Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
ASEE
Paper ID #47587

Simulation across the Mechanical Engineering Curriculum

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Simulation across the Mechanical Engineering Curriculum

Abstract
The increasing complexity of technical challenges and the growing power of computers have made computer simulation central to engineering practice. This literature review shows how simulation has been used across the curriculum: in introductory design, engineering science, detailed design, simulation methods, and capstone design. Here, we discuss finite element analysis (FEA), computational fluid dynamics, multibody dynamics, systems modeling, electric circuits, and power transmissions. The literature has more examples of FEA being used across the curriculum than the other simulation methods so we focus on FEA. A given simulation package may only be covered within a single course, typically at the upper level and after the underlying mathematics and engineering science are covered. However, simulation does not need to be so confined. In particular, FEA has enabled introductory design experiences, revealed solid mechanics concepts, and empowered students to analyze complex parts in machine design. Although FEA is often used in capstone, there is little evidence to show that students use it proficiently, while anecdotes raise concerns that students are unprepared to use simulation reliably in authentic contexts. Several themes emerge from these examples of weaving simulation through the curriculum. Simulation tools are used in education in two ways: learning to perform simulations and using simulation to learn other engineering skills. Continued improvement in engineering education should use both approaches, which are complementary. Students can use simulation early in the curriculum if they are led to focus on a narrow modeling goal (such as analysis of trusses or flow in channels) and are offered templates and detailed tutorials. When simulation is used to introduce new engineering science concepts, similar scaffolding is needed to keep the focus on the course content. Engineering science courses are also a key opportunity for students to learn to validate models. Students tend to pick up software best from following tutorials; thus, class time should focus not on showing how to use the software but on things like how to formulate problems, interpret results, and use those results to deepen understanding of physical phenomena. By using these strategies, simulation can be used in every engineering course, deepening theoretical understanding and preparing students to use simulation as they begin their careers.

Introduction
This paper reviews the use of engineering simulation software across the mechanical engineering (ME) curriculum, focusing on the undergraduate level. We searched the literature for creative uses of simulation in engineering education by querying Google Scholar and the ASEE PEER archives with keywords such as “finite element analysis” or “Ansys” plus “engineering education.” We also checked the papers that those papers cited or were cited by. Most of the accounts we found were in ASEE conference proceedings. The literature has more examples of FEA being used across the ME curriculum than any other type of simulation method; also, because FEA can easily be misused, there are several papers specifically on teaching students to avoid FEA modeling errors. As a result, this paper puts disproportionate weight on FEA and offers a survey on other methods. The following sections each address different modeling domains, namely finite element analysis (FEA), computational fluid dynamics (CFD), multibody dynamics (MBD), system dynamics, electric circuits, and power transmissions. Subsequent

sections discuss the literature for various modeling domains; the rest of this Introduction gives a general overview of issues that apply to any educational use of engineering simulation.

Simulation tools have revolutionized engineering practice. By offering greater detail than is possible with hand calculations, and with less cost than prototyping and testing, simulation enables faster product development and more comprehensive exploration of the design space. For these reasons, engineering students should learn simulation.

Simulation is also revolutionizing engineering education. Like how writing can be taught directly ("learning to write") or used to enrich learning of other subjects ("writing to learn"), we could describe use of simulation in education as "learning to simulate" versus "simulating to learn."

One could be concerned about early introduction of simulation in the curriculum because it is challenging and requires specialist knowledge to be used productively and safely. Indeed, it seems that mechanical engineering students typically learn simulation through upper-level or graduate courses dedicated to a specific domain (e.g., FEA or CFD) or within a course on mathematical methods in engineering (e.g., using Matlab to solve differential equations). Thus, some assume that simulation can only be used late in the curriculum, after differential equations, computer programming, and engineering science courses. However, this paper cites numerous examples of simulation being used earlier in the curriculum as a digital lab and in quantitative design exercises.

Although there are few papers that discuss the general use of simulation in engineering education, Whiteman and Nygren offer a rich overview of use of numerical software in engineering curriculum [1]; despite having written more than 20 years ago, they anticipated key pedagogical factors to consider. We summarize their insights here. Whiteman and Nygren reviewed the learning process models of Piaget, Kolb, and Apple, and note that under each model, learning starts with engaging the learner with the new concept, and that there is a later stage for applying the new concept. Therefore, software can enrich the learning experience for beginners with a topic by enabling active experimentation. Later, as students develop mastery, the efficiency of software allows them to solve more types of problems in more ways than would be practical with hand calculations. Other benefits include the following:

- Software gives results that would be cumbersome to obtain otherwise. For example, typical problems on kinetics in dynamics address a snapshot in time, whereas software makes it easy to observe evolution of systems over time.
- Software promotes thinking in mathematical symbols.
- Software makes it easy to validate results.
- Software reduces solution time, giving more time for other aspects of problem solving such as formulation and consideration of alternative approaches.

Whiteman and Nygren recognize that there are disadvantages to using software. Students can treat the software as a black box and solve problems by trial and error. It takes time to learn software. Students get bored by lectures that show software procedures. However, these disadvantages can be managed. For example, instructors can keep students engaged by teaching software procedures in lab and instead using software in class to visualize solutions; also, to save time and focus on course content, instructors can offer solution template files that students can modify.

Finite Element Analysis

Finite Element Analysis is a way to use numerical methods to solve partial differential equations; although it can be applied to a variety of types of physics, in this paper we focus on FEA for structural analysis. FEA packages include Abaqus, Ansys Mechanical, COMSOL, and MSC Nastran; FEA is also available within some Computer Aided Design (CAD) packages such as SolidWorks, Autodesk Inventor, and Creo.

First-Year Courses

FEA has been incorporated in several introductory course experiences.

- Students analyzed a cellular beam in FEA and compared it with experiments [2].
- Pre-college students revised the design of a bracket prior to 3D printing and testing it [3].
- First-year students used FEA to design brackets with the mock goal of supporting a suspended walkway [4]. They then made and tested the brackets, and compared results with model predictions. The first-year students were mentored by seniors taking an FEA course and both populations enjoyed that interaction.

Although students at the introductory level can only use FEA to solve a limited range of problems and need guidance in doing so, FEA enables analysis to drive design earlier in the curriculum than would be possible without computer tools; as a result, introductory experiences can help students see the purpose of analysis prior to extensive coursework in engineering science.

Statics

Truss design projects have consistently been successful in statics. Because trusses are under simple compressive or tensile loading, a student only needs to know the maximum rated loads for each member. In contrast, most other design of structures or machines requires the concept of stress. Bridge Designer is a free program that enables these projects in educational settings [5], [6]. Student in statics have also used FEA for this purpose [7], [8], [9], [10], which shows that students at that level are not limited to using educational software but instead are capable of beginning to use professional tools. To model a truss, not much theory is needed for someone to set up a model, and not many software features are needed to implement one. In fact, FEA of trusses is so simple that students in statics doing hands-on design of a model truss apparently chose to use FEA to aid their design [11] without having been given training. FEA in statics has also been used to illustrate static determinacy and spring mechanics [12].

Solid Mechanics

FEA can build intuition about solid mechanics in ways that are not possible with physical representations. This is not to say that hands-on experiences are not valuable. Consider hands-on experiences ranging from simple qualitative demonstrations to lab experiments. Simple demonstrations can readily build intuition: a student can squash or stretch putty to observe the

Poisson effect, or can draw shapes on a pool noodle and observe how they deform under torsion or bending [13]. Unfortunately, these demonstrations are limited because we are generally experiencing bulk phenomena whereas stress and strain vary continuously through the material; the putty and the pool noodle show deflection, not strain directly. These demonstrations are also most vivid for large deformations whereas solid mechanics formulas are typically most applicable for small deformations. Quantitative experiments offer valuable experience with test equipment and allow application of solid mechanics knowledge. However, it takes additional knowledge to properly rig and instrument a sample; even then, the resulting data is typically limited to forces, displacements, and strains at discrete points. Photoelasticity can show stress contours but students have difficulty interpreting contours or quantifying their observations [14]. The cost of lab space, equipment, and materials can be limiting. In contrast to these real-world experiences, FEA enables students to create geometries, apply loads and constraints, and use any material; by following their curiosity, students are rewarded with full stress and strain profiles. Demonstrations, experiments, and computer models are thus complementary.

Engineers who use solid mechanics theory often use FEA as part of their analysis. Although FEA can simplify some analysis it does not reduce the importance of traditional content; in fact, building models requires conceptual knowledge of solid mechanics, and validating models requires mastery of analytic methods [12]. Teaching FEA in a solid mechanics course bolsters later FEA education by making these connections explicit.

Students have programmed models of 2D elements, offering another perspective on the relationship between stress, strain, and displacement; students also analyzed beams and made shear and bending moment diagrams [10]. For realistic problems, it is cumbersome to make shear and bending moment diagrams without some kind of computer tool so it is beneficial to use FEA for this purpose. A web-based FEA tool was developed focusing on modeling 2D rectangular domains, illustrating internal force, St. Venant's principle, and different loadings [15]. That tool was developed 20 years ago and is unfortunately no longer available; there may now be little demand for similar tools because general-purpose FEA tools have become more available and easier to use.

FEA models in solid mechanics can be validated against lab experiments, such as

- Beams including ones with a transverse hole or tapered sections [16]
- A T-section on knife supports under four-point bending [17] (this scenario is deceptively difficult to model and thus a rich learning opportunity)
- Photoelastic specimens with a plate with hole, notched plate, and point load [14]

Although solid mechanics courses typically focus on analysis, FEA enables students to use these concepts for design exercises. FEA tools for structural analysis were used by students to design structural members, such as a signpost dealing with combined wind and weight loads, and a floor supported either as a cantilever or by a truss [18]. In another case, students analyzed various beams, designed a signpost (as mentioned above), and designed seatbelt buckles—all within 32 h out-of-class and 8 h in-class [19].

A simplistic FEA tool enabled students to remove material from a bracket with the goal of minimizing mass while having stress remain below a limit [20]; the tool was only used in a research study but participants expressed interest in having the tool be used in a solid mechanics course. That tool automated most modeling tasks so users only controlled the part geometry. Although that interface lowered the cognitive load, it is unclear whether such simplification is necessary.

Machine Design

FEA is a natural fit for machine design, and indeed two popular textbooks each devote a chapter to FEA [21], [22]. FEA can be used to visualize stresses in machine parts, namely gears, threaded fasteners, pressure vessels, and machine frames and cases [23], as well as keys [24] and rolling-element bearings. Although FEA has substantial overlap with machine design, it still takes craft to connect these topics. Machine parts typically fail in fatigue at stress raisers or sites of contact. Stress raisers can require dense meshes, not all FEA packages account for fatigue, and contact is a complex nonlinear phenomenon; therefore, FEA activities in machine design must be scaffolded. Partly because of these difficulties, stock parts such as gears, bearings, and keys are typically designed using standards and vendor guides rather than FEA so instruction on design of these parts should focus on those well-established methods.

Machine design supports learning FEA by introducing advanced stress analysis topics such as stress concentrations and multiaxial failure theories, which are essential for FEA. For example, structures such as an automobile frame can be analyzed using these theoretical concepts from machine design [25].

Some do shaft design using FEA [16], [26], [27]. However, that approach should be taken with caution because shafts tend to fail due to stress raisers such as shoulders and keyseats. It is difficult to model an entire shaft while resolving the details of these features. Moreover, not all FEA packages include fatigue modeling. With that said, some have had success with students modeling individual features such as shoulders [17]; keyseats are possible but require large model sizes [28]. Additionally, iterative design of shafts requires many FEA skills and is very time-consuming [27]; for students to make the most of this deep learning opportunity, the content and activities must be carefully be sequenced and paced. Some have found that it works best to combine FEA with hand calculations, using hand calculations to find an initial dimension, and to convert raw FEA stress results into fatigue stresses [26].

Although FEA mostly finds use in machine design for static stress analysis, it is useful for other phenomena. Most notably, normal modes analysis of a shaft system reveals critical shaft speed [26].

Vibrations

In undergraduate ME education, FEA is mostly used for stress analysis. However, the finite element method is equally applicable to other domains and, in industry, it is often used for other analysis types. In a vibrations course, FEA has been used to model a system with two oscillating masses, as well as a rotating machine mounted on a beam [29]. These scenarios can be compared with experiments [30]. Computer tools are needed anyway for systems as simple as two point masses; in principle such a system can be modeled analytically but because finding the eigenvalues would require solving a 4th degree polynomial it would be impractical to solve the problem by hand. Furthermore, FEA on such simple systems can be the beginning of learning normal modes analysis for more complex structures. For example, simpler examples led to students performing modal analysis on an airplane wing [31].

Several modules have been developed that span solid mechanics, machine design, and vibrations, through which students use FEA to analyze a cantilever for a feed-roll [32]. This approach exemplifies how a single part will be analyzed from multiple perspectives to ensure that it meets various criteria.

Vehicle Design Competitions

SAE International organizes several competitions such as Formula and Baja, ASME organizes the Human Powered Vehicle Challenge, and there are many similar competitions around the world. Although these competitions are co-curricular activities, they can also be incorporated into the regular curriculum through courses on vehicle dynamics or through capstone design. Teams are typically scored on a combination of vehicle performance and engineering analysis; FEA helps with both. In traditional coursework, FEA is typically applied to individual parts or small assemblies and, although analysis of parts for competition vehicles is worthwhile, we focus our discussion here on design of the chassis.

The chassis of a competition vehicle is typically a space frame made of welded tube stock, a composite monocoque, or a hybrid combining a space frame and composite surfaces. Although it is essential to design a chassis that can safely bear loads and protect the driver in an accident or rollover, it seems that the most challenging aspect of the design is minimizing chassis weight while having high torsional rigidity, which allows good vehicle handling.

FEA is used differently in design of competition vehicles than in previous experiences that students are likely to have. Students who are used to modeling 3D parts with brick elements find that this approach is unworkable for a chassis, where beam elements are more applicable for tubes [33] and shell elements are generally suitable for composite surfaces. Moreover, structural FEA in courses typically focuses on stress analysis, whereas rigidity is a major goal for competition vehicles. FEA on SAE vehicle chassis has been reviewed in detail [34]. Because of these differences, vehicle design competitions can give students experience with FEA that is relevant to engineering practice but may otherwise be absent from the curriculum, which points both to the value of the competitions and the need for curricular reform.

Dedicated Course on FEA

Of course, FEA is taught in courses that focus on the method itself and a separate review could be written on that topic alone. Here, we mention a few examples of innovative approaches from the literature.

- Based on common mistakes made in industry and by students, instructors developed activities that trigger expectation failures caused by these mistakes [33]. For example, students were asked to analyze a simply supported beam—but because the supports were at the bottom, rather than the neutral axis, the stress was different from what would be predicted by Euler-Bernoulli beam theory and students found it challenging to select the best element type.

- To verify the analysis, a checklist based on industry practice has been used to guide students through the steps of analyzing parts based on real-life objects [35].
- A course used several homework problems that expose common FEA errors, such as a (non-)convergence study on a singularity in an L-bracket, or analysis of a truss model that is revealed to not be connected properly [36]. The course culminates in design of a beam with notches and holes that would merit a combination of hand calculations and different meshing strategies.
- Courses dedicated to FEA can meaningfully involve industry; in one case, students were given general requirements for a truck wheel and devised ways to reduce weight [37].
- Recognizing that students are not motivated to study FEA if the course starts simply with deriving a stiffness matrix for an abstract network of springs, an instructor instead started the course by introducing a project on reverse-engineering a flexure from the James Webb Space Telescope; as students learned new techniques through the course, they would revisit this task to improve their models [38].

Capstone Design

By the time they reach the capstone design experience, students may be prepared to apply FEA in open-ended contexts. There are many accounts of students doing so but the variability of individual projects makes it difficult to generalize. One instructor has noted several common issues, namely lack of recall on best practices from prior courses, doing analysis for its own sake (without using it to improve the design), not doing all relevant analysis (e.g., ignoring buckling), and doing a poor job of showing results (e.g., showing extraneous results, illegible results, or assuming the reader can interpret raw results) [39].

An Integrated Approach

A major initiative was made to integrate FEA and CFD across the curriculum [40] at Cornell. FEA was covered in a material properties lab and a dedicated course, while CFD was covered in a fluids and heat transfer lab, and an advanced fluid dynamics course. There were three main elements to their strategy:

1. Using canonical examples with known theoretical results or test data, which enabled comparisons and easy inclusion by instructors in courses.
2. Hosting tutorials on a public wiki owned by the institution, which enabled students to learn the software on their own, freeing up class to focus on concepts and problem solving.
3. Presenting numerical concepts “just-in-time,” which motivated students to learn the concept by tying it to an engineering goal.

Three of the main tutorials followed a common nine-step sequence; survey data shows that students value that consistent format [41].

Summary of use of FEA across the curriculum

FEA has been used throughout the mechanical engineering curriculum, with strategies matching the specific courses. To briefly summarize:

- First-Year Design: FEA enables analysis-driven design, especially with guidance such as templates or working in a limited design space.
- Statics: FEA is used for analysis and design of trusses—another example of early success with FEA by using a limited design space.
- Solid Mechanics: FEA acts as a digital lab, solid mechanics calculations validate FEA models, and FEA models can be compared against physical lab results.
- Machine Design: FEA reveals stresses in common machine parts and can be used for some design.
- Vibrations: FEA models dynamic systems in a field that typically requires computer solutions anyway.
- Vehicle Design Competitions: FEA can be used to model a vehicle chassis; to do so, students typically calculate rigidity of a space frame of beam elements, which offers an experience distinct from what is available in traditional introductory FEA courses.
- Introductory FEA: Innovative approaches focus on avoiding the errors commonly encountered in industry, which mostly occur in formulating a physical problem into a finite element model and interpreting results; common errors include poor element selection and improperly loading and constraining the model.
- Capstone Design: FEA can be put into practice. Pitfalls include failure to follow best practices, superficial analysis, and poor presentation of results; these show the need for comprehensive and cumulative instruction in FEA across the curriculum.

This general pattern of benefits and best practices may be applicable to other domains. The Cornell curriculum is one example of using FEA and CFD software systematically across the curriculum.

Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) uses numerical methods to predict fluid flow, typically by solving the Navier-Stokes equations; many CFD packages also model related phenomena, most notably, heat transfer. CFD packages include COMSOL, Cradle CFD, Fluent, and Star-CCM+. CFD has found use in numerous courses. However, CFD seems to be primarily taught within upper-level technical elective courses dedicated to the method; innovative approaches to teaching such courses are reviewed in Ref. [42]. This discussion offers a few interesting examples of CFD being used outside of these courses; even more are reviewed in the introduction of Ref. [43].

CFD has been used in first-year courses. First-year students were taught several types of simulation (FEA, CFD, and MBD) and, with support of teaching assistants, were able to pursue open-ended projects [44]; a plurality of students modeled heat transfer with fins. At another institution, first-year students took a cornerstone course on microfluidics and learned CFD as part of that experience [45]. Students benefitted from the course focusing on one type of flow (channels), from a list of problem-solving tips, and examples from other projects. Upon entering a later fluid mechanics course, those students had higher confidence and were better at answering conceptual questions, compared with students who had taken a cornerstone course on robots [46].

Of course, CFD has also been used in fluid mechanics courses to model numerous scenarios such as flow around a rotating disk, flow past a cylinder, and an automotive muffler [47].

CFD may be more aptly tied to heat transfer than fluid mechanics. Heat transfer analysis is typically based on Fourier's law of conduction and the Navier-Stokes equations, which are what CFD solves. In contrast, introductory fluids courses often make much use of Bernoulli's principle and the Reynolds transport theorem, which require problems to be formulated differently from CFD models. CFD can easily model various conductive heat transfer scenarios and convective transport under laminar flow; of course, topics such as turbulent flow and natural convection are possible but would require more skill. The literature has examples of CFD being used in heat transfer to address practical topics. One heat transfer course was re-designed to use a major project on modeling heat transfer in friction stir welding [48]. CFD also was used to model various aspects of fuel cells in a chemical engineering course on transport phenomena [49], which includes heat transfer.

It is beneficial to distribute use of CFD across multiple courses. Earlier, we mentioned the integrated approach to FEA and CFD used at Cornell [40]. Additionally, at the University of Michigan-Flint, CFD was used across lectures and labs in fluids and heat transfer to study practical situations such as particulate flow in an elbow and finned heat sinks [42].

In summary, CFD has been used constructively across the curriculum, including first-year courses, fluid mechanics, heat transfer, and courses focused on CFD. Compared with FEA, the literature on CFD in education is leaner. Given the similarities between the domains, it seems possible that CFD could be used more broadly across the curriculum with strategies akin to those that work in FEA.

Multibody Dynamics

Multibody Dynamics (MBD) software solves the equations of motion for an assembly of parts. MBD is powerful enough to model a vehicle but also suitable for modeling a mechanism. MBD packages include Adams, Ansys Motion, SimCenter Motion, and Simpack; motion simulation is also a feature of some CAD packages.

Compared with FEA and CFD, which are based on partial differential equations, MBD uses simpler methods to solve equations of motion; that simplicity means less knowledge of numerical methods is needed, and setting up models is much easier. At the same time, MBD can radically expand the systems that students can model; for example, in machine kinematics, a crank-slider is relatively simple, a four-bar linkage uses more complicated equations, and systems that are more complex are impractical to model analytically.

MBD was used by first-year students to model linkages and vehicle crash tests [50].

MBD was used in four exercises in an undergraduate dynamics class on kinematics and kinetics of particles and rigid bodies [51]. After a 1 h introductory lecture on use of the software, students were able to complete the activities using tutorials posted online.

MBD was used in several courses to model rotating imbalances and mass-spring-damper systems [52]; the authors state that simulation was helpful for all students, whereas solutions using a computer-algebra system (MathCAD) only benefitted students who already had a good mathematical understanding of the scenario.

Machine kinematics was once a staple course in ME curriculum but has been in decline, leading to industry not having enough engineers who can design mechanisms such as linkages and cams; it is especially unfortunate that this has happened at the same time that MBD software has become more common and useable [53]. MBD can enrich full courses on kinematics; moreover, in "hybrid" courses that combine kinematics and machine elements, MBD can enable realistic design activities in the absence of the class time to teach the full theoretical analysis [54]. MBD has been used for teaching design of linkages and cams, as well as planetary gearsets [55].

MBD has been used in vehicle dynamics courses, for example, enabling real-life projects such as analysis of trailers, surge breaks, and a vehicle for the Baja SAE competition [56].

MBD has enabled design of pick and place mechanisms for a course on design for space applications [57]; MBD was readily used for a hands-on project that also involved control design.

Overall, it seems that MBD can be threaded through the curriculum in a way that parallels FEA. Doing so may be easier than integrating FEA because MBD is simpler. A good pattern would be,

- First-Year Design: Design, following careful guidance and under a constrained scope.
- Dynamics: Provide solutions that are not analytically tractable; for example, show the evolution of a nonlinear system over time.
- Kinematics: Analyze and design linkages and cams.
- Vehicle Dynamics: Model and design suspensions and vehicles.

Systems Modeling

Systems modeling software—also called model-based design, system dynamics, or 0D-1D—typically has a user interface that resembles a block diagram. These systems include electric, hydraulic, and pneumatic elements, as well as plants, sensors, and controllers. The use of these tools in courses on system dynamics and controls is well established; most textbooks have content tied to software, specifically Simulink and Matlab. Other packages include Amesim, Dymola, and Easy5.

Systems modeling software has found use outside of those contexts, however, including the following examples.

- Systems modeling software was used in a first-year course on engineering problem-solving, enabling students to model projectile motion with air resistance, as well as control of a satellite tracking antenna [58].

- Systems modeling software was taught as a topic in a second-year course on computing for engineers [59], leading to students being able to solve ordinary differential equations.
- A dynamics course was revised to have its first week show the connections between kinetics, kinematics, and simulation [60]. Simulation enabled students to solve complex problems within that first week, prior to learning the related mathematical techniques.
- A dynamics class used experiments with an oscillator along with a systems modeling simulation to analyze the data [61].

Perhaps systems modeling software is typically introduced at the senior level because it is assumed that users need to already know the underlying mathematics (mainly differential equations). However, systems modeling software has a strong potential for being used in earlier courses because the user interfaces are simple. Furthermore, with solvers that automatically select time steps, users can typically find solutions without knowledge of numerical methods. The examples noted here show that students can successfully use systems modeling software if given the opportunity early in the curriculum.

Systems modeling software should be used in dynamics. Sloboda notes that dynamics is typically taught with a "snapshot" approach in which instantaneous accelerations are found, rather than governing differential equations [60]. In practice, the behavior of a dynamic system over time is typically more useful than simply knowing the instantaneous acceleration or even the differential equations. Perhaps time-varying solutions are rarely found in dynamics because that requires knowledge of differential equations (which not all dynamics students have taken), or perhaps the issue is that computers are typically needed to obtain solutions for nonlinear systems or systems of higher than second order. Unfortunately, a "snapshot" approach is limiting and students are understandably confused about the purpose of problems asking for instantaneous accelerations. The mathematical challenge of modeling dynamic systems is thus a reason to use simulation software in courses on dynamics.

In summary, although systems modeling software is often used in industry for modeling multidomain systems, because it makes it easy to solve differential equations, it can be used in courses preceding ordinary differential equations and, after that course, can be used to solve problems that are inconvenient or impossible to solve by hand. Perhaps the most significant gain to be found is in dynamics courses, where systems modeling software can extend "snapshot" solutions to show behavior of systems over time.

Electric Circuits

Electronic circuit simulators can solve dynamic circuits problems and with not much more effort than drawing a circuit diagram. SPICE is a popular open-source package; some commercial tools run on it, such as Multisim. It seems that these tools are used mostly within electrical engineering programs, or in upper-level circuits courses outside of electrical engineering, but not within introductory courses for non-majors. An interdisciplinary introductory course was developed to give first-year students exposure to various engineering majors; that course used simulation to enable beginners to do quantitative analysis in electrical engineering, and dynamics analysis in mechanical engineering [62]. That account is one of few that discuss use of circuit simulation software outside of courses focusing on circuit analysis.

Although mechanical engineers often deal with systems that have electrical components, that connection is often made late in ME curriculum, after differential equations. Electronic circuit simulation software can bring electrical systems into early design courses.

Power Transmission

Many machine design courses focus on design of power transmissions, including components such as gears, bearings, shafts, and keys. Before computers were available, power transmission design required numerous rote calculations. Now machine design is often taught using spreadsheets or computer algebra systems, which can streamline calculations and link analysis across components; at least one popular textbook includes templates or solutions using Excel, Matlab, TKSolver, and Mathcad [21]. In industry, several software packages are used, such as KISSsoft, MASTA, and Romax; unfortunately, it seems that few have use in academia, with only one paper in the ASEE PEER archives referring to any of these products [63].

Power transmission design software can enable machine design students to design whole systems, instead of needing to focus on components. This software is easy to use and could be used in introductory courses; it could naturally find use in capstone design or in graduate courses. Due to limited use in academia, best practices in integrating this software are not yet clear.

Conclusions

Although simulation software is mostly taught in upper-level engineering science courses, there are examples of simulation enriching the whole curriculum, from giving first-year students experience with physical phenomena to enabling seniors to carry out complex design activities.

Now, it is valid to be concerned that engineers would use simulation without adequate understanding of either the underlying physics or the numerical methods. This concern is especially valid for FEA and CFD which, unlike the other types of simulation discussed here, are used to solve partial differential equations, require skill in meshing and applying boundary conditions, and can readily give misleading results. However, that concern should be taken as a reason to teach simulation when new physical concepts are being introduced so that students get experience using analytic models to validate computer simulations.

Simulation should be across the ME curriculum. The ways to do so would be different depending on the type of simulation.

- FEA is now common in undergraduate mechanical engineering programs and there are worthwhile uses for it across the curriculum but most programs do not do much FEA outside of a course dedicated to the subject. The literature contains numerous creative uses of FEA across the curriculum so there are ripe opportunities for programs to immediately increase their use FEA.
- CFD could also be used across the curriculum in ways analogous to FEA. However, many new activities would need to be developed.

- MBD is not currently used much in undergraduate curriculum but students pick it up easily when given the opportunity. MBD can enable the dynamics course to no longer be limited to "snapshots" and can re-energize instruction on mechanisms.
- Systems modeling software is ubiquitous in courses on system dynamics and controls but not currently used much beyond that. It could be used anywhere for solving differential equations.
- Electric circuits simulation could be used more in circuits classes and to introduce circuits concepts in earlier courses.
- Finally, there are many types of specialized simulation software that are used in industry (we focus here on power transmission, but fluid power and wind turbines are other examples). These types of software seem to not be used much in education. However, if they were to be used in education, they would give students experience with detail design calculations and, by streamlining that work, enable students to link concepts and think at the systems level.

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