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# The Design Process, Ideation, and Computer-Aided Design

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## Abstract

Largely due to engineering design applications such as computer-aided design, most engineering graphics curriculums have changed significantly since the middle 1980's. The content of an engineering graphics course is governed by the needs of students taking the course. This paper focuses on the engineering graphics curriculum at Western Washington University. The Engineering Technology Department at Western Washington University has changed its graphics focus from design communication to design development. Within the curriculum, topics covered include the design process, ideation sketching, conceptual modeling, documentation drawing, parametric design, and tolerance specification. This paper discusses these topics plus student outcomes and future developments.

## Introduction

The field of Engineering Graphics is in a state of change. Historically, in an engineering graphics course, students have been taught the principles of drafting. Recently, Computer-Aided Drafting/Design (CAD) applications have significantly changed the way that graphics has been taught. Today, it is common to find CAD as part of the beginning graphics curriculum. As CAD technologies evolve they affect the Engineering Graphics curriculum. Many instructors and institutions are introducing solid modeling within the beginning graphics curriculum. Anyone that took an engineering graphics course before the middle 1980's remembers the traditional approach to graphics. Topics covered at a minimum usually consisted of geometric construction, lettering, multiview projection, and dimensioning. Are these topics still important today? Almost anyone with experience in the graphics industry and with experience teaching engineering graphics can present a logical argument for or against the topics listed above. With the increased use of CAD in the graphics curriculum, what competencies should an engineering or technology student have upon completing an introductory engineering graphics course? Should the emphasis be on CAD, drafting, visualization, or the design process? This paper does not try to directly answer these questions. It only presents an approach to teaching graphics by one specific engineering technology department.

The needs of students within an engineering graphics course should be one of the primary factors used to determine the content of the course. Colleges and departments of engineering and technology vary in scope and nature. An institution with programs heavy in construction, architecture, and environmental engineering would approach graphics differently from an institution in which mechanical and manufacturing programs dominate. This paper focuses on the engineering design graphics curriculum within the Engineering Technology (ET) Department at Western Washington University (WWU). WWU's ET Department has ABET accredited programs in Manufacturing and Electronics Engineering Technology, and additional programs in Plastics Engineering Technology, Industrial Technology, Industrial Design, and Technology Education. The Industrial Technology program has options in Industrial Graphics, Supervision, and Vehicle Design.

The engineering design graphics curriculum at WWU emphasizes the design process, ideation sketching, and three-dimensional modeling within its introductory courses. In the first and second quarter graphics courses, students use the design process to solve engineering design problems. Within the design process, students use graphics in a way that simulates the concurrent engineering of a modern industrial environment. Topics addressed in the curriculum include ideation sketching, technical sketching, three-dimensional modeling, documentation drawing, parametric design, tolerancing, and assembly modeling. This paper addresses the rational for this approach to graphics and the curriculum approaches used by the courses' instructors. In addition, this paper discusses ideation sketching approaches, the use of CAD in the curriculum, and innovations under development such as rapid prototyping and integrated manufacturing.

**Objectives of Graphics Sequence**

We live in a three-dimensional world. When solving a design problem, an engineering student has to be able to think and visualize in three dimensions. With the increased capabilities of solid modeling packages, two-dimensional documentation drawings are becoming a down-stream step in the design process. At one time, the primary goal of the engineering design graphics sequence at WWU was the development of students' ability to communicate design intent through the language of engineering graphics. While this is still considered an important outcome, it is no longer the principle goal. The department has shifted its engineering design graphics emphasis from design communication to design development. Engineering Design Graphics I (EDG I), the first course in the sequence, has the following goals:

- To develop the necessary visualization and freehand drawing/sketching skills which will enable students of design (engineering, industrial, architectural, etc.) to express graphically a rapid succession of ideas in seeking the solution to a specific design problem.

- To develop initial CADD (Computer-Aided Design and Drafting) skills and the understanding of the concepts associated with 3-D solid modeling as part of the design process.

As stated in the first objective for EDG I, a focus is on the development of visualization skills. Visualization can be defined in multiple ways. The way that faculty at WWU define design visualization might be different from the typical engineering graphics definition of visualization. Giesecke [1] defines visualization as the ability to study a "sketch and interpret the lines in a logical way in order to piece together a clear idea of the whole" (p. 107). WWU's definition is similar to Madsen, et al. [2]. Madsen defines visualization as "the process of recreating a three-dimensional image of an object in a person's mind"(p. 936). Faculty that teach engineering design graphics at WWU define it as the ability to take an idea from your mind, develop it, and recreate it on paper or within a CAD system.

The second course in the engineering design graphics sequence, Engineering Design Graphics II (EDG II), introduces students to the utilization of a high-end parametric modeling application (Pro/ENGINEER) within the design process. This course has the following goals:

- To develop the ability to solve engineering design problems utilizing a parametric modeling application.

- To develop the ability to incorporate design intent into parametric part and assembly models.

- To develop the ability to document an engineering design, including tolerance specification.

An important driving goal of the ET Department is to develop curricula that mirror a concurrent and integrated engineering environment. Barr and Juricic's [3] model, shown in Figure 1, is a good representation of how WWU's ET Department approaches the teaching of engineering design graphics. Many of the functions identified on the model represent tasks to which students are exposed. Table 1 displays functions from the model covered within each of WWU's engineering graphics courses.

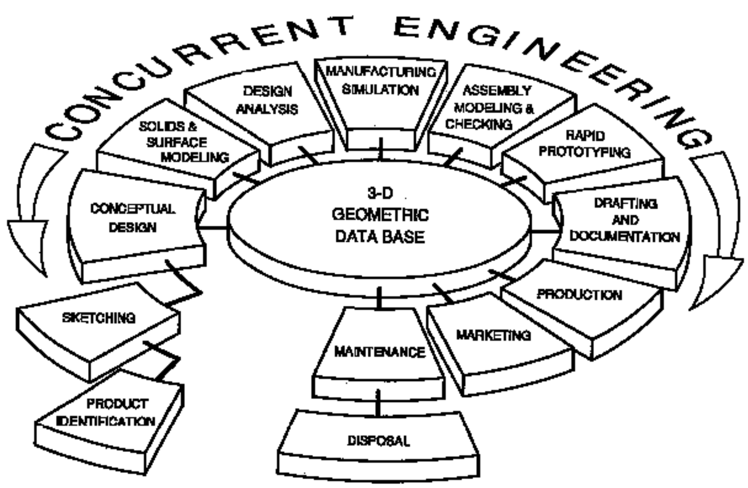


*Figure 1: 3D Geometric Models and Concurrent Engineering (Barr and Juricic, 1996)*

| ENGINEERING DESIGN GRAPHICS I | ENGINEERING DESIGN GRAPHICS II |
|---|---|
| Product Identification | Product Identification |
| Sketching | Sketching |
| Conceptual Design | Conceptual Design |
| Solid & Surface Modeling | Solid & Surface Modeling |
| Rapid Prototyping | Design Analysis |
| Drafting and Documentation | Manufacturing Simulation |
| | Assembly Modeling & Checking |
| | Rapid Prototyping |
| | Drafting and Documentation |

*Table 1: Engineering Design Graphics Functions*

## Design Process and Ideation

Most faculty members in WWU's ET Department cover the design process at the beginning of EDG I. Within this course, this process is used to solve various design problems. Typically, students work on design problems individually so that every student gains experience with managing the creative process. This is in contrast with EDG II, where one group design project is required so that students gain experience with the various issues of teamwork. In both courses, the following five-step design process is used: Problem Statement, Design Specifications, Design Concepts, Design Selection, and Design Details [4]. These steps support the goal of using sketching and CAD to generate a rapid succession of design concepts, while providing students with a structured approach to develop their project management skills. One of the key lessons for students with this approach is that significant effort must be spent at the beginning of the process carefully defining the problem before any concepts are developed. In addition, this process allows multiple ideas to be developed, evaluated, and improved based upon the carefully developed problem definition and design specifications.

The Problem Statement and Design Specifications steps of the design process require students to identify and focus on the problem under investigation. Problems selected for each course come from topics to which students can easily relate. An example is the design of a flashlight. Students must define the problem and develop specifications. They must also generate concepts through the use of ideation sketching, construct CAD models, and eventually document the final design concept. Examples of other design projects utilized in both engineering design graphics courses include a nutcracker, corkscrew, CAD workstation, and home entertainment center. In addition, the ASEE Engineering Design Graphic Division student design project has been used as a problem. While developing problem statements, students are encouraged to think in broad and general terms so as not to imply a solution in the statement of the problem. Once they have defined their problems, students develop a set of design specifications. Specifications are grouped according to design functions and design objectives. This process allows students to separate the functionality of a design from other criteria that might be important, such as cost, color, and weight. Students begin with qualitative descriptions of their desired objectives and functions, and then use these to develop quantitative specifications that include ideal and acceptable ranges, and rankings of the importance of each specification.

Once students have defined their problems and developed specifications, they must utilize ideation sketching to create design concepts. Ideation sketching is the use of artistic and/or creative sketching to solve a design problem. This type of sketching is used to remove barriers that might be present when trying to design on a CAD system or when designing using technical sketching. Ideation sketching has no set rules governing the orientation of design concepts. A description of how faculty help students develop ideation sketching skills is given in the next section. Students are required to develop several concepts for each design, and several iterations of each concept. Each iteration of sketches further refines the previous iteration. As students refine ideas, sketches become clearer and more readable.

| SPECIFICATION | BENCHMARK | CONCEPT 1 | CONCEPT 2 | CONCEPT 3 |
|---|---|---|---|---|
| Cost | 0 | + | + | - |
| Color | 0 | 0 | + | + |
| Flexibility | 0 | 0 | 0 | + |
| Functionality | 0 | - | 0 | 0 |
| | | | | |
| Total | 0 | 0 | 2 | 1 |

*Table 2: Example of a Benchmark Analysis*

Within each course and within each problem, students develop at least three viable concepts. Each concept is evaluated based on the specifications set during the Problem Identification and Specification steps. Two analysis methods are used to help identify the best concept of the three: Benchmark Analysis and Weighted Scoring. The Benchmark Analysis compares the specifications set for each concept with an existing design. Concepts are rated as either better (+), the same (0), or worse (-) on each specification. This method provides a quick analysis tool that allows students to identify their strongest designs out of a large set of concepts. Table 2 is an example of this. The Weighted Scoring method assigns weighted values to specifications. These values are based on the relative importance of each particular specification. After assigning a weight, each concept's features are rated on how closely they meet the specification. A weighted score is determined and the concept with the highest score is selected as the concept to further develop. This method is more accurate, but more time consuming, so students do not apply it until they have narrowed the number of potential concepts down to a manageable size. Table 3 is an example of a Weighted Scoring Table.

| SPECIFICATION | WEIGHT | CONCEPT 1 | | CONCEPT 2 | | CONCEPT 3 | |
|---|---|---|---|---|---|---|---|
| | | SCORE | WEIGHTED SCORE | SCORE | WEIGHTED SCORE | SCORE | WEIGHTED SCORE |
| Cost | 3 | 4 | 12 | 5 | 15 | 2 | 6 |
| Color | 2 | 3 | 6 | 4 | 8 | 4 | 8 |
| Flexibility | 4 | 3 | 12 | 3 | 12 | 4 | 16 |
| Functionality | 5 | 1 | 5 | 3 | 15 | 3 | 15 |
| | | | | | | | |
| Total | | | 35 | | 50 | | 45 |

*Table 3: Example of a Weighted Scoring Table*

Based on the design evaluation, students select one design concept from their conceptual designs. Within each course, students then develop a 3D CAD model of this concept. During the CAD modeling, students further evaluate and modify the design. After the 3D model is complete, students produce documentation drawings. Within EDG I, documentation drawings consist of orthographic views of the design, with necessary dimensions and annotations. Within EDG II, designs typically consist of multiple components. Students produce detailed working drawings of each part and an assembly drawing of the assembled design. Detailed drawings in EDG II require tolerance annotations, including geometric tolerances when necessary.

**Ideation Sketching**

Our approach to utilizing drawing in the design process is based upon that of Barr and Juricic [5,6]. Students learn that engineering graphics contributes to the design process at three levels: ideation sketches, communication drawings, and documentation drawings. Ideation sketches are generally drawn early in the design process to begin the development of design ideas. Communication drawings are used to share ideas with everyone from design team members to customers, and range from those drawings used to continue design development to those that are used in formal design presentations and advertisements. Documentation drawings or engineering drawings contain the information that is required to build the parts in a design and complete the assembly. Documentation drawings are now almost exclusively done on computers, but ideation sketches and some communication drawings are still drawn by hand, sometimes on the nearest blank sheet or flat surface. EDG I concentrates on developing ideation sketching skills and communication drawings, with only a cursory description of documentation drawings. EDG II is centered on the development of a complete set of documentation drawings.

In order to teach students to confidently create ideation sketches that actually resemble real objects, EDG I faculty utilize techniques that are often found in beginning drawing classes in an art department. For the first half of EDG I, students use techniques such as contour, modified contour, gesture, and negative space drawings to help develop their visualization skills [7,8]. It is somewhat strange to see students in an engineering graphics class drawing pictures of flowers and bookbags, but the approach is effective. The advantage of these art-based methods is that they encourage students to concentrate on drawing what they see rather than their stored mental image of the object. For example, many people have difficulty accurately drawing something as simple as a table. This is because they know in their mind that all of the legs are the same length, yet if a table is drawn with all of the legs equal in length it will have improper perspective, as the legs that are farther away actually look smaller. This practice helps students to see and visualize more accurately, and it also gives them more confidence in their drawing abilities. In the middle of the term, students are then taught techniques such as iteration drawings, and asked to sketch their design ideas for their assignments before they create drawings on the computer. Once again, the goal of this is not to make the students into artists, but to help them develop the skills to quickly and clearly sketch their ideas on paper for the purposes of both their own clarification and communication with other members of their design team. This approach is effective; it also is not unheard of in engineering graphics [9,10]. In fact, the results of using an art-based approach have been positive, so it is somewhat surprising that this approach is not used more commonly.

## Computer-Aided Design and Prototyping

Along with an understanding of the design process and sketching skills, one of the primary goals of WWU's engineering design graphics sequence is help students develop three-dimensional visualization and CAD modeling skills. This goal recently received additional support through a five year partnership between WWU and The Boeing Company [11]. During the first phase of this partnership, Boeing supplied funds for a modern computer-aided design facility. This laboratory is utilized to teach design, modeling, prototyping, and concurrent engineering.

Within the development of visualization and CAD modeling skills, the focus in EDG I is different than the focus in EDG II. The focus in EDG I is on conceptual design. This course utilizes Rhinoceros (Rhino) as its primary CAD package. Rhino is a NURBS based conceptual three-dimensional application. The conceptual modeling capabilities of Rhino allow students to design solid and surface models through the use of intuitive tools. Used in conjunction with ideation sketching and a strong emphasis on the design process, students are able to be creative, without the restrictions set by many high-end CAD applications. Since the visualization objective of the course is to allow students to develop design ideas through sketching and CAD modeling, Rhino, being an excellent ideation tool, allows students to produce conceptual models within the design concept stage of the design process.

The focus in EDG II is on concurrent engineering and capturing design intent. This course utilizes Pro/ENGINEER as its foundation CAD package. Parametric modeling and design principles are emphasized to include bottom-up assembly modeling. Students enter this course from EDG I with skills in conceptual CAD modeling. Pro/ENGINEER introduces them to an application more restricted in its modeling approach. Within this course, students utilize the design process and may use Rhino within the ideation process, but final assembly designs and drawings must be completed in Pro/ENGINEER. Various modules of Pro/ENGINEER are used to include Part, Assembly, Drawing, Format, and Manufacturing.

Students in EDG I individually solve several major design problems. In EDG II, students develop one of these problems further. Within EDG II, students work in teams to solve a major design problem that is based upon one of their EDG I projects. This approach allows students to bring their concepts from EDG I to the solution of the design problem in EDG II, and also allows them to begin to develop teamwork skills. In EDG I, students model the problem in Rhino. In EDG II, students develop and model the problem in Pro/ENGINEER.

In addition to the CAD modeling skills learned in these two courses, other applications are available for students who want to strengthen their CAD background. Graphics faculty are currently considering adding an introduction to SDRC's I-DEAS to the EDG II course along with Pro/ENGINEER. I-DEAS is currently used in the department's machine processing and plastics courses, so there is a good chance that it will be part of the

EDG II curriculum soon. In addition, I-DEAS and Catia are also taught within separate junior level courses on advanced CAD modeling.

When students obtain a broad base of CAD skills in the engineering design graphics curriculum it helps them to develop visualization skills. Design projects are also used in the curriculum to help students develop visualization skills through the development of design concepts using sketching and CAD modeling. The engineering design graphics faculty believe that while it is important for students to see a design concept within a CAD application, it is also important to see an actual prototype of a concept. The second phase of the Boeing partnership centered around rapid prototyping. Within the design process of both EDG I and EDG II, students are required to produce conceptual models. Prototypes are produced of these concepts utilizing either three-dimensional printing methods (Stratasys's Genisys) or fused deposition modeling methods (Stratasys's FDM). This is an important step in the design process. After the prototype is produced, a student has the opportunity to refine the design. In EDG I students each produce an individual design, usually not one of the major projects, so that they can see the relationship between their original sketch, their computer model, and the rapid prototyped part. In EDG II, students produce a rapid prototype of their team design project. In this case students are not only able to see the visualization chain from sketch to computer model to part, but they can also examine some of the assembly issues of their design. Within the assembly designs produced in EDG II, the interface and fit between components can be simulated and tested.

Pro/ENGINEER, I-DEAS, and Rhino are utilized in upper division manufacturing, plastics, vehicle design, and industrial design courses. The plan of the faculty within the ET Department is to integrate course projects to simulate an integrated manufacturing environment. Currently, one design project is integrated within EDG I and EDG II. Future developments in WWU's ET Department will have design problems developed in the two graphics courses to be integrated into other engineering technology and design courses. Possibilities include manufacturing processes, numerical control operations, quality assurance, and computer-integrated manufacturing. This approach will allow students to practically see the steps required in a typical manufacturing environment. For example, within this integration students will develop, refine, model, and document designs in the engineering design graphics sequence. Then in manufacturing processes courses, students will create manufacturing plans and fabricate the actual design. Finally, quality control, metrology, and finite-element analysis courses will allow students to analyze and inspect their designs. This is part of the ET Department's long-term goal of developing a concurrent engineering approach throughout the entire curriculum.

**Course Assessment and Student Feedback**

Faculty have collected a limited amount of assessment material from EDG I and EDG II. The ET Department graphics committee created a qualitative survey for EDG I and received feedback from 79 students in fall 1998 and 109 students in fall 1999 regarding how the course met their expectations, what they felt they gained from the course, and what role they saw visualization and sketching playing in the design process. Overall, most students enjoyed the class and rated it highly, with many saying they would recommend the course to others. This also was evident on the university course evaluation form, where the average course rating for all sections during the same term was 4.3 out of 5 in fall 1998. In general EDG I exceeded student expectations, and the majority of students found that they had learned more and had more fun than they expected they would. The large visualization and freehand drawing aspect of the class also received general approval. Quite a few students expressed appreciation for the role of visualization and freehand drawing in the design process. A few students even expressed surprise at their own ability to draw at the conclusion of the class, although a small number (<5%) of respondents felt that there was too much freehand drawing in the class. As with the visualization and drawing sections of the class, students had many comments on doing design projects, and all of them were positive. Many students also expressed an appreciation for the role of a design process. Students' understanding of and appreciation for the design process was also evident in the work that they turned in for their projects, some of which was very impressive for an introductory course.

As of this time, we do not have any equivalent data for EDG II, although a similar form is being developed for this course. A limited amount of student feedback has been obtained from the university course evaluation forms. As with EDG I, a majority of the student comments toward EDG II have been positive, especially from students having the opportunity to take the new EDG I and EDG II curricula. An original concern of the faculty was the migration of students from Rhino to Pro/ENGINEER. This concern focused on the transfer of student skills in Rhino's NURBS and Boolean based modeling concepts to Pro/ENGINEER's parametric, feature-based modeling concepts. This concern did not prove to be well founded. Despite Pro/ENGINEER's initially steep learning curve, by the end of the course, a majority of the students in EDG II were able to utilized basic part modeling (protrusion, cuts, blends, sweeps, etc.) and assembly modeling tasks to solve design problems. In addition, students were able to use Pro/ENGINEER's Drawing mode to document engineering drawings, to include tolerance specification. By the end of EDG II, most students were pleased to have the opportunity to learn an engineering application such as Pro/ENGINEER.

As part of the ET Department's overall assessment plan a more quantitative survey form will be developed for both EDG I and EDG II in the near future. In addition, EDG I and EDG II students will also begin to develop portfolios of their work once the faculty have agreed upon a process of portfolio review. Nevertheless, even with only a partial assessment strategy in place it is evident to faculty that students in EDG I and EDG II are benefiting from the emphasis that is placed on design and visualization as part of the engineering graphics curriculum, in which students are taught various hand and computer-based graphics techniques as tools for design rather than ends in themselves.

**Conclusion**

WWU's Engineering Technology Department considers its engineering design graphics courses to be the main foundation for the Manufacturing and Plastics Engineering Technology, Industrial Technology, and Industrial Design programs. Students majoring in these programs are expected to apply the skills they learn in engineering design graphics in other courses throughout the curriculum. The primary goal of the engineering design graphics curriculum is on the development of design skills. Within this goal, specific objectives are the development of design visualization and computer-aided design skills. Within EDG I, this objective is met through the use of ideation sketching and conceptual CAD modeling. EDG II reinforces these goals and addresses an additional objective of the graphics curriculum of the capturing of design intent through the use of a parametric modeling application. Within each graphics course, a strong emphasis is placed on the design process. Students are required to develop design specifications and concepts. Concepts are further refined through three-dimensional modeling and prototyping. Qualitative assessment of the revised engineering design graphics curricula in the ET Department at WWU shows that the introductory courses are meeting their goals and preparing students well for their future classes.

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