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STRIKING A BALANCE BETWEEN ENGINEERING SCIENCE AND ENGINEERING DESIGN: CREATION OF AN INTERDISCIPLINARY ENGINEERING PROGRAM

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Abstract

The core goal of this new program is to provide an undergraduate engineering curriculum that prepares students to work as design engineers at the boundaries of two or more traditional engineering disciplines. The proposed interdisciplinary program, focusing on engineering systems and engineering design, encompasses the study of theories and methodologies that develop creative solutions to open-ended engineering design problems. Graduates of this program will use modern design methodologies, simulation, analysis and optimization techniques to develop safe and functional solutions to complex interdisciplinary design problems while adhering to constraints involving economics, reliability, durability, aesthetics, ethics and social impact (including legal and environmental issues).

Keywords: Design education, curriculum, creative education, design training

1. Introduction

The Department of Basic Engineering at the University of Missouri – Rolla (UMR) is a service department for the campus, teaching the engineering orientation course, the freshman engineering design course, statics, dynamics, mechanics of materials, and several general engineering design courses. During the Spring 2002 semester, a committee of Basic Engineering Department faculty members was charged with the task of exploring ideas to include an ABET-accreditable degree-granting program within the department's mission. From this work, a proposal emerged for the development of an interdisciplinary engineering program. A preliminary curriculum (which builds on the common freshman year for engineering), tentative course descriptions, and specialty track guidelines (including example tracks) were developed. The proposed curriculum meets current campus guidelines for BS engineering programs, such as a limit of 128 credit hours and six credits of unrestricted free electives. The proposed interdisciplinary degree program effectively uses the existing department and campus teaching resources to provide students a flexible but rigorous curriculum that can be shaped to suit their educational and career objectives. This paper discusses the process through which the proposed UMR interdisciplinary degree program was conceived, structured, and enhanced.

2. Background

The Basic Engineering Department at UMR is composed of faculty with a variety of backgrounds, including mechanical, electrical and petroleum engineering, physics and engineering mechanics. The interdisciplinary engineering program builds on these strengths which include teaching and research expertise in design and systems; extensive experience in teaching multidisciplinary courses (freshman design, engineering mechanics, senior design [1]); a strong focus on engineering education; extensive interest, experience and research in using technology to enhance learning; and a strong engineering campus with 15 traditional (single-discipline) engineering majors.

Consideration of these strengths led to the idea of creating a flexible, interdisciplinary engineering degree program that gives students significant control over course selection. Some background work done toward designing the curriculum is described in this section, while the following two sections report on planning and implementation.

Preliminary interest surveys of the proposed program were conducted with students at UMR, and key results are shown in Table 1. In particular, responses to questions concerning level of interest in our proposed degree program (after reviewing a program description and base curriculum), level of concern regarding finding a job with the degree, and level of interest in attending graduate school are noted. A seven-point Likert scale was used for all responses.

Table 1. Preliminary student interest survey in the proposed degree program.

Sample source	*n*	% highly interested in program (≥ 5 on Likert)	% highly concerned about job possibilities (≥ 5 on Likert)	% highly interested in graduate school (≥ 5 on Likert)
BE 20 students (freshmen)	85	43	52	59
BE 50 students (predominantly juniors)	56	55	39	59

To summarize Table 1, the survey suggests that there are significant numbers of students currently attending UMR who are interested in a program such as the one proposed. Furthermore, interest in the proposed program increases as students learn more about engineering and the types of jobs available. It also appears that such knowledge lessens students' concern about job availability for program graduates compared to the more traditional programs.

Engineering degree preferences of high school seniors in Missouri and surrounding states were also investigated, and these findings are summarized in Table 2. A substantial number of high school students expressed an interest in non-traditional engineering degrees. Combining those students expressing an interest in majors of (a) engineering science, (b) other engineering technologies, (c) general engineering, and (d) general engineering-related technologies, a pool of 2,921 potential students (with an average ACT score of 28.7) was found from Missouri and surrounding states. In the Fall 2001 semester, only 78 students from this pool enrolled at UMR.

Table 2. ACT results for Missouri and surrounding states (AR, IL, IA, KS, KN, NE, OK, TN) for graduating class of 2001.

Educational major	ACT test sample	ACT average	UMR yield
Engineering science	8	28.4	0
Other engineering technologies	43	28.1	1
General engineering	2244	28.8	60
General engineering-related technologies	626	28.6	17

Preliminary research shows that surrounding states currently offer non-traditional engineering degree programs that are related to our proposed program. Examples include Interdisciplinary Engineering (Purdue University), General Engineering (University of Illinois), Systems Engineering (University of Arkansas at Little Rock) and a variety of bio-engineering programs. Our intent is not simply to "catch-up" but to offer a unique and needed interdisciplinary engineering program. We believe the focus of our program on systems integration and engineering design addresses these needs. Additionally, our program is envisioned to be a quick-response home for cutting-edge technical tracks in areas such as micro-electrical machines, nanosystems and bioengineering.

3. Designing the Curriculum: The Plan

As reported in the previous section, a survey of UMR students revealed a significant interest in a flexible, interdisciplinary engineering degree program. In addition, examination of engineering degree preferences of high school seniors revealed significant interest in non-traditional engineering degree programs. With these meaningful indicators in hand, we decided that the next step toward developing the new degree program was to work out a plan of action to include the following:

- ***Continue Gathering Customer Needs.*** Companies that employ engineering graduates can be considered an important customer of a new degree program. Our plan includes developing a web-based survey and targeting specific groups of company representatives through various campus contacts to develop a thorough set of customer needs [2, 3].
- ***Survey related programs***. An informal survey revealed that Missouri universities do not offer a program similar to the proposed program, while some universities in surrounding states do appear to offer such a program. We decided to expand and formalize this survey in order to collect ideas and further define the need.
- ***Study ABET requirements***. To become accredited in the US, engineering programs must undergo an ABET (Accreditation Board for Engineering and Technology) evaluation. In recent years ABET requirements have been significantly revised. A recent paper by Felder and Brent [4] will serve as a guide as we develop the curriculum and design individual courses
- ***Define and develop tracks***. Requirements for tracks must be carefully defined so that students are exposed to significant depth and breadth in two fields of study.
- ***Decision science for defining the curriculum: QFD.*** A recent paper by faculty from Old Dominion University describes a method of using decision science to prioritize courses and course content to help meet program objectives [5]. The application of Quality Functional Deployment (QFD) and other engineering design techniques for this purpose appears to be a powerful approach to curriculum revision [6, 7].
- ***Investigate educational software.*** The new degree program will grow out of the Basic Engineering Department. This department has a history of focusing on innovations in education, including technology in the classroom. The plan includes examining how some of the current research in this department might be expanded to enhance the new curriculum.
- ***Organize an external review***. Design and engineering curriculum experts will be asked to review the new program.

These seven tasks are currently underway as a part of a one-year NSF planning grant to develop the new curriculum. Preliminary results will be presented in the next section.

4. Designing the Curriculum: Implementation

4.1 Gather Customer Needs

In this phase of the program planning, we gathered customer needs from prospective employers of an interdisciplinary engineer graduate. We solicited the needs from three sources: the Dean of the School of Engineering's Industry Advisory Council (IAC), the University's Corporate Development Council and other engineering industry contacts known to the authors. In general, this pool represented automotive, appliance, industrial equipment, electronics and energy companies as well as government and military labs. The Dean's IAC (consisting of ten members) provided verbal feedback at one of their regularly scheduled meetings. The remaining sources completed the web-based program survey (sample size of 18). Key results of the survey are presented below in Table 3. The survey questions, where appropriate, used a Likert scale. In the survey we listed an initial set of skills that we deemed important for our graduates to possess and asked the respondents to indicate their importance. Additionally, a free response section allowed additional skills to be identified by the respondents. These responses, along with the verbal feedback from the IAC, were used to generate an initial set of customer needs for the degree program and are summarized in Table 4. The list of needs is weighted based on the frequency with which they occurred in the responses.

Table 3. General program questions on the web-based survey.

Question	Response range	Avg. resp.
1. Does your company have a need for engineers that are broadly educated across several disciplines?	[1=Not at all, 7=Yes, in all cases]	4.94
2. Do the engineers who design products in your company use a systematic design methodology, such as QFD, design for six sigma, FMEA or other approach?	[1=Not at all, 7=Yes, in all cases]	4.67
3. Do the products your company produce involve multiple engineering domains (such as mechanical and electrical)?	[1=Not at all, 7=Yes, in all cases]	5.95
4. Based on the program description, does this interdisciplinary engineering program provide the key skills that your engineering employees need?	[1=Not at all, 7=Yes]	4.73
5. Would you be more likely or less likely to hire a graduate of this interdisciplinary engineering program than from a traditional engineering program?	[1=Less likely, 7=More likely]	4.06
6. How important is it to your company to hire graduates from an ABET accredited engineering program?	[1=Not at all, 7=Extremely important]	6.11

After gathering customer needs, one of the most surprising needs that we previously overlooked in the initial planning stage is that of project management expertise. This was a free response need that appeared with great frequency across our respondents. Another need emphasized (and receiving a top weight) is to ensure that interdisciplinary engineering graduates have an appropriate depth of engineering skills regardless of what two traditional engineering fields provide their breadth. This need complemented our desire to create a broad-based engineering degree that maintains, and even augments, students' technical prowess.

Table 4. Weighted customer needs gleaned from industry surveys (5 = most important, 1 = least important).

Customer need	Wt.
Engineering technical skills	5
Generate creative solutions	5
Possess knowledge of multiple engineering domains	4.5
Curriculum contains design content	4
Students are able to work in teams	4
Know how engineering fits with other organizational functions	4
Communication/presentation skills	4
Understand project management techniques	4
Flexibility in course selection	4
Possess prototyping skills	3.5
Emphasize conceptual design	3
Know how to gather customer needs	3
Able to plan and facilitate meetings	2
Possess knowledge of metals/polymers/elastomers	1
Apply six-sigma methods	1
Apply statistical methods	1
Understand thermodynamics	1
Interpret drawings and schematics	1
Perform tolerance analysis	1

4.2 Survey related programs

We have completed a survey of programs related to interdisciplinary engineering in order to gain ideas and further assess needs. The survey included local programs in Missouri and surrounding states as well as other programs in the US and abroad. The information collected on these programs includes ABET accreditation status (US programs), a measure of the flexibility of the programs in terms of engineering and science electives (free and restricted), and the number of courses that contain a significant engineering design component. Table 5 shows the results of this survey for some of the programs examined. This information was gathered primarily from university web sites and published course descriptions, which may or may not be continuously updated as programs evolve.

Note that many of the programs in Table 5 are located outside the US, while just a few can be considered to be local (Missouri and surrounding states). The UMR Interdisciplinary Engineering program, as envisioned, has a strong design component (5 courses) and a significant number of free engineering electives (7 courses), as compared to other universities in our region.

4.3 Evaluate ABET requirements

At first glance, the 2003-2004 criteria for accrediting engineering programs posted on ABET's web site (www.abet.org) appear to be fairly straightforward. Criterion 8 states that "Each program must satisfy applicable Program Criteria (if any)." The Program Criteria provide guidelines on interpreting the basic level criteria for a given discipline. We originally planned to seek ABET accreditation under the program criterion titled "Nontraditional Programs," however, this category is no longer included under Program

Criteria. This fact along with the "if any" addendum on the above quote implies that we must focus on meeting the General Criteria for Basic Level Programs.

Table 5. Survey of Programs Related to Interdisciplinary Engineering

University, State/Country	Degree	ABET (IP = in progress)	Free Engr. Courses	Restricted Engr. Elect	Sci/Math Elec.	Design Courses
Cardiff University, England	Integrated Engr.	N/A	0	4	0	7
Grand Valley State University, Michigan	Engineering	yes	7	2	6	7
New Mexico Highlands University, New Mexico	Engineering	IP	3	0	0	5
Purdue University, Indiana	Interdisciplinary Engr.	no	21	0	2	0*
Smith College, Massachusetts	Engineering Science	IP	3	0	2	2
Stanford University, California	(Individually Named)	no	12	1	12	7
University of Aberdeen, Scotland	Integrated Engr.	N/A	0	9	0	7
University of Denver, Colorado	General Engr.	yes	4	0	0	7
University of Florida, Florida	Engineering Science	yes	7	0	0	5
Univ of Illinois - Urbana-Champaign	General Engr.	yes	4	2	0	7
University of Missouri-Rolla, Missouri	Interdisciplinary Engr.	IP	7	0	1	5
University of Newcastle, Australia	Mechatronic Engr.	N/A	1	3	0	4

* No design courses are specified, though they may be included.

ABET outcomes listed under Criterion 3 (3a-k) have been the focus of attention among engineering educators in recent years. Two of the outcomes (3b and 3c) focus on the student's ability to *design* experiments, systems, processes or components. It appears that these design-related outcomes will be easily met by our new curriculum. Outcome (3d) emphasizes the student's ability to function on *multi-disciplinary* teams. Given that the new curriculum is multidisciplinary by nature and will contain several project courses, outcome 3d should be addressed by the program. Additional issues related to ethical responsibilities, effective communications, global/societal context, life-long learning and contemporary issues are addressed in outcomes (3f)-(3j). Special attention will be paid to these issues so that these outcomes are addressed. Additional outcomes relate to applying math, science and engineering (3a) and identifying, formulating and solving engineering problems (3e). These outcomes will primarily be addressed by carefully formulating the track requirements. A final outcome relates to the ability to use engineering techniques, skills, and modern engineering tools (3k). We anticipate that this outcome will be addressed by careful course design.

Relative to outcomes (3a)-(3k), engineering programs must have an assessment process as well as evidence that the results of the assessment process are used to improve the program. Guidance for course learning objectives and assessment methods addressing outcomes (3a)-(3k) are given in the paper by Felder and Brent [4]. This reference also proposes a strategy for integrating curriculum and course development to meet ABET guidelines. This recent and timely work provides a framework for developing a new engineering curriculum. We are in the process of evaluating this and other references to make sure we address ABET requirements while developing program and course-level requirements.

4.4 Define and Develop Tracks

The heart of the interdisciplinary engineering program is the significant flexibility it gives to students to combine two or more traditional engineering and science fields. The need for engineers with broad technical knowledge that can be applied in design fields is supported by our customer need survey and the desire to obtain such a degree is confirmed by student interest surveys. Within our 128 credit hour curriculum, we have defined 21 credit hours as flexible engineering hours, termed a *specialty track*. This is in addition to the six hours of free electives that may be drawn from any discipline on campus. In order to meet certain ABET guidelines (as discussed above), we have drawn up an initial set of guidelines for students when designing their specialty track:

- A specialty track consists of at least 21 credit hours, to be achieved through seven 3-credit hour courses or some combination of lecture/lab courses. The student should work with an Interdisciplinary Engineering faculty advisor during the first semester sophomore year to develop a track and obtain approval.
- The courses in a track should be selected to give significant exposure in at least two areas of engineering or one area of engineering and one area of science. Due to the interdisciplinary intent of the degree, normally a track should contain no more than 12 credit hours selected from a single academic department.
- Normally 12 of the 21 credit hours must be engineering courses. The remaining hours may be selected from engineering, science and/or advanced math courses.
- At least 3 credit hours must be 3xx level (upper-level undergraduate technical electives).

Initially four sample tracks have been developed in the areas of Product Design, Energy Systems and the Environment, Robotics and Control and Industrial Automation and Control. The review of related programs and the industry need gathering has led us to formulate a fifth sample specialty track of Mechatronics. Ultimately, we view the specialty tracks as a quick-response mechanism to provide instruction in cutting-edge fields such as nanotechnology, biomechanics or fuel cells.

4.5 Making decisions about the curriculum: Using QFD

At the end of our preliminary internal program study, we formulated a baseline curriculum that defines a Bachelors of Science in Interdisciplinary Engineering. The baseline curriculum met institutional requirements such as number of credit hours and also incorporated the flexibility of interdisciplinary tracks (as described in Section 4.4). As part of that baseline, we identified five new courses that unify the interdisciplinary tracks under the umbrella of interdisciplinary engineering. The sophomore year begins with Design Representations, a 3-credit course that teaches students to represent objects by drawing (sketching, side views, perspective, exploded views) and using computer tools (solid modeling, assembly drawings). Modeling, Simulation and Prototyping of Dynamic Systems is a 3-credit course to be taken during the first semester of the junior year. This lecture course will teach students to model multi-domain systems using a bond graph approach, which leads to state space equations for simulation and design activities. The course will include studies of systems incorporating more than one traditional engineering field, such as transducers and actuators, simulation of nonlinear systems using numerical methods, and modeling by physical prototyping. The second semester junior year includes the course Junior Design Project, which is a 2-credit lecture/lab interdisciplinary project course. This course will be structured around varying projects where students will model a product mathematically and physically. Simulation of the mathematical model will be confirmed by testing of the prototyped product. The senior year includes Engineering Design Methods and Engineering Design Projects as a two-course sequence (Stone and Hubing, 2002). The first course teaches modern design methodology and prototyping. The second course builds on the methods course using a semester-long design or redesign project and covers more advanced design and manufacturing topics such as TRIZ [8] and design for manufacture and assembly techniques. Students work in teams, utilizing techniques taught in earlier courses to complete each step of the design project. The baseline curriculum also included the fundamental mathematics, science and engineering courses as well as the seven engineering/science electives that make up the interdisciplinary tracks.

To assess our initial curriculum, we applied a quality functional deployment (QFD) technique to measure how well the curriculum meets the industry and student-based customer needs. This approach is similar to that of Kauffmann et al. [5]. QFD is a powerful tool that relates customer needs to product characteristics through the use of a matrix commonly referred to as a "house of quality." Although this technique is traditionally used in product development and industrial applications, its flexibility allows utilization in any application where content and alternatives need to be related to program goals or requirements.

The meat of the QFD is an interaction matrix that maps "hows" (curricular content) to "whats" (customer needs), a fragment of which is shown in Fig. 1. We identified customer needs and desired attributes and ranked them based on priority and importance (see section 4.1). These are listed on the left-hand side and represent "what" should be addressed. Along the top of the house of quality are the core and proposed track courses, representing "how" the customer needs will be met. We then assigned each course a relationship value of nine, three, one or zero based on its effect or contribution to each of the customer needs (9=high interaction, 3=medium, 1=low, 0=no interaction - A larger range on the scale provides more variation and makes the final relative prioritization more accurate). The bottom displays the importance of each course (found by multiplying each relationship value by the customer need weight and summing over the course column). This provides a means of comparison based on each course's contribution to the weighted customer needs. Percentage of total importance is also shown for a more graphical interpretation. In this way, the QFD process ensures that customer needs are incorporated into the program criteria and requirements.

The top courses based on the calculated importance are in the column headings of Fig. 1. It is interesting to note that two thirds of the top courses are base curriculum and new courses that would be housed in the proposed Interdisciplinary Engineering Department. Also note that the top courses not in the Interdisciplinary Engineering Department are each from a separate department, reinforcing the curriculum's intent to combine two or more traditional engineering disciplines. Though not shown here, the analysis showed that each proposed track has relatively the same importance, supporting the flexible nature of the curriculum.

We incorporated a horizontal sum into the QFD to assess how well each customer need was being met. Similar to the importance rating for the courses, the horizontal sum totaled the relationship values for each customer need, and then multiplied that number by the weight given to that particular customer need. The results showed that the initial curriculum was weak in addressing project management, communication/presentation skills, and knowing how engineering fits with other organizational functions. Concerning the project management need, this finding presented us with two possibilities: either incorporate project management skills into the interdisciplinary courses or add an existing project management course from another department. Our choice was to include project management topics in our freshman and junior design courses. For the remaining two needs, we have added formalized communication and presentation instruction to all of our design courses and have added topics on organizational fit to the senior level engineering design projects course. Additionally, we have designated a communications course requirement as part of the general humanities and social sciences block of courses.

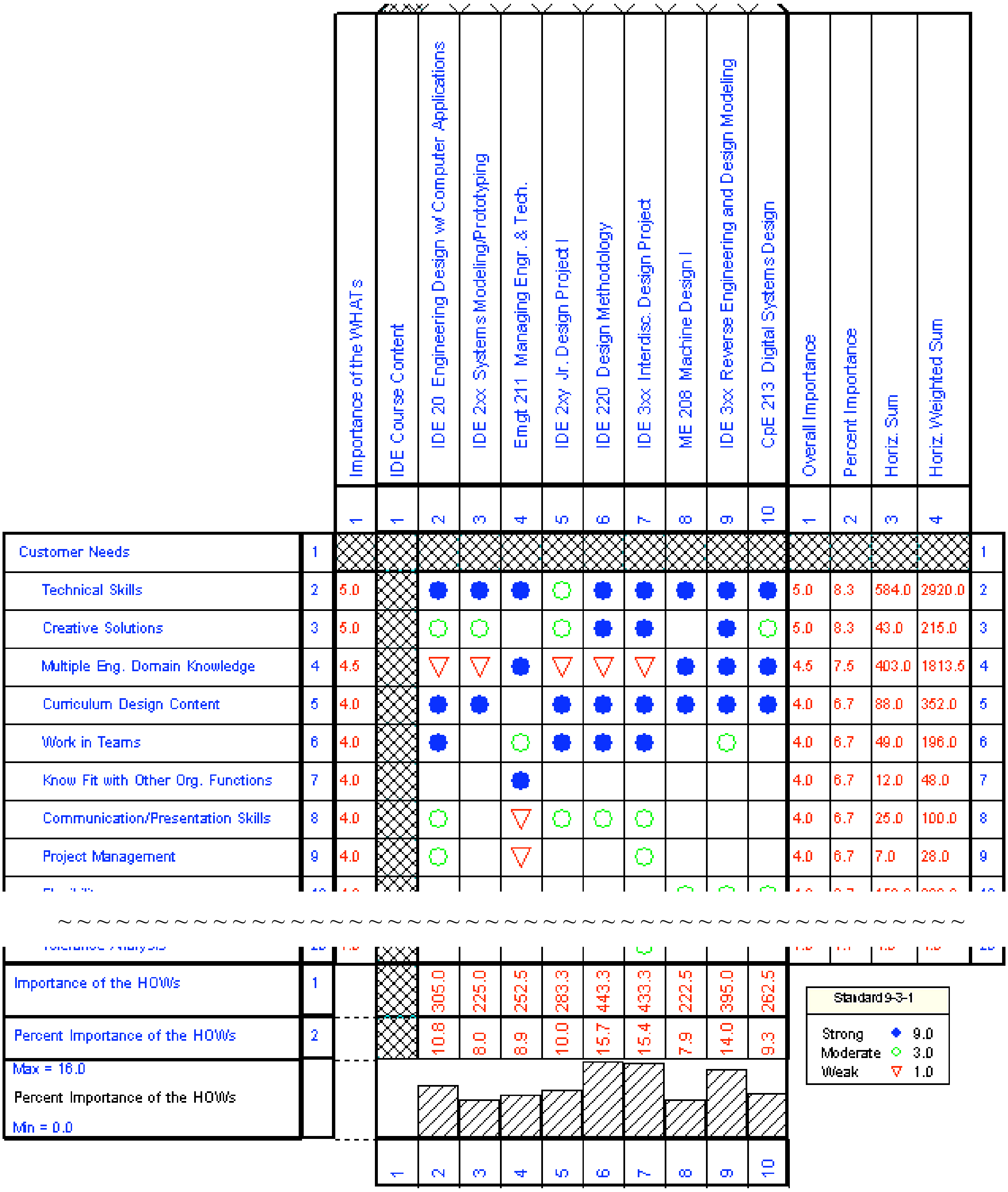

Figure 1. Fragment of the QFD analysis of the Interdisciplinary Engineering curriculum.

4.6 Software integration

There are many opportunities for effective use of software to enhance the proposed program. Potential software usage can be broken down into three broad categories: instruction, student tools, and delivery.

- ***Instruction.*** Instructional software can be developed to teach or assist professors in teaching various topics to students. For example, software models for simple machines can be developed to illustrate design concepts. Using animation and three-dimensional rendering techniques, machine subsystems could be highlighted, animated, and discussed in detail. The interrelationship of subsystems could be animated, and students could disassemble the model to examine how the pieces fit together. Another use for instructional software is to enhance topics traditionally taught only with the printed page and the classroom chalkboard. For concepts that are difficult to visualize and learn from the static page, instructional software offers a wide variety of animation possibilities. Interactive software applications and simple games can also help accelerate the learning process for students.
- ***Student Tools.*** Student tools are envisioned as computational aids that can enable students to perform advanced or complicated calculations required for design. In some instances, students would be expected to learn the computational method. For these situations, the software would be more tutorial in nature, explaining the calculation process to students. In other instances, students might merely need to use the results of a calculation in their design process, but they would not be expected to perform the calculation by hand. For these cases, the software might simply be an easy-to-use “black box” that would facilitate the accomplishment of other educational objectives.
- ***Delivery.*** With the ready availability of the Internet, it may be appropriate to deliver some courses or some portions of courses online. Remedial or supplementary content might also be available using the Internet capability. The suitability of distance delivery depends largely on the individual course and its contents.

The faculty of the Department of Basic Engineering have an ongoing interest in the development and use of technology in the classroom [9, 10, 11]. Since the interdisciplinary engineering program will grow out of this department, the focus on technology in the classroom will be maintained.

5. Conclusions

The impact of this new, interdisciplinary program will be twofold: 1) it will attract students into engineering that are not satisfied by a traditional, less flexible engineering discipline; and 2) it will meet high-tech industry needs. We believe that the increased flexibility incorporated in our program will appeal to a large number of bright students who are not interested in traditional engineering programs with rigid requirements. The program will also meet increasing industry demands for broad-based product and systems designers capable of immediately working in interdisciplinary engineering areas such as mechatronics, nanosystems and bioengineering.

Using modern design methods to “design” our new curriculum has led to insights that would otherwise have been overlooked. The identified industry and student-based customer needs have led to several changes in our baseline curriculum as well as additional interdisciplinary tracks that are desired by industry. The use of this approach as an ongoing curriculum analysis tool will ensure that our program continues to produce engineers that are prepared for today's rapidly changing technology.

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