Session Number: 1793

Towards An Engineering Education Capability Maturity Model

María M. Larrondo Petrie, PhD
College of Engineering, Florida Atlantic University

Abstract

There are many skills and capabilities considered crucial to an engineer. Colleges of engineering and engineering accreditation boards have developed curricula and criteria that assess mastery of the requisite mathematical, scientific and engineering foundation. However, other critical skills and capabilities, such as technical writing and oral communication skills, problem solving skills, interdisciplinary team collaboration skills, leadership skills, ethics and creativity are assumed to be interwoven across the curriculum. The capability and maturity of engineering students in these areas are seldom formally assessed.

This paper proposes an Engineering Education Capability Maturity Model designed to improve the process of tracking, assessing and improving engineering students' capabilities in these often neglected areas across their undergraduate years. The Engineering Education Capability Maturity Model is an adaptation of an integrated process improvement model used in software systems engineering, called the Capability Maturity Model (CMM). Model-based process improvement uses a model to guide the improvement of an organization's processes and aims to increase the capability of work processes. Process capability is the inherent ability of a process to produce planned results. This paper presents an overview of the CMM and proposes three CMM-based models for improving the process capability of the engineering institution, the engineering faculty and the engineering student.

Introduction

In 1986, the Software Engineering Institute (SEI) at Carnegie Mellon University with the Mitre Corporation began developing a multi-level model-based process improvement model called the Capability Maturity Model[1,2] (CMM). The CMM model was based on earlier quality management work by Deming[3], Crosby[4], and Juran[5]. The model determines an organization's *process capability*, the inherent ability of a process to produce planned results, as the capability increases the results become predictable and measurable, and the most significant causes of poor quality and productivity are controlled or eliminated.

The first CMM model developed was the Capability Maturity Model for Software (SW-CMM). Its use enhances the capabilities of the software development organization to deliver software on time, within cost, and meeting the objectives of the system and the customer. This documented success resulted in the proliferation of CMM-based models to improve engineering processes, which in 1998, prompted industry, the US government, and the SEI to begin the Capability Maturity Model Integration[6] (CMMI) project to provide a single, integrated framework for improving engineering processes in organizations that span several disciplines. The success, acceptance and maturation of CMM-based models warrant a closer look at their potential application to improve the process of engineering education.

This paper presents an overview of the CMM-based models and proposes models that can be used to evaluate the capability maturity level of an engineering educational institution and of an engineering student. The proposed models are then integrated to existing documentation requirements for higher education accreditation by Professional (ABET), Regional, and National accrediting organizations.[7]

An Overview of the Capability Maturity Model

The SEI developed the CMM to assist the Department of Defense in assessing the quality of its contractors. An organization's process maturity is rated on an ordinal scale from 1(low) to 5 (high) based on earlier work by Deming[3]. Deming's rating was based solely on a 110 questionnaire. The CMM bases their rating on a survey with required evidence to verify the answers. The CMM provides principles and practices that lead to better products and the model organizes them in five levels, providing a path to incremental adoption of best practices, more process visibility and control, and improved products. Figure 1[1] shows the progression through the levels. Trying to skip maturity levels could be counterproductive, because each level forms a foundation from which to achieve the next level. An organization can adopt specific process improvements at any time, even before they are prepared to advance to the level at which the specific practice is recommended. However, it should be understood that processes without proper foundation fail under stress. So following the CMM framework tends to produce stability in process improvement since the required foundations have been successfully institutionalized.

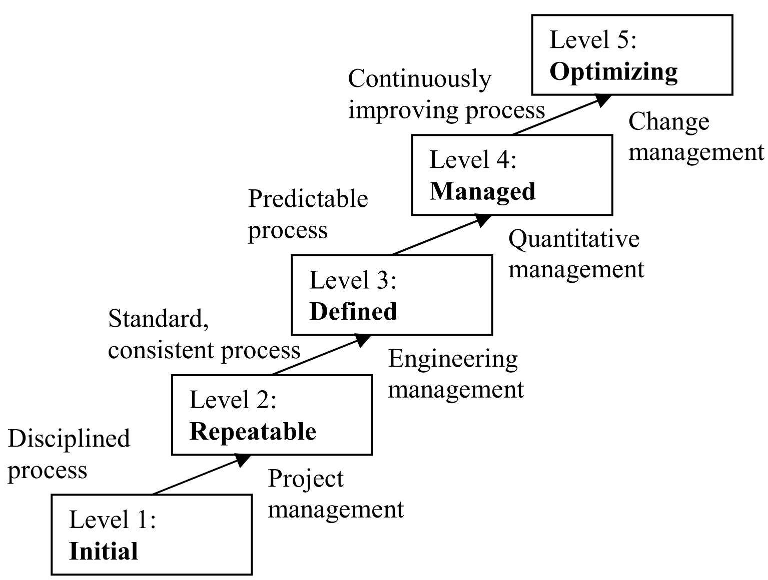

Figure 1: The Five Stages or Maturity Levels of the Capability Maturity Model

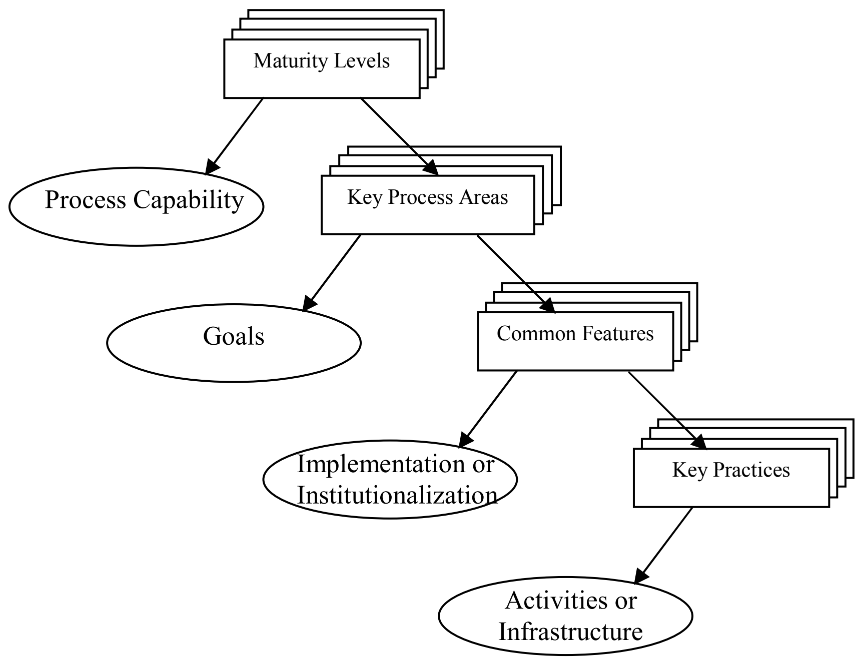

Figure 2. The Internal Structure of the Maturity Levels in CMM

Each maturity level, except Level 1, can be decomposed into the structure shown in Figure 2[1]. A maturity level indicates a capability to perform a process with predictable results and is associated with a set of *key process areas* on which an organization should focus as part of its improvement effort in order to achieve their goals. Each key process area is organized into five sections called *common features*:

- *Commitment to perform* – the policies, leadership practices and actions that ensure that the establishment and continued use of the process
- *Ability to perform* –the practices that address resources, training, orientation, tools, and organizational structure that ensure that the organization is capable of implementing the process.
- *Activities performed* – the practices that address plans, procedures, work performed, corrective action, and tracking.
- *Measurement and analysis* – the process measurement and analysis practices that ensure that procedures are in place to measure the process and analyze the measurements.
- *Verifying implementation* – the management reviews and audits practices that ensure that activities comply with the established process.

These common features specify the *key practices* described by activities or infrastructure, that when collectively addressed accomplish the *goals* of the key process area. An organization is satisfies a key process area when the process area is both implemented and institutionalized.

The five capability maturity levels

The descriptions of the five capability maturity levels of the Capability Maturity Model for Software Development, SW-CMM, and their corresponding key process areas are:

Level 1: Initial – The processes are characterized as ad hoc, reactive and occasionally even chaotic. Few processes are defined; i.e., inputs to processes are not identified, and transitions from inputs to outputs are undefined and uncontrolled. The productivity and quality characteristics of similar projects vary widely because of the lack of adequate structure and control. Projects may have goals of improved productivity and quality, but managers do not know current levels of quality and productivity for similar projects. Success depends on individual effort, not on team accomplishments. To advance to the next level, a level 1 organization needs to impose more structure and control on the process to enable more meaningful measurement.

Level 2: Repeatable – Organization has policies for managing a software project and procedures to implement those policies. Disciplined processes are established to identify the inputs and outputs of the process, the constraints and the resources used to produce the final product. Basic project management practices are used to track cost, schedule and functionality. Problems in meeting commitments are identified when they arise. There is some discipline among team members, so that successes on earlier projects with similar applications can be repeated. The organizational requirement for achieving Level 2 is that there are policies that guide the projects in establishing the appropriate management processes, their project planning and tracking are stable and earlier successes can be repeated. The project's process is effectively controlled by a project management system, following realistic plans based on the performance of previous projects. The key process areas addressed by Level 2 organization in the SW-CMM are:

- Software configuration management
- Software quality assurance
- Software subcontract management
- Software project tracking and oversight
- Software project planning
- Requirements management

Level 3: Defined – The software process for both management and engineering activities is documented, standardized, and integrated into a standard software process for the organization. All projects use an approved, tailored version of the organization's standard software process for developing and maintaining software. This level includes all characteristics for Level 2.

- Peer reviews
- Intergroup coordination
- Software product engineering
- Integrated software management
- Training program
- Organization process definition
- Organization process focus

Level 4: Managed – Detailed measures of the software process and product quality are collected and used to quantitatively understand and control both the process and the products. This level includes all characteristics for Level 3.

- Software quality management
- Quantitative process management

Level 5: Optimizing – Continuous process improvement is enabled by quantitative feedback from the process and from testing innovative ideas and technologies. This level includes all characteristics of Level 4.

- Process change management
- Technology change management
- Defect prevention

People Capability Maturity Model

The CMM is designed to measure process capability rather than the capability of people in the organization. In 1995, Curtis, Hefley and Miller proposed the *people capability maturity model*[8] to measure and improve the knowledge and skill of the workforce within an organization.

This model has five levels, named the same as those in the CMM. The model identifies each level with key practices that identify how the organizational culture is changing and improving. An overview of each level is shown in Table 1.

Table 1. People Capability Maturity Model [8]

Level	Focus	Key Practices
5 – Optimizing	Continuous knowledge and skills improvement	Continuous workforce innovation Coaching Personal competency development
4 – Managed	Effectiveness measured and managed, high-performance teams developed	Organizational performance alignment Organizational competency management Team-based practices Team building Mentoring
3 – Defined	Competency-based workforce practices	Participatory culture Competency-based practices Career development Competency development Workforce planning Knowledge and skills analysis
2 – Repeatable	Management takes responsibility for managing its people	Compensation Training Performance management Staffing Communication Work environment
1 – Initial		

At the *initial* level, an organization does not take an active role in developing its personnel. Management skill depends on past experience and personal communication skills. There is no formal management training. People-related activities are not placed in the larger context of motivation and long term goals. At this level, managers tend not to acknowledge staff talents as a critical resource, few incentives are in place to align individual goals with those of the organization, and there is no systematic plan for the professional development of the individual.

In an organization that is at the *repeatable* level, staff growth and development is a key responsibility of managers. The main focus is to establish basic work practices among the employees, e.g., managers discuss job performance with employees rewarding outstanding performance, and compensation takes into account equity, motivation and retention.

An organization at the *defined* level has strategic plans to locate and develop needed talent. Staff is rewarded as core competencies are mastered and skills are developed. The focus is on encouraging employees to participate in meeting the company's business goals.

At the *managed* level, teams are built around knowledge and skills that complement one another, team-building activities lead to team spirit and cohesion, and mentoring plays an important role. The organization sets quantitative goals for increasing core competencies, and analyzes trends to determine how well the practices are increasing critical skills. At this level, increased performance is motivated across individuals, teams and organizations.

At the highest level, the *optimizing* level, the entire organization is focused on improving team and individual skills. The organization is proactive in strengthening staff practices, not waiting to train as a reaction to a problem or crisis. Data is analyzed to predict potential performance improvements through either changing current practices or adopting new, innovative techniques. All employees are focused on improving the individual, team, project, organization and institution, institutionalizing the optimization effort.

The People Capability Maturity Model has an assessment framework that is useful not only for evaluating an organization but also for planning improvement programs. Adoption of the model has been shown to develop capabilities of employees, build teams and cultures, motivate and manage performance, and shape the workforce.

A Personal Capability Maturity Model

The previous two models focused on measuring an organization's process capability maturity in developing a product and in developing its workforce. A third model associated with the CMM, the Personal Software Process[9] (PSP) proposed by Humphrey, centers on the individual software engineer. This model recognizes that process improvement can and should begin at the individual level. The PSP provides a structured set of process descriptions, measurements and methods designed to improve an individual software engineer's personal performance. Using the PSP forms, scripts, and standards, the individual estimate and plan their work, defining processes and measuring the quality and productivity of their individual effort. A fundamental premise of the PSP is that everyone is different and a method that proves effective for one engineer may not be suitable for another. By helping the engineer measure and track their own work, the individual can determine the methods that are best for them and increase the accuracy of the estimates.

When an individual is charged with estimating and measuring their own performance, an individual might be sensitive to the use of metrics collected on an individual basis. It is important to realize that there are private and public uses for different types of process data. It should be clear to the individual and the organization which process data metrics are private to the individual. Private process data is to be used only by the individual to improve their process and performance and is not to be used by the organization to evaluate the individual. Examples of metrics private to the individual software engineer include: defect rates (by individual) and errors found during development. Some process metrics are private to the software project team but public to all team members. Examples of these include: defects reported for major software functions that have been developed by a group (not traceable to an individual), and errors found by the team during formal technical reviews. Public metrics summarize information that originally was private to individuals and teams. Examples of public metrics include: project-level defect rates not attributable to an individual, actual vs. estimated efforts and actual vs. estimated time duration.

Proposed Engineering Education Capability Maturity Models

The previous sections described in detail three CMM-based models: the original CMM for Software development, the People CMM, and the PSP for individual software engineers. In addition to these, numerous CMM-like models[6] have been developed and used with documented success in software systems engineering: Systems Engineering CMM, Software Acquisition CMM, Systems Engineering Capability Assessment Model, EIA/IS 731 Systems Engineering Capability Model, Systems Security Engineering CMM, FAA Integrated CMM, IEEE/EIA 12207, ISO/IEC 15288, ISO/IEC 15504, and ESI Project Framework. The success and adoption of these models in systems engineering led the U.S. Department of Defense and the Software Engineering Institute at Carnegie Mellon University and the National Defense Industrial Association to jointly develop the Capability Maturity Model Integration[6] (CMMI) with associated assessment and training materials.

The documented success of the CMM motivates the exploration of developing a CMM-based model for engineering education, the Engineering Education Capability Maturity Model. The need for three models seems appropriate: one that addresses the process capability of the engineering institution, one that addresses the process capability of their individual faculty and staff, and one that addresses the process capability of the individual student.

Proposed Capability Maturity Model for the Engineering Educational Institution

The same framework of the original CMM using 5 levels of process capability maturity, described in Figure 1, can be followed when describing the capability maturity of the engineering institution.

Level 1: Initial – At this lowest level few processes are defined. Processes are adhoc and mostly reactive. Productivity and quality vary. Success depends on individual effort. Current levels of quality and productivity of peer programs/institutions are not known. To advance to the next level, the institution needs to identify and analyze peer programs, define its mission, goals, and objectives, and impose more structure and control on the process to enable more meaningful measurement.

Level 2: Repeatable – The institution has developed policies for managing the educational programs and procedures to implement those policies. Disciplined processes are established to identify the inputs and outputs of the process, the constraints and the resources used to produce the final product. Basic project management practices are used to track cost, retention and productivity and compare them with peer institutions. There is some discipline among faculty in documenting course syllabi, goals, objectives, learning outcomes, results and feedback, so that successful course delivery can be repeated. A strong curriculum for each degree program includes engineering sciences, humanities, social sciences, communication skills and an appropriate professional component. The institutional requirement for achieving Level 2 is that there are policies that guide the degree programs in establishing the appropriate management processes, their program planning and tracking are stable and earlier successes can be repeated. The program's process is effectively controlled by a program management system, following realistic plans based on the performance in previous terms. The key process areas addressed by Level 2 institutions are:

- Degree program and course management
- Quality assurance
- Management of adjunct faculty
- Program and course tracking and oversight
- Program planning
- Identification of peer institutions

Level 3: Defined – The educational process for both management and educational activities is documented, standardized, and integrated into a standard process for the institution. Mission, goals and objectives are published in the catalog and posted. All programs use an approved, tailored version of the institution's standard process for developing and maintaining degree programs and courses. This level includes all characteristics for Level 2.

- Learning outcomes for each course is published in syllabi
- Documentation of strategies to achieve learning outcomes
- Mission statement for University and College of Engineering are published
- Educational objectives for each engineering program are published and appear in the catalog
- Peer reviews of proposed programs and courses
- Integrated program management
- Training program
- Involvement of constituencies in reviewing and updating educational objectives
- Institutionalized processes
- Faculty credentials are documented

Level 4: Managed – Detailed measures of the educational program and courses are collected and used to quantitatively understand and control both the process and the programs. This level includes all characteristics for Level 3.

- Documentation and implementation of functional feedback and assessment processes designed to determine whether intended outcomes are being achieved
- Quality management
- Quantitative process management
- Comparison with peer institutions
- Documentation sufficient staff allocation and compensation
- Documentation of good facilities and strong institutional support
- Involvement of constituencies in evaluating program outcomes

Level 5: Optimizing – Continuous process improvement is enabled by quantitative feedback from the process and from testing innovative ideas and technologies. This level includes all characteristics of Level 4.

- Process change management
- Technology change management
- Defect prevention
- Total faculty involvement
- Documentation feedback results in changes in program

These five levels and the key process areas that have been identified with each level are a beginning towards building a Capability Maturity Model for Engineering Educational Institutions. Accreditation agencies, such as ABET[10] tend to accredit institutions that are at level 5 in our model. The proposed model gives institutions that have not been accredited a framework that could yield the necessary process definition, implementation, assessment and improvement to eventually attain accreditation. The model provides a common language to discuss progress in process improvement and a logical progression in achieving higher capability maturity levels.

In the CMM for Software advancing from level 3 to level 4 requires having software applications that store and provide access to important documents, automatically accumulate metrics, and track progress through the process. Such a tool would be very useful for storing program descriptions and requirements, course syllabi and expected learning outcomes, sample exams and assignments, scanned examples of student work, program and course assessment and survey results, and a myriad of other documents that usually are only compiled and examined when a program is undergoing accreditation. The archive of documents provided by such a tool would allow

- ongoing evaluation and process improvement,
- comparison of course outcomes and assessments to
    - courses offered in subsequent semesters within the institution and
    - courses offered at peer institutions, and
- the tracking of collection and timely submission of required documents

Proposed Capability Maturity Model for the Engineering Faculty

The Person Capability Maturity Model and the Personal Software Process models can be adapted to yield a Capability Maturity Model for Engineering Faculty. The faculty has responsibilities in the areas of research, teaching and service. Often assessment of faculty teaching capability is only limited to publicly-posted student evaluations, these often indicate popularity rather than achievement of the learning outcomes and course goals. Establishing a CMM for Engineering Faculty could produce data that would be of use to administrators and serious students trying to assess to capability of the faculty, as well as to the individual faculty seeking improvement in teaching skills. A five-level CMM-based model could also be controversial if it is misused in a penalizing the faculty in their evaluations for establishing high goals in their outcomes and not attaining them. This potential misuse requires classification of private vs. public data and a determination of what can and cannot be used in faculty evaluations or public assessments.

Proposed Capability Maturity Model for the Engineering Student

Like the CMM for Engineering Faculty, the CMM for the Engineering Student can be based on the five-level Person Capability Maturity Model and the Personal Software Process models. To avoid the controversies stated in the Capability Maturity Model for the Engineering Faculty, the student documentation submitted over the four years of studies to track improvement of skills will not be used when calculating grades. Instead it can be utilized by advisors, administrators tracking retention, and other professionals not directly responsible for student grades. The CMM for Engineering students will not track mastery of fundamental science, math, engineering and technology skills, other than tracking timely progress through the curriculum. The real value of the CMM for Engineering Students would be to track improvement of skills and capabilities that are acquired over their school years and life in general, e.g., technical writing and oral communication skills, problem solving skills, interdisciplinary team collaboration skills, leadership skills, ethics and creativity are assumed to be interwoven across the curriculum. The capability and maturity of engineering students in these areas are seldom formally assessed.

A CMM for the Engineering Student could track and improve these “neglected” skills across a series of four interdisciplinary, hands-on engineering courses, which engineering students would encounter as a freshman, on the “bridge” between sophomore and junior years, and in a two-semester senior capstone design course.

In these four courses, designated assignments could be made that require the student to electronically post the technical reports of their designs to the CMM for the Engineering Student management tool. The student is asked to estimate the time it would take the student to complete the assignment and the grade the student expects to receive, after completion the actual time is recorded by the student, this would only be visible to the student and serves to improve the student’s ability to predict the time and effort required. The engineering faculty grades the assignment on its technical content, while adjuncts specializing in technical writing grade the language, format, and grammar of those designated assignments posted to the CMM management tool. Standardized evaluation forms for evaluating the written and oral presentations should be developed by the engineering institution for consistency and comparison. Students will rewrite the technical report until a satisfactory submission is accepted by the technical writing grader. Final approval of the technical writing grader is worth a certain amount of points on these class assignments to motivate student completion. The same could be done with oral presentations, standardized forms are developed for evaluation by the faculty and peers, the evaluation results are dated and posted to the CMM management tool, a video tape of the presentation can also be digitized and posted to the tool for later comparison. Also posted to the management tool would be designated team project design reports and assessments of the individual’s team leadership and collaboration skills by the faculty and team members. This will document improvements in communications, team and leadership skills. The student can post additional evidence of skills, such as office held in a student professional society, participation in competitions, or hours volunteered in the community. Exercises and surveys designed to expose students to ethical decision making and creative problem solving could also be exercises designated in these four classes for posting by the student on the CMM management tool. The tool could also guide the student each year in formulating long and short term goals and strategies to achieve them, and ask the student to self-evaluate how they did at the end of the year. Feedback can be solicited by the student from their academic advisor, the career development advisor, professor, and peers. The archiving of the estimates vs. actual effort and grades, and archiving projects and evidence of improvement over time would motivate the student to plan to achieve realistic goals, develop more realistic estimates of efforts, and attain a personal best in their next submission – as the individual is competing against him or herself. The tool would also allow the student to generate a portfolio of their work.

Future Work

The College of Engineering at Florida Atlantic University plans to develop the three proposed models generally in more detail, identifying the key process areas at each level and the activities that would produce improvement to the process capability. A grant proposal is being prepared to develop the Capability Maturity Model management tool for the engineering college and for the engineering student models, integrating results from the student CMM management tool database as feedback to the college assessment plan. Once the tool is in place a long term study will be conducted to study the impact of the use of the proposed CMM models on the quality and retention of students.

Bibliography

[1] Carnegie Mellon University, Software Enginering Institute (Principal Contributors and Editors: M. C. Paulk, B. Curtis, M.B. Chrissis), *The Capability Maturity Model: Guidelines for Improving the Software Process*, Reading, MA: Addison-Wesley, 1995.
[2] Humphrey, W. S. *Managing the Software Process*, Reading, MA, Addison-Wesley, 1989
[3] Deming, W. E. *Out of Crisis*. Cambridge, MA: MIT Center for Advancement Engineering, 1982.
[4] Crosby, P. B. *Quality is Free*. New York: McGraw-Hill, 1979.
[5] Juran, J. M. *Juran on Planning for Quality*. New York: MacMillan, 1988.
[6] Ahern, D. M., A. Clouse, R. Turner, *CMMI Distilled: A Practical Introduction to Integrated Process Improvement*, Reading, MA: Addison-Wesley, 2001
[7] Council for Higher Education Accreditation. http://www.chea.org/
[8] Curtis, B., W.E. Heffley, and S. Miller. *People Capability Maturity Model*, Technical Reports SEI-CMU-TR-95-MM-001 and -002. Pittsburgh: Software Engineering Institute, Carnegie Mellon University, 1995.
[9] Humphrey, W. *A Discipline for Software Engineering*. Reading, MA, Addison-Wesley, 1995.
[10] ABET Criteria for Accrediting Engineering Programs (EC2000) http://www.abet.org/criteria.htm

Biography

MARIA M. LARRONDO PETRIE: Dr. Petrie is Associate Dean for Academic & International Affairs, and Professor of Computer Science & Engineering at FAU College of Engineering. With over thirty years of experience in education, she is an ASEE Minority Division Board Member, Vice President of Research of the Latin American and Caribbean Consortium of Engineering Institutions, and has served on the ACM SIGGRAPH Education Board.