AC 2007-690: CONTINUOUS QUALITY CONTROL AND IMPROVEMENT: AN ENGINEERING DEPICTION OF A CONFOUNDED SIMPLE CONCEPT

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Continuous Quality Control and Improvement: An Engineering Depiction of a Confounded Simple Concept

Abstract

Criteria 2 and 3 of the EC 2000 have been extensively explained by professionals but engineers often find the literature very confusing because of inconsistent uses of terms and sometimes convoluted representations of the necessary actions. In this paper, the two Criteria are depicted as a dual-loop feedback control system and the terminologies interpreted in terms of process control and quality assurance. This helps remove the mystifications over an originally simple concept and makes the criteria easily understandable to engineers. Application of the representation helped faculty understand the criteria and facilitated the implementation process.

Introduction

The Engineering Criteria 2000 (EC 2000) represents a major paradigm shift in engineering program assessment and accreditation. The major changes are reflected in Criteria 2 and 3. Criterion 2 requires that an accredited engineering program establish a set of program educational objectives consistent with the institutional missions and have a process in place to evaluate the objectives and the attainment of them. Criterion 3 calls for an accredited program to formulate a set of program outcomes that support its educational objectives, to assess periodically the level of achievement of the outcomes, and to use the assessment results for further improvement of the program [1].

The central idea behind Criteria 2 and 3 is not new. It is simply the concept of assessment and improvement routinely used in quality control and other fields. Since it is a change from the traditional prescriptive approach, it has generated tremendous discussions. Numerous papers have been published, expert lectures given and workshops held; but most faculty members find the literature more puzzling than enlightening. Aside from a lack of prior experiences in education program assessment by engineering faculty, some particularly confusing aspects of the accreditation literature include: (1) the bewildering assortment of terms (objectives, outcomes, outcome indicators, performance targets, inputs, processes, outputs etc. [4]), (2) the inconsistent use of normally interchangeable terms such as goals, outcomes and objectives to mean different things [2], and (3) the perplexing (to engineers) representations of the implied relationships and entailed actions. As Rogers [5] recognizes, confusion over the language of assessment discourages the faculty from getting engaged in the assessment process. A program faculty is a discourse community that speaks a particular language. Educational assessment professionals do not necessarily use the language of their discipline consistently in communicating with those outside their discipline [5]. Indeed, the language differences have contributed to the confusion over an originally simple concept.

In this paper, an engineering depiction of Criteria 2 and 3 is provided in the form of a dual-loop control system. The basic concept and the terminologies are explained in terms of process control or quality assurance with which most engineers are familiar. Based on this depiction, steps to implement the criteria are summarized. Through application in the author's home program, the depiction and steps were found helpful in giving the faculty a unified understanding of the criteria and a clear sense of what needed to be done for a successful and program-enhancing accreditation process.

Depiction of Criteria and Process

If we momentarily shun some of the confusing literature and study the EC 2000 document itself [1], we will find that Criteria 2 and 3, which occupy about a page in the document, are fairly straightforward to understand. The two criteria rather unequivocally call for quality control through activities at two levels. Criterion 2 requires periodic *evaluation* of the career and professional accomplishments of the graduates against established goals called *program educational objectives*. This is about evaluation of the ultimate product quality after delivery – the professional and career performance of graduates in the workplace. Criterion 3 requires *assessment* of abilities that students acquire by the time of graduation in order to attain the program objectives. These abilities, called *program outcomes*, are simply quality attributes measurable during production that indicate or influence the final product quality. Further, these attributes should be alterable (or controllable) by program actions so that assessment results can be used for quality improvement. While there seems to be a myriad of terms used in the literature designed to shed light on the criteria, the use of terms in the criteria themselves is rather consistent: *evaluation* of *educational objectives*, and *assessment* of *program outcomes*.

The two criteria clearly describe two nested feedback control loops that are commonly used in industrial process control or quality assurance: an objective evaluation loop (Criterion 2) and an outcome assessment loop (Criterion 3), as depicted by the block diagram in Figure 1.

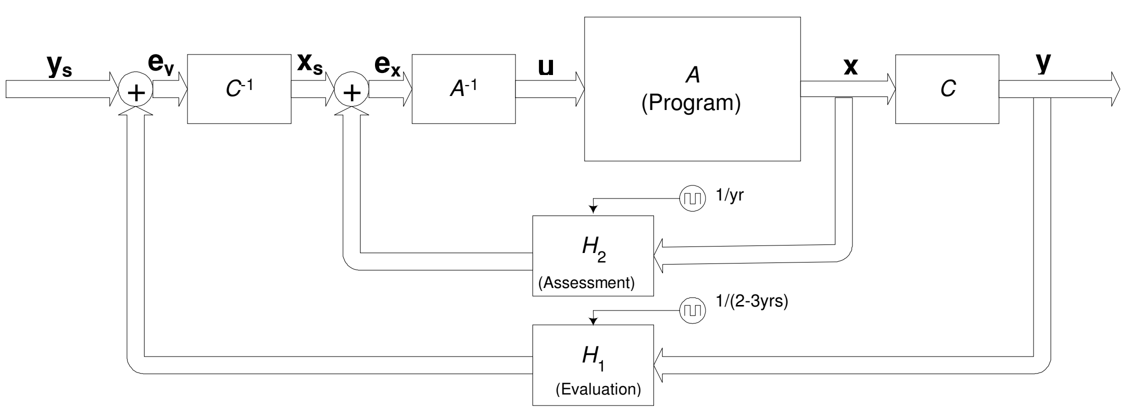

Figure 1. Depiction of EC 2000 Criteria 2 and 3 as a dual-loop feedback control system.

Before we give a narrative description of the relationships and actions represented by Figure 1, let us first define the symbols and variables used in the figure:

y – Quality vector of graduates (process outputs). As defined in Criterion 2, **y** is a vector of measurements of the career and professional achievements of graduates in the workplace three to five years after graduation.

$\mathbf{y}_s$ – Target vector (process set points) for graduate quality **y**. It is what a program works to achieve and is called program *educational objectives* in Criterion 2.

x – Student attribute vector (process states). Criterion 3 calls **x** *program outcomes* and defines it as a set of measurable abilities students acquire by the time of graduation. **x** indicates the state of program and is alterable or controllable by program actions **u**. It influences **y** via mapping matrix *C* and thus affects attainment of educational objectives $\mathbf{y}_s$.

u – Program action vector (process inputs). **u** represents all program actions (courses, teaching methods, and other educational activities) that influence program outcomes **x** through matrix *A*.

A – Matrix defining how program actions **u** affect outcomes **x**. It defines the relationship of two vectors and is thus a matrix. *A* is a model of the academic program (the process or plant).

C – Matrix that defines how program outcomes **x** influence graduate quality **y**.

H_1 – Instruments used to measure graduate quality **y**. Measurement of quality is referred to as *evaluation* in Criterion 2, so H_1 may be called evaluation instruments or methods. Measured **y** is compared with $\mathbf{y}_s$ via an output feedback loop. This loop is the educational objective evaluation loop required by Criterion 2. It is suggested that **y** should be measured at least once every two to three years [sampling frequency ≥1/(2-3 years) as indicated by the clock pulses].

H_2 – Instruments used to measure outcomes **x**. Measurement of outcomes is referred to as *assessment* in Criterion 3, so H_2 may be called assessment instruments or methods. Measured **x** is compared with set points $\mathbf{x}_s$ via a state feedback loop. This loop is the outcome assessment loop specified by Criterion 3. It is suggested that **x** should be measured at least once a year (sample frequency ≥1/year as indicated by the clock pulses).

$\mathbf{e}_y$ – Difference vector (output errors) between educational objectives $\mathbf{y}_s$ and measured graduate quality **y**. $\mathbf{e}_y$ indicates the level of attainment of the educational objectives. Through matrix C^{-1}, $\mathbf{y}_s$ and $\mathbf{e}_y$ are mapped into to outcome targets $\mathbf{x}_s$ and $\Delta\mathbf{x}_s$ (necessary changes in $\mathbf{x}_s$).

$\mathbf{x}_s$ – Outcome target vector (state set points). This has been referred to as performance targets, rubrics, metrics or some other terms in the literature.

$\mathbf{e}_x$ – Difference vector (state errors) between outcome set points $\mathbf{x}_s$ and measured outcomes **x**. $\mathbf{e}_x$ indicates the level of attainment of expected outcomes. If a difference (often called shortcoming in the literature) exists, $\mathbf{e}_x$ results in, through A^{-1}, changes in program actions **u** which are to be implemented for program improvement.

The process depicted by the block diagram in Figure 1 can be described as follows. What an educational program does (**u**) produces near-term graduate characteristics **x** (outcomes) and the relationship between the two is represented by matrix *A*, which is a model of the process (the academic program) to be controlled. Outcome vector **x** consists of the process state variables that determine the longer-term graduate quality **y** through matrix *C*. **x** is measured (assessed) frequently during the process as part of the quality control system. Shortcomings or insufficiencies in **x** are translated via A^{-1} into improvement actions, which are changes in program actions **u**. Graduate quality in the workplace, which is the ultimate output of the educational program, is measured (evaluated) and compared against educational objectives or quality targets $\mathbf{y}_s$. Shortcomings in quality **y** are used to adjust outcome targets $\mathbf{x}_s$ via C^{-1}. In summary, the outer loop in Figure 1 evaluates attainment of educational objectives (Criterion 2) while the inner loop assesses the outcomes (Criterion 3).

This process specified by Criteria 2 and 3 is commonly used in industry for product quality control. For a product, the ultimate quality is how it performs when used by the consumer or user. The users are thus often surveyed to *evaluate* the product quality by the product producer or various consumer report organizations. Based on user expectations, costs, manufacturing capabilities and other factors, the producer defines and periodically refines the quality objectives for the product. The quality measures are usually not directly measurable during production (e.g., reliability of an automobile) or impractical to measure routinely. A set of product or process attributes are determined as quality control variables during production. These variables, which we call outcomes, influence the long-term product quality and can be *assessed* during production for agile quality control. The quality objectives determine the targets for the during-production quality control variables (outcomes) and consumer feedback data are used to modify these targets. Shortcomings are translated into product or production process changes to improve the product quality.

Implementation Procedure and Further Discussion

Based on the depiction presented in the last section, a logical procedure for implementing Criteria 2 and 3 is apparent and can be summarized as the following six steps:

1. <u>Defining quality vector **y** and establishing educational objectives $\mathbf{y}_s$</u>

The first step in implementing the criteria should be defining the quality variables and establishing the quality targets, i.e., educational objectives. ABET broadly defines the quality variables as career and professional achievements of graduates, and thus the educational objectives must be targets in terms of these achievements. ABET expects each program to determine the achievements and objectives according to the institutional missions. To define a set of objectives that are attainable by a program and meaningful to the clientele the program serves, various constituencies must be involved in this process. Obvious constituencies to include are employers of graduates, program faculty, alumni, and graduate or professional schools graduates may attend after graduation.

2. <u>Formulating outcome vector **x**, determining matrix *C* and outcome target vector $\mathbf{x}_s$</u>

With the educational objectives (quality targets) defined, the next step is to determine a set of assessable program outcomes that influence or predict the long-term quality of the graduates. These outcomes are skills, knowledge and behaviors acquired by students in their matriculation through the program that affect their ability to reach one or more of the educational objectives. ABET prescribes 11 outcomes (*a* trough *k*). A program does not have to use the 11 outcomes as stated by ABET and may define its own, but the outcomes formulated must: (1) explicitly or implicitly (via a mapping) include the 11, and (2) sufficiently influence the long-term graduate performance and thus support attainment of the educational objectives.

The influence and sufficiency of **x** are indicated by the *C* matrix. The constituencies (perhaps most importantly alumni, employers or potential employers, of which industrial advisory boards or IABs usually consist) should be involved in defining *C*. The entries in *C* may be binary (0 or 1) or multi-valued (say, 0, 1, 2, 3), which indicate the constituencies' opinions on which outcomes and to what extents the outcomes affect a student's achievements in the workplace. Sufficiency of **x** requires that *C* be a sufficiently full matrix, which means that each row (or column) corresponding to a quality variable has at least one and preferably several nonzero entries; in other words, one or more outcomes contribute to the attainment of each objective.

After **y**, $\mathbf{y}_s$, **x** and *C* are defined, the outcome target vector $\mathbf{x}_s$ can be determined, symbolically, by evaluating $\mathbf{x}_s = C^{-1}\mathbf{y}_s$ as Figure 1 indicates. Although, *C* is not really a numerical matrix that is invertible or pseudo-invertible, the concept is correct. If relationship *C* between **x** and **y** is known, objectives $\mathbf{y}_s$ can be converted into $\mathbf{x}_s$ by examining *C*. Depending on the assessment methods and scales used, $\mathbf{x}_s$ may be numerical, linguistic or both. It specifies the targets the outcomes need to reach to attain the educational objectives. The faculty may perform this inversion as *C* is already established, but involvement of employers and alumni (or the IAB) would be extremely beneficial.

3. <u>Forming matrix *A*</u>

Matrix *A* maps program actions to the outcomes; in other words, *A* is a model of the academic program (process or plant in control system jargons) that describes how the program inputs (**n**) affect the program states (**x**). Felder and Brent [2] discuss in detail how to design and teach courses to achieve outcomes. In essence, they describe how to formulate *A* and use *A* to design **u** for desired **x**. Besides course content issues, they present several teaching strategies, which are also part of **u**. Although **u** mainly consists of the courses (contents and teaching methods), it should also include other activities a program employs to affect students' characteristics.

While **u** may be directly mapped to **x**, some suggest a two-step method [2]. For a course or another educational activity whose actions are represented by vector $\mathbf{u}_i$, a vector $\mathbf{z}_i$ of learning achievements is defined so that $\mathbf{z}_i$ results from $\mathbf{u}_i$ and results in $\mathbf{x}_i$, a subset of **x**; or symbolically:

$$\mathbf{z}_i = A_{i,1}\mathbf{u}_i$$
$$\mathbf{x}_i = A_{i,2}\mathbf{z}_i = A_{i,1}A_{i,2}\mathbf{u} = A_i\mathbf{u}_i$$
$$A = \sum A_i$$

In plain words, the actions in a course or activity produces a set of leaning achievements through one matrix and the learning achievements map to the outcomes via another matrix. The two matrices multiply to form a product matrix indicating how the actions affect the program outcomes. The overall A matrix is the sum of product matrices for all the courses and activities.

$\mathbf{z}_i$ is referred in the literature as "outcome-related learning objectives" [2] or some other terms. Despite the modifiers included, the word "objectives" could cause confusion with "educational objectives". As a result, "learning achievements" is suggested, which seems more descriptive and less confusing.

The program faculty is most familiar with the effects of $\mathbf{u}$ on $\mathbf{x}$ and thus should be the primary group that determines A.

4. <u>Conducting quality and objective evaluation</u>

As discussed in Step 1, two concepts are involved: one is the graduate quality vector $\mathbf{y}$ and the other is the educational objectives $\mathbf{y}_s$, which is also a vector. Technically, $\mathbf{y}$ is a variable vector to be evaluated while $\mathbf{y}_s$ is a constant vector against which $\mathbf{y}$ is compared as illustrated in Figure 1. Naturally, one way to conduct the evaluation is a two-step process: (1) measure $\mathbf{y}$ by some numerical or categorical scale, and (2) compare it against $\mathbf{y}_s$. The two steps may not be performed by the same people. In practice, however, the two-step process may not be practical since the evaluation scales and objectives cannot be accurately defined and calibrated, and they are usually linguistic and fuzzy. An alternative and more practical approach is a one-step method, in which graduate achievements are directly measured against the objectives by some scale such as "below", "meet", and "exceed". This one-step method combines the H_1 block and the comparison node in the outer loop in Figure 1, and it directly produces $\mathbf{e}_y$, the level to which the objectives are achieved.

Since the graduate quality (achievements and performance) in the workplace is evaluated, the employers (including graduate and professional schools) are the most important group to be surveyed. The graduates themselves could provide some self-evaluations, but their responses should probably weigh less. In addition, some other measures, such as percentage of graduate achieving certain distinctions, if appropriate for a program, may be included.

5. <u>Conducting outcome assessment</u>

Outcome assessment is a critical part of the process and various methods (H_2) have been a topic of intense discussions. Many references are available and a detailed account is omitted here. Felder and Bent [2] list 21 program-level or course-level assessment tools, and Prus and Johnson [3] provide a summarization of the strengths and weaknesses of many commonly-used assessment methods. Multiple assessment instruments, both direct and indirect, should be used. It is advisable to use a consistent scale (say, a 5-point ordinal scale) so that data can be easily integrated to give a final composite score.

6. Loop closing

As Figure 1 indicates, the process is typically executed in a discrete-time fashion. Since outcome data are collected at least once a year, loop closing should be done at that frequency as well. The inner assessment loop should be closed every year, and the outer evaluation loop closed every two to three years. As executors of the entire process, loop-closing actions are carried out by the program faculty. A yearly faculty retreat is a good format. Necessary loop-closing actions include the following:

- If objective evaluation data are collected during the year, the outer loop should be executed. As discussed in Step 1, this can be a two-step or one-step process. By either method, $\mathbf{e}_y$ is determined and the following need to be done:

    - $\mathbf{e}_y$ indicates the level of attainment of the objectives, which, together with the data, should be documented as results pertinent to Criterion 2.

    - If $\mathbf{e}_y$ shows a lack of sufficiency in attainment of objectives but the related outcome targets are met (see next action), then adjustments in the outcome targets (symbolically $\Delta\mathbf{x}_s$) are needed.

  This is a good time to re-evaluate educational objectives $\mathbf{y}_s$ as called for in Criterion 2. Since societal needs, institutional goals, program capabilities and other factors may change, the appropriateness of the objectives should be periodically evaluated by the constituencies. For the same reasons, the accuracy of matrix C should be re-examined and necessary improvements made.

- The inner loop is activated and executed at least once every year. Outcome assessment data are assembled, graded, maybe weighted and integrated into a composite score for each outcome. The final scores are compared with outcome targets $\mathbf{x}_s$ to determine $\mathbf{e}_x$ and the following need to be done:

    - $\mathbf{e}_x$ indicates the level of attainment of outcome targets, which, together with the data, should be documented as results permanent to Criterion 3.

    - If $\mathbf{e}_x$ shows shortcomings, it is converted into changes in program actions (symbolically $\Delta\mathbf{u}$) by performing a conceptual inversion of A or by executing $\Delta\mathbf{u} = A^{-1}\mathbf{e}_x$. Vector $\Delta\mathbf{u}$ contains the necessary changes in the courses, teaching methods, and other supporting program activities that need to be made to ensure achievement of the outcome targets, and consequently attainment of the educational objectives. The changes are probably the most important results of the loop-closing actions and are to be implemented and documented for Criterion 3.

This is also the time when matrix *A* should be re-examined and modified, if necessary, to ensure accuracy.

Summary

Criteria 2 and 3 of the EC 2000 are depicted in engineering terms and steps to implement these criteria are presented based on the depiction. It is hoped that the interpretations and steps give engineering faculty a clear, concise, and easily comprehensible overall picture of how the terms relate to one another and what needs to be done to implement the criteria.

References

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