Engineering program outcomes and assessment: A sustainable, systematic process for continuous improvement

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ABSTRACT: The USA Accreditation Board for Engineering and Technology adopted recently a new set of criteria for evaluating engineering programs. One of these (criterion 3) refers to program outcomes and assessment. The paper describes the design and implementation of a sustainable, systematic process for defining and assessing program outcomes. This process involves analysing each outcome into elements, defining a set of attributes for each element, selecting outcome indicators and performance targets, and. developing special rubrics for accurate assessment of student skills. The paper also presents a systematic way of addressing specific program outcomes through course and curriculum design. Each outcome is assessed in a group of selected courses in an effort coordinated by several faculty members. Course changes are implemented as necessary to increase student achievement in critical areas. The focus of this effort is to create a process that facilitates the continuous improvement of a program.

INTRODUCTION

The USA Accreditation Board for Engineering and Technology (ABET) adopted recently a new set of criteria for evaluating engineering programs. One of these, criterion 3, refers to Program Outcomes (POs) [1]. POs *describe what students are expected to know or be able to do by the time of graduation from the program*. A systematic process must be in place to assess the achievement of all the POs before students graduate. This process needs to be ongoing to ensure the continuous improvement of each program.

The paper describes the design and implementation of such a systematic process in the Aerospace (AE) and Mechanical (ME) Engineering Programs at San Jose State University.

PROGRAM OUTCOMES AND ASSESSMENT

ABET Criterion 3 requires engineering programs seeking accreditation to demonstrate that their graduates have:

a. an ability to apply knowledge of mathematics, science, and engineering.
b. an ability to design and conduct experiments, as well as to analyze and interpret data.
c. an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability and sustainability.
d. an ability to function on multi-disciplinary teams.
e. an ability to identify, formulate, and solve engineering problems.
f. an understanding of professional and ethical responsibility.
g. an ability to communicate effectively.
h. the broad education necessary to understand the impact of engineering solutions in a global and societal context.
i. a recognition of the need for, and an ability to engage in life-long learning.
j. a knowledge of contemporary issues.
k. an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Outcome Elements and Attributes

Because outcomes are rather comprehensive and difficult to assess as stated, Felder and Brent [2, p.19] suggest that each outcome be analysed into *elements* – different abilities specified in the outcome – and that a set of *attributes* be defined for each element – actions that explicitly demonstrate mastery of the abilities specified. For example, outcome (b) can be analyzed into four elements with associated attributes for each element as follows:

(b1) Graduates must have an ability to design an experiment. To demonstrate this ability students should be able to:

- Define the goals and objectives of the experiment.
- Research any relevant theory and previously published data from similar experiments.
- Select the dependent and independent variable(s) to be measured.
- Select appropriate methods, proper range / values, the appropriate number of data points needed, and the appropriate equipment / instrumentation for measuring these variables.

(b2) Graduates must have an ability to conduct an experiment. To demonstrate this ability students should be able to:

- Familiarize themselves with the equipment in our labs.
- Calibrate the instruments they need to use.
- Follow proper procedures to collect their data, given an experimental setup.

(b3) Graduates must have an ability to analyze a set of experimental data. To demonstrate this ability students should be able to:

- Carry out the necessary calculations.
- Perform an error analysis of their data.
- Tabulate and plot their experimental results using appropriate choice of variables and software.

(b4) Graduates must have an ability to interpret experimental data. To demonstrate this ability students should be able to:

- Make observations and draw conclusions regarding the variation of the parameters involved.
- Compare their results with predictions from theory, computer simulations or other published data and explain any discrepancies.

Attributes for all 11 outcomes have been defined for both the AE and ME Programs at SJSU [3]. To ensure that students acquire higher-order skills in each outcome, attributes were defined for each of the six levels of Bloom's taxonomy in the cognitive domain [4] and for each of the five levels in the affective domain [5]. Reference [6] provides excellent guidelines for defining outcome attributes.

Outcome Indicators and Performance Targets

Two outcome indicators are used to assess student attainment of program outcomes: (a) course performance ratings based on graded student and (b) student surveys. To satisfy Criterion 3, performance targets were defined as follows:
(a) The scores earned by all students in the assignments and test questions, which pertain to a particular outcome, in each course where this outcome is measured, must be at least 60%[1].
(b) The ratings pertaining to this outcome, given by at least 70% of the students in each class surveyed, must be "I agree" on a 3-point Likert scale.

If these targets are met in the courses chosen for assessment of an outcome, the outcome is achieved and no further action is needed in this course.

Rubrics

For accurate assessment the development and use of special rubrics for each outcome is necessary. This is especially critical for outcomes that involve soft skills, such as teamwork. An example of such a rubric is shown in table 3 for outcome (d). In addition to assigning scores for their teammates, each team member is asked to write one or more paragraphs about the work of each member on the team, including themselves. These narratives are meant to amplify the ratings given by (a) identifying the strengths and weaknesses of each individual and (b) suggesting ways in which his / her work can be improved. Team members evaluate also the effectiveness of the team as a whole.

Outcomes Assessment

Figure 1 shows the process for assessing outcomes. Each course contributes to at least one of the outcomes. Hence, a particular outcome is addressed in several courses. Nevertheless, a subset of these courses is selected for assessment purposes, using the following requirements:

Table 3. Rubric for assessing ability to function on a team

Criteria	Member 2	Member 3	Self
Quality of Technical Work: Work is correct, clear, complete, and relevant to the problem. Equations, graphs, and notes are clear and intelligible.			
Commitment to Team / Project: Attends all meetings. Arrives on time or early. Prepared. Ready to work. Dependable, faithful, reliable.			
Leadership: Takes initiative, makes suggestions, provides focus. Creative? Energetic? Brings energy and excitement to the team. Has a "can do" attitude. Sparks creativity in others.			
Responsibility: Gladly accepts work and gets it done. Spirit of excellence.			
Has *abilities* the team needs. Makes the most of these abilities. Gives fully, doesn't hold back.			
Communication: Communicates clearly when he/she speaks and when she/he writes. Understands the team's direction.			
Personality: Positive attitudes, encourages others. Seeks consensus. Fun to deal with. Brings out best in others. Peacemaker. Pours water, not gasoline on fires.			
Average grade			
Grading scale: 5 – Always, 4 – Most of the time, 3 – Sometimes, 2 – Rarely, 1 – Never NB: If you award high scores to everyone, regardless of their contribution, team members who have worked unduly hard or provided extraordinary leadership will go unrecognised, as will those at the other end of the scale who need your corrective feedback.			

- Each outcome should be assessed in several courses to ensure that students acquire an appropriate level of breadth and depth in the skills of this outcome.
- The number of courses assessed for each outcome should be kept low to minimize faculty workload.
- ABET requires that all graduates have the skills described in all 11 outcomes. As a result, elective courses alone cannot be used to make a case that a program meets a particular outcome.
- A large number of engineering students transfer to SJSU from community colleges in their junior year. Since we do not receive assessment data from these colleges,

[1] Corresponds to a grade of C-, the lowest passing grade in core courses.

freshman and sophomore courses are excluded for program assessment purposes.

Tables 1 and 2 show the courses selected for each of the two programs and the outcomes addressed in each course. Information on the content of each course can be found in [3]. Three of the courses (ME111, ME113, and ME120) are common for both programs.

For each of the courses listed in tables 1 and 2, the course coordinator must show evidence that the course includes the necessary elements to satisfy a particular outcome and collect / analyze data to show that performance targets are met. Moreover, for each outcome there is a designated outcome champion. Champions validate the evidence presented by course coordinators for individual courses and have the final word on whether the performance of a program is satisfactory with regards to their outcome. They meet with course coordinators and instructors, discuss their findings and make recommendations for course improvements. Outcome champions provide an additional level of accountability and ensure consistency in the process.

Outcomes are assessed on a six-year cycle. Each semester one outcome is assessed, the same one for both the AE and the ME programs. Thus, it takes five and a half years to complete the assessment of all 11 outcomes and this corresponds to the frequency of the accreditation visits, which occur every six years. Examples of outcomes assessment can be found in [3].

COURSE DESIGN

Students acquire the skills described in the POs mostly through the curriculum of each program. Hence, curriculum and course design play a critical role in ensuring that students are indeed prepared in these skills at the time they graduate.

Course Learning Objectives

Course design begins with the definition of specific, detailed, and measurable learning objectives. A course learning objective (CLO) is an intent, communicated by a statement, describing what students should be able to do with a particular topic in the course. Mager [7], Gronlund [8], and Stice [9] provide excellent suggestions on how to write CLOs.

Table 1. AE Program – Outcome Matrix

	Outcomes										
	3a	3b	3c	3d	3e	3f	3g	3h	3i	3j	3k
ME111	B[1]			B	C[2]		✓[3]	B	C	B	
ME113	B			B	B		B	B	B	B	
ME120	✓	C		C			C				C
AE162	B	C	B	C	C		C	B	C	B	C
AE164	B	C		C	B		C	B	B	B	C
AE167	B				B			B	B	B	
AE170A, B	✓		C	C	✓	C	C		C		C

Table 2. ME Program – Outcome Matrix

	Outcomes										
	3a	3b	3c	3d	3e	3f	3g	3h	3i	3j	3k
ME101	B				B						
ME106	B	B		✓			B				B
ME111	B			B	C		✓	B	C	B	
ME113	B			B	B		B	B	B	B	
ME114	C	C			B		B		B	A	
ME120	✓	C		C			C				C
ME154	✓		C	✓			✓		✓		
ME 195 A, B	✓		C	C	✓	C	C	B	C		C

[1] B represents levels 3 and 4 in Bloom's Taxonomy.
[2] C represents levels 5 and 6 in Bloom's Taxonomy.
[3] ✓ Outcome is addressed but not assessed in this course.

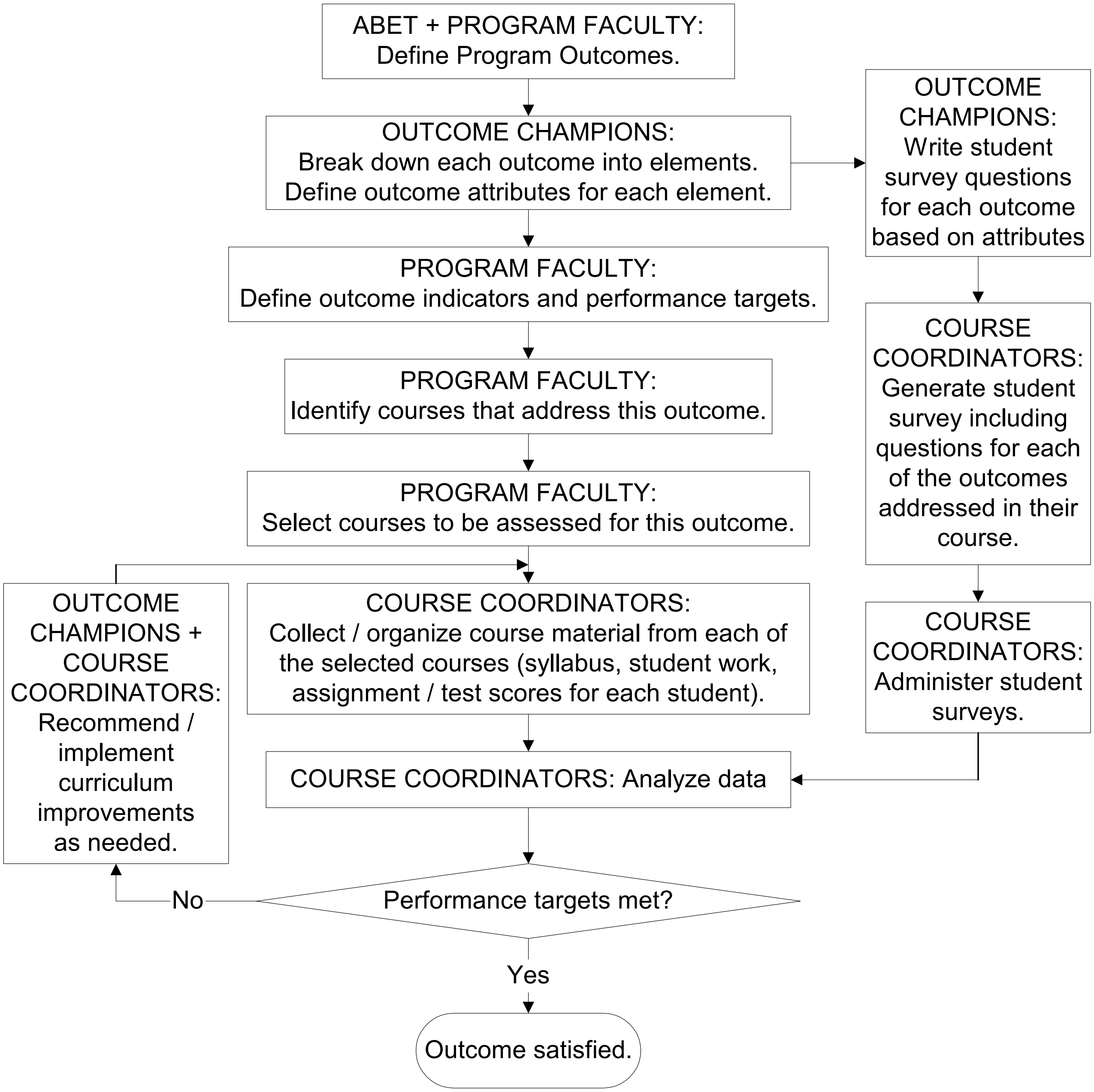

Figure 1. Outcome assessment flow chart.

Obviously, CLOs must represent a subset of the skills described in the POs. Table 3 presents a few examples of CLOs from an aerodynamics course and shows how they contribute to POs. Why are CLOs so important in course design? First, they allow instructors to critically evaluate the relative importance of topics and the allocation of instructional time per topic, so they can easily identify and eliminate extraneous course material. For example a course may have 30 – 45 CLOs. Collectively, these CLOs should exercise all levels of Bloom's Taxonomy. The distribution of CLOs for a typical course on the Bloom's taxonomy scale (cognitive domain) might be as follows:

- 10-20% are written at level 1-knoweledge (ex. define the aerodynamic center of an airfoil). Students can master these CLOs on their own, simply by reading the textbook or with a minimum amount of direct instruction.
- 10-20% are written at level 2-comprehension (ex. explain aerodynamic lift using first principles). Students can master these on their own, with a minimum amount of direct instruction, or small group discussion.
- 50-60% are written at level 3-application (ex. calculate aerodynamic forces on bodies by integrating surface pressure and shear stress distributions). This category usually represents the bulk of the CLOs in most

engineering courses. It involves application of mathematics, science, and engineering principles to solve well-defined problems (exercises). Students may get a first exposure to the solution of these problems by reading textbook examples. However, it is necessary for them to see a step-by-step solution demonstrated by the course instructor, followed perhaps by problem solving in small groups while being coached [11]. Lastly, a variety of homework problems done individually, will help solidify their problem solving skills. A large percentage of time in most engineering courses is spent helping students master level 3 skills.

- 10% are written at level 4-analysis (ex. solve open-ended problems), 5-synthesis (ex. design an airfoil to meet certain requirements), or 6-evaluation (ex. define a set of figures-of-merrit and use it to compare airplanes with similar mission requirements). CLOs at levels 5 and 6 are found usually in design courses and it is not necessary to include them in every engineering course. On the other hand, it is essential to include some CLOs at level 4 in every course, as they represent the minimum level of skill required if a student is to have working knowledge of the material. Needless to say, the instructor and the students must spend a considerable amount of time, in class as well as outside of class, for the students to become proficient in level 4 skills or above.

Two common mistakes in many engineering courses, are (a) to spend a great deal of time in class addressing level 1 and 2 CLOs, and (b) to cover too many topics or otherwise a large amount of material. As a result of these two mistakes, there is usually not enough time to teach students important level 4 skills. While content is important, it is not useful unless it serves as the vehicle to help students acquire important problem solving and design skills. Content taught at levels 1 and 2 or even 3 is of little practical value in the real world of engineering.

CLOs also offer an effective way to communicate course expectations to students and give a clear picture of what they should be able to do, if they pass the course. This is important for instructors of follow up courses as well as for new instructors who may be teaching the course for the first time.

Table 3.
Examples of CLOs from AE162 – Aerodynamics[1]. The right-hand column shows the POs addressed by each CLO [10].

Course Learning Objectives	*PO*
27. Design and perform[2] an experiment to study the performance of an airfoil, analyze and interpret the results from this experiment, compare with analytical / computational predictions and other published experimental data[3], and explain any discrepancies[4].	3b 3d 3g 3i 3k
36. Use the method of images to discuss and calculate aerodynamic interference for (a) wings flying in the vicinity of each other (i.e., wing/tail/canard combinations, biplanes, formation flying, etc.), (b) wind-tunnel boundaries, and (c) ground effects.	3a 3e
44. List several examples of regional, national, and / or global contemporary problems related to aerodynamics (ex. environmental issues, natural resources and energy conservation, etc.) articulate a problem / position statement for each, and explain what makes these issues particularly relevant to the present time.	3d 3g 3h 3i 3j

Course Learning Activities

With a set of specific, detailed, and measurable CLOs in hand, the course coordinator may proceed to design lectures, in-class activities, assignments, projects, and experiments that teach the skills described in each CLO and offer students opportunities to practice these skills. Some of the new assignments, introduced in several courses for the purpose of addressing specific POs, are shown in Table 4.

Table 4.
Assignments designed to address critical areas of the POs.

Course assignment	***Courses in which assignment was introduced***	***PO***
Students design the experiments they will perform in the various laboratories [12].	ME113-Thermodynamics ME114-Heat Transfer ME120-Experimental Methods AE162-Aerodynamics AE164-Compressible Flow	3b
Students discuss economic, environmental, social, political, ethical, safety, liability, and manufacturability constraints in their design of aircraft / spacecraft.	AE170A&B-Aircraft / Spacecreft Design	3c
Students are taught team skills and required to assess formally the performance of their teammates using specific criteria.	ME120-Experimental Methods AE162-Aerodynamics AE164-Compressible Flow AE170A&B-Aircraft / Spacecreft Design ME195A&B-Senior Design Project	3d
Students identify, formulate, and solve open-ended problems.	ME111–Fluid Mechanics ME113-Thermodynamics ME114-Heat Transfer	3a 3e

[1] Only 3 selected CLOs are shown in Table 1. The complete list can be found in reference [10].
[2] Outcome 3d is met as students work in teams of 3-4 to design and perform their experiment, as well as to write their lab report.
[3] Outcome 3i is met as students research the literature for published data.
[4] Outcome 3g is met as students submit a full lab report for each experiment.

Some of these problems involve integration of material from two or more courses [13].	AE162-Aerodynamics AE164-Compressible Flow AE165–Flight Mechanics AE167-Aerospace Propulsion	
Students research, present, and discuss in class safety, ethics, and liability issues in AE.	AE170A&B-Aircraft / Spacecreft Design	3f 3h
Students research, present, and discuss in class contemporary engineering applications and their impact in a global and societal context [14].	ME111–Fluid Mechanics ME113-Thermodynamics ME114-Heat Transfer AE162-Aerodynamics AE164-Compressible Flow AE165–Flight Mechanics AE167-Aerospace Propulsion	3h 3j

Course Assessment

Figure 2 shows the process of course assessment. When performance targets are not met for a particular outcome in a course, outcome champions, course coordinators and instructors discuss and implement improvements and the course is reassessed until the targets are met. If course performance targets are met for an outcome, the course is re-assessed after six-years. If a course addresses more than one outcomes, as is usually the case, the same course may be re-assessed for a different outcome in the following terms. An example of course assessment for a specific outcome is shown below.

AE170A&B – Aircraft Design: Fall 2002 – Spring 2003 Assessment of Outcome 3c[5]

Course activities related to outcome 3c: Students (a) discuss airplane design in class during lectures, (b) design airplanes and write 12 detailed design reports, (c) give 4 design briefings in the course of the year, (d) respond in writing, individually to over 100 design questions and (e) participate in the SAE Aero-Design West Competition, which involves the design, manufacture and flight testing of a remotely-controlled, heavy-lift, cargo airplane. In this competition, they make an oral presentation to a panel of experts from industry and they are graded on their report, drawings, ability to predict their payload as well as on the performance of their airplane.

Course Assessment: AE170A&B met the performance targets for outcome 3c.

Student Performance Summary: Student performance exceeded the targets. In AE170A, 71% of the students performed at 85% or higher, while in AE170B 83% of the students performed at 85% or higher. All students performed at 60% or higher in both courses. In general, students followed the design process fairly well and were creative in providing solutions to any problems they encountered.

Student Survey Results: In general, student responses showed a high level of confidence in design skills, with attribute (3c-11) being the only exception. It should be noted that some of the attributes listed on the survey are emphasized more in AE170A, while others in AE170B. This explains the different levels of agreement in the two parts of the course, for some of the attributes.

Table 5. AE170A&B student survey results[6].

This course has increased my ability to:	Agree	Not sure	Disagree
3c-1 Develop a flow chart of the design process.	29% (67%)	(17%)	71% (17%)
3c-2 Define "*real world*" problems in practical (engineering) terms.	71% (100%)	29%	
3c-3 Investigate and evaluate prior or related solutions for a need I am trying to address.	86% (67%)	14% (17%)	(17%)
3c-4 Develop constraints and criteria for evaluation.	86% (83%)	14% (17%)	
3c-5 Develop and analyse alternative solutions.	57% (83%)	29%	14% (17%)
3c-6 Choose the "best solution" considering the trade offs between the various solutions.	86% (83%)		14% (17%)
3c-7 Develop final performance specifications.	100% (67%)	(33%)	
3c-8 Communicate the results of my design orally as well as in writing (sell the design).	86% (100%)		14%
3c-9 Build a prototype and demonstrate that it meets performance specifications.	NA (67%)	NA	NA (33%)
3c-10 List and discuss several possible reasons for deviations between predicted and measured design performance.	71% (83%)		29% (17%)
3c-11 Choose the most likely reason for deviation between predicted and measured design performance and justify the choice.	57% (50%)	14% (50%)	29%

Recommendations for Course Improvements: After the first flight tests in AE170B, a class meeting should be devoted to discuss (a) possible reasons for deviation between predicted and measured performance of their airplanes, and (b) how much difference between predicted and measured performance can be attributed to each factor.

[5] AE170A&B addresses 6 outcomes (see table 1); only the assessment of outcome 3c is presented here.

[6] The numbers w/o parenthesis are the survey results from AE170A, while the numbers in parenthesis are the results from AE170B.

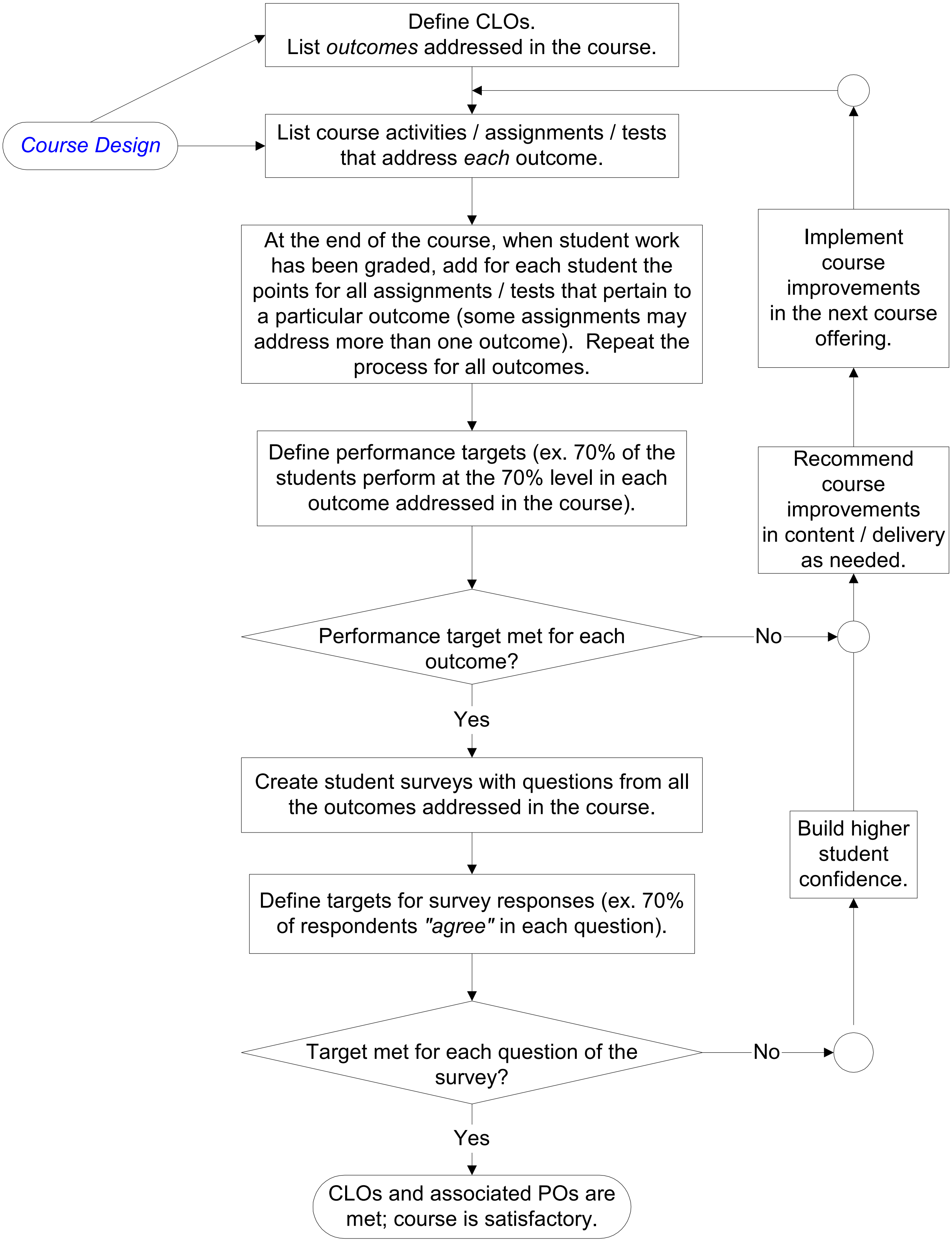

Figure 2. Course assessment flow chart.

CONCLUSION

The paper described the design and implementation of a systematic process to define, address, and assess Program Outcomes. The AE and ME Programs at San Jose State University have been using this process since 2002. In Fall 2005 ABET evaluators found this approach most comprehensive and expressed their satisfaction that it is indeed used to improve both programs.

A number of significant challenges that can be anticipated in sustaining such a process are:

a. Convincing faculty of the value of assessment, as the idea of continuous assessment is fairly new to higher education.
b. Structuring the process without undue increase in workload.
c. The evaluation criteria for faculty in most engineering schools emphasize research productivity rather than teaching. Course development, assessment, and program improvement do not carry nearly as much weight in the retention, tenure and promotion process [15].
d. Lack of communication about teaching, learning and course content [16].

To promote continuous program improvement a paradigm shift in faculty culture is needed. The evaluation criteria for faculty should give equal emphasis on course / laboratory development and quality teaching and recognize that assessment is an integral part of both. In addition, institutions need to promote the exchange of ideas among faculty regarding teaching, learning and assessment practices. As Robert Hochstein explains in the foreword of reference [17]: *Ultimately, quality in the undergraduate experience is defined by quality in teaching. The reward system in higher education simply must recognize professors who are effective in the classroom, who spend time with students, and who engage their colleagues in talk about teaching. Without such a commitment, fine words about strengthening undergraduate education will be simply a diversion*. This paradigm shift over time will lead more faculty to:

(a) Reflect on what works well and what needs to be improved in their courses.
(b) Communicate more with their colleagues about teaching practices, student learning and expectations for course content.
(c) Utilize feedback from all sources to modify their courses, so they can maximize student performance in critical areas.

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