Int. J. Engng Ed. Vol. 17, Nos. 4 and 5, pp. 455–459, 2001
Printed in Great Britain.

0949-149X/91 $3.00+0.00

On the Role of CAx in Design Education*

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The tension that has been created by the industry pull for CAD and CAE skills in engineering graduates is explored by surveying the current state of industry practice. Proposing that industry needs are a predictor of changes in engineering education, examples from computer-aided drafting, computer-aided design, computer-aided engineering and computer-aided manufacturing are provided. The paper concludes with support for multidisciplinary capstone projects in the educational experience and a brief look at trends that might predict the rate of adoption of CAD in educational programs.

ON THE ROLE OF CAX IN DESIGN EDUCATION

THE PROPER ROLE in education for Computer Aided Design, Computer Aided Drafting, Computer Aided Engineering and Computer Aided Manufacturing (all denoted for simplicity as CAx here) is muddled by a variety of factors. Cost both in terms of hardware and software and the time required to obtain a minimum proficiency are readily identifiable culprits. More subtle issues revolve around education in reusable concepts versus training to acquire skills and tool proficiency.

The pull from industry [6, 9, 10, 15, 16] for engineering graduates with CAD and CAE skills can be viewed as one side of a supplier-consumer relationship. Although I propose that industry needs [16] and current state of practice are early predictors of requirements for college graduate skills, I caution that there are significant lags in this relationship. For example, it takes 4 to 5 years to complete an engineering degree. Since the initial portions of an undergraduate curriculum are typically non-specialized, it may only take 2 to 3 years once a specific evolving need is identified. Continuing into graduate education to get a better handle on such new topics adds another 1 to 2 years.

On the other hand, industry requires 4 to 8 years to assimilate and employ new engineers with these skills. Leading industry companies working with university researchers [4] bring new methods, approaches and concepts to educators' attention over a number of years. As more companies adopt these practices, the need for graduates starts to rise. Entry positions will be filled with new engineers, and as the body of knowledge matures, engineers with advanced degrees will be brought in. Still, the needs for internal leadership in such new areas outstrips the education process and leaders are found largely from industry sources.

* Accepted 27 August 2000.
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The really challenging problem is to identify those new areas that are truly lasting, fundamental and worthy of the long term investment. This is a problem for all: students, academic leaders and industry. Like many such broad questions, there is no single answer, but a discussion will likely clarify matters and help many parties move forward.

I restrict this discussion to the mechanical disciplines at the exclusion of electronics and software systems to avoid struggling with the analogous examples which will be required to provide a comprehensive picture. Further, the life cycle of design ranges from conceptual design through preliminary design to detailed design but I will restrict my remarks to the application of CAx to preliminary and detailed design where the role of such computer tools is easier to see. Application of these tools to conceptualizing is harder to discuss and, while it might be a good area for research as part of the broader educational experience, I wish to stick to the more readily deployable aspects of CAx that might be used, for example, in a fourth-year capstone project.

THE PROBLEM WITH CAX

Taking computer-aided design/drafting as the meaning of CAx for the moment, a problem arises because of the significant skill investment required for workaday proficiency in current tools. Designers express artifact designs in 3-D CAD models but, in practice, are almost entirely consumed by the effort to properly capture the geometry in the CAD tool. Little capacity is left for issues of functionality, layout, component selection, or analysis. In recognition, design teams are staffed with other discipline engineers that tackle these problem areas. The fundamental challenge is to raise the designer above the level of a data entry clerk.

Industry design positions are being filled with degreed engineers. Yet there is little traditional educational content in the rote skills of using the CAD tool. Clearly, there are worthy topics in graphics, software design and user interface within the construction of the CAD program, but designers are chosen from the engineering domains of the artifact to be designed, not the domain of computer-aided graphics. Mechanical, electrical and aerospace engineers are taught circuits, structures, aerodynamics, and mechanisms. This does not give them the skills in CAD tool operation required of many of today's designers [9, 12].

For the time being, I set aside the high monetary cost of CAD hardware and software. While it is a very real barrier to entry, it can be worked. Hardware costs are falling as PC workstations have become usable. Software costs can be managed through support by industry sponsors or vendor grants. I would rather address other aspects of the problem which remain after funding is found.

THE ROLE OF CAX IN INDUSTRY

Let me tour the state of practice in the various incarnations of CAx circa '98–'99 before turning to potential ways that education might rise to meet these needs. Looking ahead though, I propose to mimic core industry practices, such as design teams and design tool integration, in educational settings [6, 7, 10, 15].

Computer-aided-design/drafting

First, I need to clarify the meaning of this phrase. Computer-aided drafting probably arose as the direct electrification of the drawing board. Computer tool skills centered around replicating the engineering drawing on the computer screen with a paper plot as the final deliverable. The detailed design process was drawing based, and still is in many industry locales.

Computer-aided design has come to reflect more the design activity as captured in the electronic database of the 3-D model and CAD tool. Less focus on the delivery of print drawings and more on the expression of design and design intent in an electronic format is implied. The new frontier is now the application of design aids, standard parts libraries, and product data management during geometry capture.

The skills required to fruitfully apply CAD tools are very extensive, despite vendor advertisements to the contrary. Further, these are hard to generalize and abstract from the particular tool because good practices are evolving rapidly. Large scale designs are driving front line practices with a tremendous pace. Market forces compel the CAD product vendors to incorporate features and functionality long before a coherent practice and methodology has emerged.

Currently, it is widely held that detailed design must be done in CAD and making the design expression as captured in the CAD tool data base available to other members of the design team is seen as the near-term future of the industry. The benefits in time to market reduction and elimination of wasted labor are easy to see and it is very hard to doubt this value proposition. Capturing the design geometry early is essential to this process. The designer's activity is the first point where ability matches opportunity and therefore the designer is saddled with capturing product geometry. This becomes the primary representation tool for other team members, from analysis to project engineering to marketing.

Industry emphasis on CAD in design varies with the phase in the product life cycle. CAD has been a fruitful economic advantage in detailed design because manufacturing productivity gains are possible when CAD is coupled with computer-aided manufacturing. Achieving these gains is problematic largely, in my opinion, due to the organizational walls between engineering and manufacturing. Further, for the past several years, the application of CAD has migrated forward in the design process to where CAD is an essential visualization tool for the conceptual design team.

CAD can be shown to substantially aid in proposal design activities. For example, we demonstrated, in the Project Design Center at the NASA Jet Propulsion Laboratory, the ability to assemble conceptual design CAD models directly from spreadsheet design tools. In addition, realistic depictions of the proposed spacecraft collecting science data on Mars or at a comet were hailed as clear differentiators that contributed to several successful proposals.

Computer-aided engineering

In the broadest sense, computer-aided engineering (CAE) probably doesn't have to include a tie to the designer or CAD, but let me focus here specifically on reusing design intent and geometry via the CAD database. Current industry practice has just a few engineering disciplines developing such capabilities: CFD aerodynamics, structures (FEM for internal loads, stress and fatigue), and mechanism design.

These heavily analytical methods are only slowly finding roles in the early design stages of large systems. Advances in solution times, model generation and output analysis have really helped, but further application to conceptual design or proposals will require efficient access to the CAD geometry database. For example, an aerospace proposal team was able to use CFD in a hypersonic transport competition only because a parallel in-house development group tackled the accompanying tool integration problem.

In my opinion, integration of these analytical methods is the most fruitful frontier to continue the process improvement, labor saving and cycle time reduction gains. Common knowledge estimates state that as much as 75% of the first pass structural engineering level of effort is spent (read wasted) in recreating the design geometry. Further, rapid iteration is critically broken. For example, in a particular industry design group, conceptual design layouts of a missile were changing twice a week, yet structural analysis of the body shell required 4 weeks.

An example of design in a narrower sense can be found in many organizations these days. Knowledge-based engineering (KBE) has been applied successfully in both detailed design and conceptual design. In the former, KBE applications help designers with materials processing specifications and standard parts selection. Boeing has demonstrated rapidly regenerating large assembly CAD models such as vertical tails via KBE computer programs. The need to migrate conceptual design databases to down-stream design activities for a quick start has created a thriving interest in driving traditional CAD tools with KBE. These detailed design CAD tools are seen as too labor intensive for conceptual design where simple parametric and table-driven interfaces are popular. KBE tools bridge this nicely, using similar input mechanisms but producing full CAD models as results.

While the abilities of KBE to reflect design knowledge, or even hint at creativity, is limited to pushing around the details within a fixed product framework, industry is deploying KBE in design activities. The aim is to relieve design engineers of tedious work and to shorten design cycle times. For educators, continued support for research in this area is likely. The topic will make good content as such for graduate elective classes, but will probably require substantial consolidation before finding a home in fourth-year design projects.

Computer-aided manufacturing

The primary payoff from concurrent engineering has probably come from the inclusion of manufacturing considerations in the design process. This appears largely as 'design for manufacturing' where simple manufacturability considerations are covered. In my experience, this is rarely more than participation in design reviews and rarely involves direct access to the CAD design database. There are notable exceptions, such as layout of the assembly line in the case of a new car design and advanced research and development projects that include generation and simulation of robot tooling sequences.

Similar design extensions in this area include 'design for assembly' and other DFx topics [1, 15]. Design-time rules for proper hole edge margins and mold draft angles are well known and frequently appear in current design for manufacturing implementations. Consideration for NC tooling capabilities and restrictions, such as minimum internal radii, are on the horizon. Longer term, progress should come rapidly in fixing the 'data food chain' from design in CAD to NC modeling to tape-out to fixture design.

Finally, let me note significant advanced research and development in these areas is underway in programs with names like Lean Manufacturing and Agile Manufacturing.

THE PROBLEM WITH EDUCATION

Supporting these industry practices and advances in education raises many issues for a design education forum [13]. Contrary to my section title, the problem is not with education per se. With no promise to expound on these issues, I simply provide a list of 'hot buttons':

- How should we reflect industry activities in education?
- How should we partition the class time among theory, methods and objects [18] when CAD tools take so long to learn to use?
- Potential activities targeted at deploying integrated CAx are difficult at the graduate level and are really hard at the undergraduate level.
- What is the appropriate division of labor between education at the university and on-the-job training at the company [16]?
- The long standing dichotomy between becoming a technical specialist or a generalist also applies to our design arena, both with respect to investment in tool skills and industry-specific domain knowledge [11, 16].

Likely elements of workable solutions

First of all, there are many venues for knowledge delivery that have arisen to tackle the continuum from training to education. Let me restrict my focus to university education in engineering at the graduate level, with a strong desire to migrate as much as possible into the undergraduate activities.

Team-based design projects have been widely instituted to address industry needs. Graduate students have the depth in their disciplines to use common design and analysis tools. Here, we can effectively advance areas such as tool integration, collaborative processes, and concurrent engineering. Capstone design classes which are prevalent even in undergraduate programs can address these areas [11].

It is my opinion that significant advances are needed to distill the activities down for effective application by fourth-year design teams and that this should be a strong area of interest for industry sponsorship. I believe industry will demand BS graduates within 5 years that have the skills of MS graduates of 3 years ago.

Industry sponsorship of design projects is essential and effective [16]. They are effective in providing real-world experiences to students as well as pushing academic programs to understanding and addressing industry needs. Successful programs such as the Harvey Mudd Clinic take effort to build and sustain, and provide an excellent model.

Somehow the skill investment in operating CAD tools must be managed so that industry practice can be incorporated into design projects. Sponsored research makes this possible for most graduate programs, but effective utilization of industrial-strength CAD tools is still out of reach for undergraduate projects. Institutions are forced to choose between providing experience with a popular industry tool or using light weight tools in the hope of delivering the generalized CAD experience.

We are even farther from employing integrated design and analysis tools or integrated design and manufacturing tools in undergraduate studies.

What changes can affect this problem?

Many educational institutions either offer for-credit classes in a CAD tool or spend a significant portion of a course building enough CAD skills to tackle an introductory discipline problem. Finding a place in an already full curriculum can be difficult. [4, 5] Perhaps a business model can be found where a university subcontracts CAD training to the industry resellers and training companies, but this won't necessarily help the curriculum pressures [15].

Over the years, the slide rule and then the calculator became accepted as basic engineering skills. It is likely that CAD experience will become an assumed skill in certain disciplines such as Mechanical Engineering [9, 14]. For better than 10 years, a FEM pre- and post-processor such as PATRAN has been a practical necessity. New MCAD tool suites such as PTC's Pro/Mechanica or SDRC's I-DEAS have made the need for CAD proficiency explicit. (One difference between requiring the ability to use a PC and requiring the ability to use a CAD tool is the breadth of applicability. How many engineering disciplines have methods that fundamentally require 3-D modeling proficiency? Acquiring proficiency in the finite-element method doesn't require writing a computer program but does require using one. How long will it be before using a FEM tool requires CAD-like assistance for geometry input and comprehending results?)

The learning curve for CAD software has traditionally been very steep, although newer tools that fit into the PC desktop look and feel claim to be easier to use. The 3-D entities on which CAD operates are becoming ubiquitous in desktop computing. NT 3.5, which came out in September, 1994 [2], brought us the piping screen saver, OpenGL and good performance without expensive graphics accelerators. [3] VRML, which came out in 1995, brought user control of 3-D spaces to the web [8] and DOOM brought it to games. 2-D clip art adorns many office documents and now a large portion of the Microsoft Office 2000 clip art collection is photo images. With 3-D objects and 3-D viewing controllers widely integrated into PC life, we can expect CAD skills to come more easily.

It is probably obvious that hardware advances drive these changes too. Today's desktop PC can quite effectively render real-time rotation of modest 3-D objects without a hardware accelerator [14]. Computational elements of the rendering pipeline found their way into the desktop CPU with the MMX Pentium instructions. Intel-powered NT PCs have made deep inroads into the existing Unix-based CAD market already and every major CAD vendor has a product version for Wintel systems.

CONCLUSION

My prediction is that market pull and the lower 'cost' of delivering CAD will lead to a wider role for CAD in engineering education. But that shouldn't be surprising. The really tough prediction is the pace of wide-spread adoption.

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