While the design studio environment has had a central role in teaching fundamental design skills in architectural education, it also provides an opportunity for synthesis of related coursework in developing architectural design solutions. However, the design studio’s traditional emphasis on conceptual design and nurturing artistic expression can result in the exploration of related technical issues such as structures and construction being relegated to a more cursory role. Architecture schools have been criticized for failing to provide sufficient technical education and preparation for the realities of practice [1]. Deficiencies in knowledge-development related to construction and building technologies has often been a specific point of criticism. This is based in part on the perception that the emphasis in design studio on aesthetics, history, and theory results in the students graduating with limited knowledge base in building technology and construction. In response, some argue that the mandate of architectural education is to cultivate skills in life-long learning and that practice is where students develop technical knowledge [2].

This debate on the extent to which architectural education should focus on technical skills has now been expanded to include the role of CAD in architectural design [3]. The drafting table has been supplanted by the computer in architectural practice [4], yet it remains a fixture in academic environments. The argument that as a design tool CAD is unsuitable or poorly matched to the task has been widespread [5, 6]. Some have argued that CAD has induced “the evacuation of creativity” in the architectural design process [5]. In contrast, others respond that computers have the potential to radically alter the process of architectural design and that digital-based design will replace traditional modes of architectural design [6].

The failure to find an appropriate role for the computer in design both in education and practice may lead to missed opportunities to exploit digital design tools for new ways of conceiving architecture. For example, the power of computer visualization has made possible new uses for perspective views as a design tool. Laseau [7] proposed that the efficiencies with which computers can generate perspectives can assist designers to focus on the experience of space. However there is also the opportunity to utilize the strengths and efficiencies of digital design to enhance learning in the technical aspects of design in which studio education is perceived lacking.

Computers in the Design Studio: Conventional Models

The conventional approach to computing in most design studios can be generalized as...
falling within one of three categories. The first two approaches, referred to as Exclusionary and Tangential use of Computers, limit the role of CAD and digital design tools. In contrast, the third approach, the digital design studio, embraces the use of computing in design. While these are broad generalizations and experimentation with variations on these categories are on-going in academic environments, a discussion of the attributes of these generalized approaches is necessary in order to consider a fourth alternative.

1 and 2: Exclusionary and Tangential use of Computers in the studio

Arguably, two common approaches to the use of CAD in architectural education, in particular the design studio, could be generalized as either “exclusionary” or “tangential.” In the “exclusionary studio” computer and CAD use is either proscribed or, if allowed, is not supported. A second approach would be the “tangential studio” studio where CAD and related visualization applications are taught as a separate course or courses and are permitted to be used to produce drawings and images typically for final presentations. Both approaches are aligned with the premise that the studio may be an inappropriate venue for learning to use. Marx stated that “students are struggling to learn how to design, much less to design on a computer” [6]. However, it is also possible that these approaches may reflect a lack of expertise in the use of the digital media among faculty. Marx also suggested that student’s struggle to learn to design on a computer is “compounded by the current lack of digital skills on the part of design faculty” which therefore “makes it difficult to create a level of consistency in teaching digital design.”

This resistance to the role of computing in design is rooted in a range of issues. One argument that has persisted is that the efficiencies of computer-aided design for architecture are production-oriented rather than design oriented [5, 8, 9] and that benefits derived from increased efficiencies in producing construction documents have not been extended to the design of buildings [6]. Therefore, the role of the design studio in academics as a venue in which students learn formal design process is not well aligned with the product that CAD applications are designed to produce.

However, the technical strength of CAD applications for tasks such as the production of construction documents also has led to the perception that digital design as a medium is inappropriate as a tool for the representations required in early stages of design process [5]. Early design processes are characterized by intentional ambiguity representations such as sketches and freehand vignettes. CAD however, due to the precision of its representations, has “accentuated the divide between explicit and implicit information” [9]. The pen or pencil sketch has retained its prominence as a design tool because it is exploratory rather than absolute, because it is inherently ambiguous, and because the degree to which the information it conveys is implied and subjective. CAD is inherently unambiguous in that its representations are explicit rather than implicit [9] and therefore considered inappropriate for early stages of the design and those of the design studio in which much of the effort is focused on the conceptual characteristics of architectural design.

The criticism of the effectiveness of CAD as a design tool is also rooted in the software itself. Critics have suggested that CAD software influences design because it must contain an implicit theory of design [5] and computer modeling processes have been perceived as being too restrictive for the representation and creation of architectural form [8]. For many designers, their experiences with the use of earlier more generic CAD applications reinforced the lack of fit between the needs of architectural designers and the products supplied by CAD vendors.
However, even when vendors modified their products in attempts to align their products with architectural practice the results failed to meet the requirements and expectations of designers. For example, the 3D capabilities of most CAD applications were often limited to either solid modeling which was inflexible and inefficient computationally or to 2½ D or 3D faces and extrusions which produced lower quality graphic representations due to computational limitations. (Figure 1).

These computational limitations were not only graphic but also reflected the practice of electronic drafting where low-level geometric entities such as lines were used as representations of architectural elements such as walls and doors. As in manual drafting, these entities possessed little if any “intelligence.” Johnson [10] argued that architects “remember and think about designs in terms of elements like walls, the correspondence between CAD elements and architectural elements should not be merely cosmetic,” adding that “representations based upon low-level geometric entities are generally incapable of corresponding to architectural elements in an appropriate manner”.

3. The Digital studio

A third “digital studio” approach is organized around the use of digital design, a process in which design decisions are made on screen rather than on paper [6]. This approach would be characterized by the use of 3D computer models at all stages of the design process. In contrast with other approaches, the “digital studio” approach is reliant on studio instructors having a high level of expertise with the software applications. At some institutions this limitation has been addressed through team-teaching in which the design studio instructor is paired with a CAD instructor [11].

However, there are curricular as well as pedagogical issues associated with the “digital studio.” In order for skills with CAD and computer modeling to be developed to the level at which they can be employed as design tools, extensive studio time must be allocated to learning to use software. Therefore, other outcomes intended for a studio course may be compromised. In order to facilitate desired studio outcomes, another approach would be to add a separate course for developing higher level CAD and computer-modeling skills which could result in students entering the studio with the required knowledge base in place.

The alternative Hybrid Studio: The traditional Studio with Task-Specific CAD requirements.

Recent advances in architectural computing have initiated a shift in the role of CAD in the design process. Among these advances, the introduction of “building modeler” applications has the potential to revolutionize both practice and education. Building modelers are characterized by applications based upon object-oriented programming and parametric design components. Commercially available building modelers are three dimensional, model-centric applications that use computer-generated objects to represent building components.

These applications provide new opportunities for education as well as practice. Object-oriented programming process applications offer command sets that are more intuitive and easy to use than generic CAD. According to Kilkelly [12], “the overriding concept of Object-Oriented Programming is the division of complex tasks into small, easily managed pieces.” OOP
applications provide benefits that include reduction of complexity, the ability to re-use or combine objects, and easy modification and extension of individual components without requiring re-coding.

The introduction of object-oriented process systems eliminates the limitations of low-level geometric representations. Instead of creating representations with lines and shapes, users work with higher-level “intelligent” representations that are architectural “objects.” Architectural elements such as walls are created as three dimensional entities which automatically clean-up at intersections and ends eliminating the need for additional editing. Additionally, in object-oriented applications “the architectural objects relate intelligently with one another” [13]. Parametric modeling capabilities and relational objects provide elements that function more intuitively: floors “know” they are to be horizontal and the components of a window “know” that they are part of a wall [14]. The result is an application that, despite its power and complexity, is easier and more intuitive to use.

The advantages of architectural CAD applications with OOP technology provide an opportunity for the design studio to utilize a hybrid model that allows for the “traditional” studio model to integrate computers in the design studio through the use of a task specific role for Computer Aided Design. The hybrid requires students to complete a specific task with CAD by utilizing a subset of a computer-aided design application to explore and integrate a specific aspect of an architectural design component into the larger context of a design studio project. Such an approach attempts to exploit the features of the software that may be most efficient while not requiring the use of CAD for any aspect of the project that students or faculty feel may be more appropriately addressed using another medium. For example, students could be required to use CAD software to analyze a site using 3D terrain modeling. Similarly, students could be required to analyze design proposals using 3 dimensional massing studies created using the software’s solid-modeling commands. This approach is based on the premise that the strengths of CAD can exploited by identifying a task or tasks that the software is most suited for and requiring it to be used for that task. However, the CAD knowledge and skill set required is also more focused since competencies with all the features of the software is not necessary to complete the task. Both students, and studio instructors, need only develop competencies with the specific commands associated with the task

Several benefits arise from this scenario:

**Emphasis on Traditional Studio:** Since the required role of the computer is supportive rather than central, the emphasis of the studio remains on design and aesthetic explorations. The use of task specific CAD requirements does not mandate changes in studio activity time-frames or sequences or prevent or limit the use of other media requirements or activities such as physical models, etc.

**Time allocation efficiencies:** Since the CAD knowledge and skill set required for the task-specific requirement is narrowly focused, the time allocated to providing software-specific instruction does not adversely impact the amount of class time that is devoted to primary studio activities.

**Media Independence:** The task specific CAD requirement does not restrict students to using digital representations and media for other project elements. Students are free to pursue other graphic techniques that either they or the studio instructor wish to pursue.
Skills with CAD and digital media as a design tool: Little and Cardenas [15] proposed that in addition to being sufficiently complex to permit an evolving design space and allowing for multiple acceptable solutions, design studio problems should also benefit from the use of design tools. In this scenario, students are provided an opportunity to expand their CAD skills and explore the use of CAD as a design tool within a studio context. For many students it could be a first opportunity to use CAD for 3D modeling tasks as well as a tool for creative problem solving processes. In addition to the opportunity to synthesize CAD skills with the studio environment, the hybrid task-specific approach also provides an opportunity to synthesize knowledge from other coursework as well. Assignments relating to construction and structures are an example of a task-specific CAD requirement that takes advantage of the affordances of an OOP application.

Experiences with the Hybrid Studio: Implementing a task-specific CAD requirement in a design studio.

A course using the hybrid computer modeling/task specific approach was selected for a third year architectural design studio. In addition to drafting and design courses, all students had completed an introductory statics and strengths of materials course as well as an introductory 2D CAD course. Therefore, the assignment assumed students were at least somewhat familiar with basic CAD operations as well as familiarity with basic structural concepts. Four of the ten students enrolled in the course had either previously taken advanced CAD courses or were enrolled in advanced CAD classes concurrently with the design studio.

With the exception of the task-specific CAD component, the hybrid studio project requirements were intentional media-independent. The CAD component required the students to use AutoCAD Architectural Desktop 3.3 by AutoDesk to create a computer model of the structural system of their design proposal in order to encourage students to integrate knowledge from introductory structures courses into the design studio. This application was available to all students in university computer labs. Designed as a model-centric application, ADT 3 includes a 3 dimensional parametric structural symbol library using the shapes American Institute of Steel Construction catalog. Lengths and heights of standard steel beams, columns, and other structural shapes can be specified parametrically. For example, students could select a beam from a list of all wide flange shapes in the AISC catalog and adjust parameters such as justification, starting and ending offsets (extensions), and trim and intersection properties (Figure 2). Structural members can be placed in the computer model using standard CAD drawing techniques, enabling users with basic CAD skills to create structural assemblies. Structural elements are easily interchangeable; a beam or column shape can be “swapped out” for a different shape and retain any parameter settings.

The project selected was a mid-rise apartment complex with a parking garage and atrium. A site located in an urban environment was selected in order to provide a context that would provide a range of design issues as well as be conducive to a mid-rise structure. Submission requirements included a physical model along with conventional orthographic drawings such as plans, sections, and elevations. The project was structured to be media-independent; students were given the choice to produce drawings and models either manually or with CAD.

The studio’s major project was divided into three phase sequence identified as “conceptualization - structural exploration - re-conceptualization”. The stated goals and intended
outcomes for the project included the following:

- Integration of related coursework in both structures and CAD.
- Provide students with experience with computer modeling concepts
- Provide students with a tangible experience in synthesizing theoretical issues with a practical (real-world) dimension in solving the design problem.

**Phase One: Conceptualization**

Over the course of the four weeks allocated for first phase of the project, students were required to develop a proposal using physical massing models and both orthographic and paraline drawings. While the parameters limited the physical size of the presentation to two 30x40 boards, no representational medium was specified or required. The conceptualization phase explored the project in more traditional studio context. The assignment requirements for the structural concepts for this phase were intentionally loosely structured and not given a high priority in the review processes. The design proposals were to indicate a “logical structural system.” However, no drawings of the structural system were required.

**Phase Two: Structural Exploration**

The structural exploration was the task-specific CAD component of the studio. Four class meetings were held in a university computer lab in order to provide students with training for the command set needed to complete the 3D structural assignment. The students were required to use computer models, created in Architectural Desktop 3.3, of a proposed 3D structural system for their project. During this phase the structural models were to be created as discrete design iterations. The project parameters mandated the use of steel frame and the nature of the project program required a multi-story structural system. However, the students were encouraged to conceive the structure as an aesthetic element by being required to represent the structure as a “stand-alone” three-dimensional composition. Explorations with cantilevers, trusses, and bracing were encouraged.

Time and skill restrictions did not allow for structural members to be sized with calculated loads. Instead, the studio focused on a conceptual approach to the structural proposal emphasizing the use a “visual approach” to structural design in order to foster a qualitative interpretation of structure [16]. Where a quantitative approach may focus more on calculations of structural loads and related stresses, a qualitative approach may focus more on enhancing visual intuition. Abdelmawla, Elnimeiri, and Krawczyk [16] proposed that “we need to enhance such intuition so students can feel when a system is not quite correct or when a structure member is not efficient.” They further proposed that enhancing visual intuition results in the principles of structures becoming an unconscious part of the students’ way of thinking:

“We all possess a purely visual intuition of structural behavior through our daily experience. We understand why columns at the bottom of a building must be larger than those at its top since they must support the accumulated weight of all the floors of a building. Without any theoretical knowledge, we are ready to say that a cantilever beam is right if shaped with decreasing depth towards its tip. The same applies to light poles or high rise buildings. We may even have aesthetic feelings about this matter and say that the form is in the first case lovely and ugly in the second. We are trying to enable the student to understand the underlying reasoning for
Phase Three: Reinterpretation

In this last phase, students were required to re-assess and refine their proposed design solutions and their proposed structural system. This phase required a synthesis of issues raised and critiqued in Phase One and Two. Phase Three culminated in a formal presentation to faculty and external critics. The Phase Three requirements included exterior perspectives, detailed plans of a typical apartment unit, a plan oblique view of the refined structural proposal, and a physical model of the proposed building.

Discussion and Assessment of outcomes

The conceptualization Phase was conducted as a “traditional” studio. Although media-independence was stressed, six of the ten students in the course chose to use CAD rather than manual graphic mediums (pencil or pencil and ink) to create the required 2D and 3D drawings in the conceptualization phase. While the projects presented at the completion of the conceptualization phase varied with the design skills of the students, all students met the requirements.

Initial activities emphasized conceptual issues and were organized to build on the students’ past experiences in the use of sketches and mass models. As the project evolved, the students were required to rely more on the use of orthographic drawings. At this point, discussions of structural systems were introduced into the critiques, with floor plans becoming the predominant tool used by students in evaluating the design for floor and beam spans and points of structural loads. Nearly all students relied on bearing walls for support throughout the structure. In general, the students expressed only passing interest in the structural components of their solution. Additionally, the critiques necessarily emphasized a broad range of architectural issues including issues related to urban design that, as with issues relating to structure, had not been addressed in previous design studios. While this may have contributed to the limited attention the students gave to the structural aspects of their design, it should be noted that the structural design component at this phase represented a relatively small part of the project grade and it is possible that there was a lack of incentive for students to invest their energies in that activity.

The structural exploration phase was divided into three time segments, each with lab sessions to provide instruction in the operation of the software followed by desk critiques. The initial critiques revealed several common characteristics among the proposals:

- Most students’ initial explorations were limited to steel frame structural systems using standard columns and beams placed on a grid closely aligned with their plans [Figure 3]. Typically, these elements were simply substituted for bearing walls; structural elements were primarily placed at locations of both exterior and interior walls, indicating a lack of awareness of structure as an architectural element or an understanding of the potential for the building envelope to be independent of the structure.

- Sizes of structural elements used were largely independent of location, indicating limited acknowledgement of structural loads. Additionally, the visual characteristics of the size of structural members were not addressed. For example, the selection of structural shapes and
sizes for tall columns were often “visually” too thin even if structurally they may potentially have been acceptable.

- All proposals were at least to some extent incomplete. In several cases where structural grids did not or could not be aligned with the phase one design, the structural model was left unresolved indicating a lack of understanding of how to proceed with a structural system for that condition.

These characteristics were attributed to a lack of applied structural knowledge as well as lack of experience with using the software. For many students, this was their initial attempt at working in 3D. There was little difficulty among even the least experienced students in understanding 3D CAD concepts as they relate to coordinates and navigation. Students commented that it was simply adding a Z value to the X and Y coordinates they were familiar with from working in 2D that experience using drawings aids such as object snaps in 2D was easily transferred to 3D. However, most students stated that they felt a lack of confidence in their ability to remember command sequences required for the task. Additionally, many students were unfamiliar with structural terminologies used in the AISC catalog and either were reluctant or lacked the necessary time to experiment with selecting and manipulating the structural shapes.

At the second critique the proposals reflected a greater variety of experimentation. Students were viewing and evaluating their computer models in both perspective and orthographic views. Additionally, it was noted that there appeared to be greater interaction among students during the process of learning to use the software. The more experienced users became proficient with the CAD more quickly and were a resource to other students as they worked through the assignment. Advances noted at the second critique included:

- A greater variety of structural members employed; W-shapes used for columns were replaced with round, square, or rectangular tube steel shapes and the sizes of members showed variations.

- In most proposals the sizes of horizontal members began to reflect the influence of span and loads.

- Some students began to experiment with bracing and trusses in the structural models.

The third and final critique was combined with the beginning of the reinterpretation phase. In addition to the computer model, students presented a physical mass model that represented a synthesis of their current structural proposal and the design for the project as a whole. Most structural models reflected consistency with the with the project proposals. The changes at this critique included the following:

- Proposals reflected an increasing awareness of the influence of structural loads and spans on member size.

- There was a noticeable increase in explorations of structural aesthetics. Several students had begun experimenting with trusses, bracing, cross-bracing, and tie-rod elements. These were selected for their architectural effect rather for structural considerations. Additionally, at this stage some proposals began to use free standing or exterior structural components as design
The structural models reflected adjustments that were influenced by revisions to their project, particularly in terms of building elevations. For example, the structure and/or building were modified to coordinate with curtain walls and at locations where structure was exposed.

In most proposals the relationship between building envelope and structure was less restrictive, reflecting experimentation with cantilevers and curtain walls.

Phase Three proved to be challenging as the students attempted to resolve inconsistencies between their project refinements and modifications to their structural system. All of the projects underwent significant revision from Phase One. However, the extent of the design revisions required in Phase Three were significantly greater for the students with weaker design proposals in Phase One. Therefore, while they may have developed the necessary CAD skills for the final structural model in Phase Two, the actual computer modeling from phase one was less useful for some students than others and a larger amount of their working time was devoted to redesign rather than refinement. Additionally, students varied in their success in producing visually and intuitively correct structural proposals in which structural member sizes and placement corresponded in some way to loads and spans. Most students attributed this to the need for additional structures knowledge before undertaking the studio as well as to time constraints. On the other hand, several students produced projects that were highly developed architectural with structural systems that were functional and in some cases highly detailed that exceeded performance expectations (Figure 6, 7).

Conclusions and Recommendations

The evolution of the structural designs over the course of the structural exploration and the reinterpretation phases demonstrated both an increase in competencies with the software and a greater awareness of the aesthetic qualities of structures. Student comments at the end of the course indicated that the task-specific CAD task contributed to their development as designers. As with all studios, the level of development of the projects varied. The extent to which the required CAD assignment contributed to this, particularly in terms of the use of CAD as the primary media in the final phase, can not be determined.

The sequence of activities was effective in meeting the goals of the studio. However, design studios are inherently demanding and time-consuming. Consequently, time allocated to activities must be well managed and coordinated. Studios using this approach should consider allocating sufficient time for the conceptualization phase relative to the skill-level of the students. Where this is not possible, instructors should give careful consideration to the project context in order to some extent limit the introduction of new design issues in addition to structures at the conceptualization phase. Additionally, while structure was discussed during critiques in this phase, a greater emphasis should be made in order to reduce the disruptions in project development. Consideration should also be given to more closely integrating the structures/CAD task with the final phase.

Design instructors should also give consideration to the role of maintaining media independence in the studio. Those instructors who feel that greater levels of media interaction in the studio is important to meet learning and skill-development goals and objectives should
consider additional parameters to specify media use in order to prevent a rush to use CAD at the various stages of the course. Lastly, consideration should be given to guest critics from engineering instructors at the structural exploration phase to provide additional insight and learning opportunities in order to enhance the studio experience.


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Figure 1. Low Level 3D Representation

Figure 2. Structural Parameters for Steel Beams
Figure 3. Structural Exploration: First Critique

Figure 4. Structural Exploration: Third Critique
Figure 5. Perspective Rendering, Phase 3 - Reinterpretation (Final Submission)

Figure 6. Perspective Rendering, Phase 3 - Reinterpretation (Final Submission)