not solely a product of software workflow completion. They require thoughtful modelling decisions, plausibility checks, validation, and the ability to correctly interpret outcomes in an engineering context. [3, 4] Nevertheless, the visualisation potential of FEA provides significant didactic value: displacements, stresses, or load paths¹ can be vividly presented on a 3D model, rendering abstract content more accessible and addressing diverse learning needs. [2, 3, 5–7]

This paper examines how FEA can be used responsibly in early engineering education and translates these insights into practical guidance: when does FEA add value as a visual-cognitive scaffold, where

¹ This paper focuses on structural mechanical investigations using FEA. Other application domains such as heat conduction and heat transfer, acoustics, and vibration analysis are not explicitly addressed or discussed, in order to maintain a clear scope and focus.

do its limits lie, and which didactic contributions can realistically be expected? A survey of teachers at Austrian HTLs² serves as a case study of current practice. Drawing on these findings, we propose a three-level model that differentiates visualisation-oriented use from validation-capable analysis and outlines appropriate framing for each. In this paper, diversity is operationalised as heterogeneity in learners' prior knowledge, mathematical confidence, spatial reasoning, and preferred problem-solving styles, and is used primarily as an interpretive lens for discussing how FEA-based visualisations may scaffold learning through accessible representations.

In addition, the scope of this paper is limited to the didactic use of structural-mechanical FEA for depicting and discussing resulting mechanical loading. It does not address stress assessment for safe design, nor does it cover lifetime or fatigue calculations; thus, the presented use cases focus on visualisation and conceptual interpretation rather than design verification or safety-relevant dimensioning. Furthermore, the paper does not explicitly investigate gamification or exploration-oriented engineering learning techniques in conjunction with simulation tools; however, such approaches appear promising and constitute a worthwhile direction for future research and development.

2 STATE OF THE ART

The literature on teaching FEA in structural mechanics consistently highlights a tension between rapid, low-threshold tool access and the methodological depth needed for trustworthy engineering decisions [2, 9]. Multiple authors report that students can quickly generate persuasive contour plots, yet this accessibility may foster overconfidence when modelling assumptions and boundary conditions remain implicit [2, 10]. Learning gains are described as strongest when simulation is embedded in a triangulation of hand calculations, FEA, and structured reflection on deviations, thereby making assumptions and limitations explicit [11]. Likewise, project- and problem-based formats are effective primarily when tasks require justification of modelling choices, comparison of solution paths, and documented plausibility/verification checks rather than mere workflow completion [4]. Interactive and visualisation-centred approaches can strengthen conceptual understanding of deformation and stress patterns and draw attention toward interpretation [6, 12], but authors emphasise that visualisation alone does not establish verification-oriented practice. Accordingly, several contributions stress the need to cultivate engineering judgement, recognising non-physical constraints, interpreting stress concentrations/singularities, and performing mesh- and sensitivity-related checks [2, 9]. Course assessment and design-project integration studies further show that competence gaps persist unless verification and interpretation are explicitly required in assessment and reporting [13, 14]. Curriculum-reform work therefore argues for coherent task chains linking structural testing/physics concepts and interpretation, supporting staged competence development rather than one-shot software training [15].

2.1 Methodological Depth as a Prerequisite for Reliable Simulation

As shown in [3], in FEA teaching and application, two fundamental approaches can be distinguished:

- The pragmatic approach is oriented toward the software workflow and primarily communicates the process steps leading to a result. Methodological background knowledge is often assumed or addressed only selectively. Competence is therefore frequently equated with tool proficiency and functional scope.
- In contrast, the theory-oriented approach emphasises FE model theory, including integration methods and solver know-how, element selection, discretisation, and abstraction of real load cases. However, in many curricula, the connection between these theoretical foundations and concrete software implementation remains abstract. [2, 4]

While both approaches serve legitimate objectives, they yield different types of results: the pragmatic approach allows for quick visualisations and preliminary insights, whereas engineering-reliable simulations require deeper methodological understanding. This distinction is critical: limited

² An Austrian HTL is a federally regulated vocational secondary school that provides a five-year, job-oriented engineering education combining general education, theoretical instruction, and extensive practical training. HTLs aim to equip students aged roughly 14-19 with solid technical, methodological, and entrepreneurial competencies, preparing them both for immediate professional practice and for further tertiary studies. Graduates complete A-level examinations and their qualification is classified as short-cycle tertiary education (ISCED level 5), with strong alignment to industrial practice through industry-experienced teaching staff. [8].

methodological depth can serve a didactic purpose through visualisation but must not be mistaken for reliable evidence in validation, sizing, or optimisation contexts.

2.2 Learning Diversity

In early training phases, the heterogeneity of learners is typically high. Students vary in terms of prior knowledge, mathematical confidence, spatial reasoning, and preferred problem-solving styles (e.g., exploratory vs. analytical). [16, 17] Visualisations can act as didactic bridges in such settings by reducing the cognitive effort required to translate between formal description and intuitive meaning, supporting causal reasoning and system structuring [18].

For simulation use in education, several key aspects emerge:

- Multiple learning styles can be addressed simultaneously (visual, exploratory, analytical).
- Varied levels of prior knowledge and tool proficiency, both among learners and instructors.
- Simulation as an opportunity to enable differentiated learning paths, where not all students need to reach the same depth; what matters is a transparent framing of the simulation's informative value.

3 RESEARCH DESIGN: SURVEY CONTENT AND EMPIRICAL INSIGHTS

A prior study [3] discussed the tension between low-threshold, tool-driven simulation and methodologically grounded FEA in engineering education. The present paper focuses explicitly on early education phases. Rather than comprehensive instruction in validation-capable FEA, the focus lies on how FEA can be employed meaningfully for educational purposes while ensuring clarity about its limitations. The core hypothesis is that applying and visualising theoretical content via FEA can support comprehension of mechanical principles. In the context of the present study, this assumption is examined primarily through teacher-reported practice and perceived didactic value.

To ground the discussion empirically, a targeted survey was conducted among teachers at Austrian HTLs (Section 3.1). The goal was to assess the current state of FEA integration in teaching and to collect practical insights that inform the action guidelines developed in Section 4.

3.1 Survey Objective and Study Design

The study was carried out as an online survey during a Ministry-organised teacher training program for CAD/FEA teachers at HTLs. A total of 52 participants responded ($n = 52$). The questionnaire included closed questions for quantitative data and open questions to capture experiences, motivations, and perceived limitations. Results were analysed using descriptive statistics and thematic categorisation.

The survey³ addressed the following topics:

- Frequency of use, as well as year levels and subjects where FEA is implemented
- Tools used, including CAD-embedded vs. standalone FEA software
- Objectives of use, distinguishing between visualisation/understanding and analysis/optimisation
- Barriers and support needs for teachers

3.2 Key Findings

FEA is already widely applied among the surveyed teachers despite not being explicitly anchored in curricula: 96% of respondents reported using FEA in teaching, indicating that adoption is largely driven by individual initiative. The degree of integration varies considerably, ranging from sporadic use to consistent application, and is most commonly concentrated in senior year levels. The dominant instructional purpose is visualisation to support understanding of theoretical concepts; teachers mainly use simulation to make mechanical phenomena visible and to foster conceptual learning, for instance by illustrating stress distributions, deformation under load, modal shapes, and natural frequencies. In contrast, using FEA for reliable calculation, sizing, or optimisation plays only a minor role in regular instruction and is typically limited to diploma projects or particularly engaged students with close teacher support. Regarding the tool landscape, CAD-embedded FEA clearly constitutes the primary entry point and is widely used in classrooms: integrated modules are frequently mentioned, and their ease of access and low-threshold workflows appear to facilitate broad uptake, whereas standalone tools are used less often and by a smaller subset of teachers. Reported barriers are dominated by time pressure and curriculum constraints; additionally, respondents highlight challenges related to methodological

³ The entire survey, including the evaluation, can be found at TU Graz Repository: <https://doi.org/10.3217/cs5pp-x4y71>

depth, including insufficient foundational knowledge among both students and teachers. At the same time, there is strong demand for support: more than 80% expressed interest in further training, and 84% explicitly requested supporting materials.

3.3 Summary of Survey Results

FEA is already established in school practice, primarily as a visualisation and understanding tool. Time and curricular constraints, as well as a lack of methodological depth, are cited as key limitations. The strong demand for professional development and teaching resources suggests that while educators recognise the value of FEA, they require guidance and frameworks for responsible use. These insights inform the staged implementation model and recommendations presented in Section 4.

4 RECOMMENDATIONS AND OUTCOMES

4.1 Use-Depth Relation of FEA in Early Engineering Education

A tiered model for FEA use in education, inspired by the approaches of VDI 2211⁴ and illustrated in Figure 1, can be derived, distinguishing three levels of application based on the required technical depth:

- **Level A** refers to established FEA for robust engineering analysis (e.g., verification, design, optimisation). This requires high methodological expertise, including model formulation, numerical effects, and result validation. Such competencies are typically developed in advanced or university-level education.
- **Level B** represents a transitional level, typically encountered in student projects or thesis work, but only under clear teacher guidance and explicit instruction. Results must be discussed jointly as assumption-dependent and highly sensitive to modelling choices (e.g., loads, boundary conditions, contacts, mesh). Outputs therefore require close supervision and should be interpreted using structured reflection prompts.
- **Level C** focuses on FEA as a tool for visualisation and conceptual understanding. The emphasis is not on numerical accuracy, but on making mechanical behaviour tangible. Didactic benefits can be achieved even with minimal methodological depth.

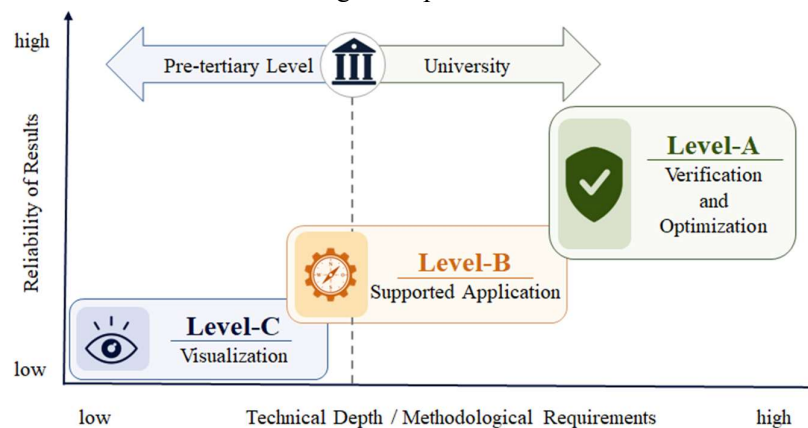


Figure 1. Three-level model for the responsible use of FEA in engineering education

4.2 Diversity Perspective: Why Visualisation Can Function as a Didactic Lever

Visualisation contributes didactically through three core mechanisms:

- **Conceptualisation and localisation:** Abstract quantities are linked to physical locations on components, aiding term formation and interpretation. Students annotate hotspots and link them to bending moment distribution.
- **Bridge between formalism and intuition:** Visualisation facilitates translation between formal input (e.g., equations, loads, boundaries) and physical meaning, lowering cognitive barriers. Given a hand calculation, students predict the deformation pattern before running the simulation.

⁴ Following the ABC concept of VDI 2211, calculation and evaluation methods can be organised into three levels (C-B-A) that trade rapid availability against statement quality, ranging from quick common-method decision aids (C) to specialist, high-effort analyses used when high certainty is required (A). [19].

- Exploration and comparison: CAD-embedded environments allow rapid variation of parameters, enabling cause-effect relationships to be discussed via contrasts ("if-then"). One-parameter sweep: students explain/predict trends.

Figure 2 illustrates this through the comparison of an analytical model and an FEA result.⁵ Visualisation is not a replacement for theory, but a didactic bridge that enables structured interpretation (load-boundary-response) and pattern recognition (e.g., symmetry, hotspots, edge effects). Dynamic visualisations (e.g., animation) further enhance conceptual clarity.

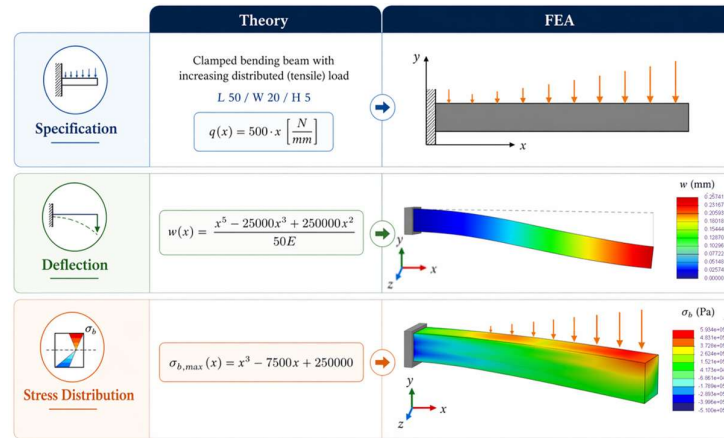


Figure 2. Application examples illustrating the use of FEA as a didactic tool for visualisation and conceptual understanding

4.3 Limitations

The empirical findings are based on a case study with HTL instructors in an FEA-relevant context. Accordingly, the very high reported adoption rate (96%) may be specific to this setting and may not generalise to other subjects, school types, or education levels. In addition, diversity is used as an interpretive framework for discussing heterogeneity in learners and teaching practices, but no direct learner data were collected (e.g., learning outcomes, self-efficacy, subgroup comparisons), which limits empirical claims about diversity-related effects.

A further limitation concerns stress interpretation and comparability across instructional approaches: in FEA, stresses are represented as local, element-based quantities that can exhibit peaks (e.g., at singularities or strong gradients), whereas school-level mechanics often relies on simplified or nominal stress measures derived from idealised assumptions. Without sufficient theoretical grounding and explicit instructional framing, particularly in more pragmatic/visualisation-oriented uses, this mismatch can encourage misinterpretation (e.g., treating local peaks as directly comparable to simplified metrics).

5 CONCLUSION AND FUTURE WORK

This paper addresses the central tension between "click-based simulation" and "simulation with depth". FEA is already widely used in HTLs, mainly as a tool for visualisation and understanding. Especially in early education stages, its value lies in rendering abstract phenomena tangible and providing visual entry points for diverse learners.

The proposed three-level model provides a practical framework for balancing benefit and limitation while preventing misinterpretation. As a next step, the educational impact of visualisation-based FEA use should be quantitatively assessed, e.g., through pre/post testing or controlled comparisons of learning outcomes. Additionally, the development of standardised teaching materials and professional development offerings is planned.

⁵ A further limitation concerns the comparability of stress results: in FEA software, stresses are computed as local, element-based quantities derived from the underlying continuum model. In contrast, classical mechanics teaching typically derives stresses from simplified nominal stress concepts. If this conceptual difference is not made explicit, FEA plots may be misread as directly comparable to analytical nominal stresses.

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