Understanding Faculty Decisions About the Integration of Laboratories into Engineering Education

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***Abstract*—This paper presents a literature review on the integration of laboratories into undergraduate engineering education. The literature review starts with a brief discussion about historical and current trends of how laboratories were (are) integrated into the engineering curriculum. This initial review indicates that although highly important to the education of engineers, laboratories often are not used to their full potential. To identify the possible reasons for that situation, the authors synthesize the scarce literature on faculty attitudes toward the integration of laboratories into undergraduate engineering education, and identify factors that could be associated with instructional decisions and approaches to teaching laboratory classes. The findings indicate that faculty decisions regarding laboratory education are shaped by a myriad of factors, including beliefs, knowledge, institutional factors such as departmental values and reward systems, and external factors such as funding agencies and professional societies. Finally, the authors discuss implications of these findings for the design of professional development programs that would foster the effective use of laboratory classes in engineering education.**

Keywords—laboratory; engineering education; beliefs; teacher; student; innovation

I. Introduction

Laboratory education plays an essential role in the education of skilled engineers [1]. Laboratories allow students to learn not only important concepts and principles, but also to develop fundamental skills to solve multifaceted problems, work with complex systems, communicate effectively, work in teams, and reflect on the societal consequences of the engineering activities [2], [3]. Despite this fundamental role, recent studies indicate a relative misuse of the full potential of laboratory education. Sheppard and her colleagues [1] revealed that most laboratory activities focus on complementing lectures instead of developing important engineering skills. Similarly, Duderstadt [4] argued that laboratory courses are "of questionable utility for teaching the most important technical skills of engineering: the integration of knowledge, synthesis, design, and innovation" (p. 33).

The education of engineers often necessitates a huge investment in laboratories, not only regarding equipment, but also in infrastructure such as large buildings, including compressed air, vapor, electricity, and water supply, among others. It also requires investment in staff and faculty development, and it demands faculty dedication and time to develop the instructional design and materials. Laboratory activities also require additional dedication that not always is recognized by institutions. Laboratory instructors often have 2-3 hours of laboratory instruction (often referred to as student contact hours) for every formal credit hour—a much higher ratio of contact hours to credit hours than a traditional lecture class.

Therefore, it is fundamental to understand why laboratories, despite the huge investment, seem to fail in developing engineering skills among students. While a great part of the current literature on the field focusses on exploring the characteristics and affordances of different types of laboratories, including physical, remote and simulation labs [5], [6], our study investigates another critical component of the learning equation: the faculty. In this paper, we review the literature on faculty attitudes toward teaching and learning to identify key factors that may affect the current practices in engineering education laboratories.

To set the context for the impact of faculty, we first review the historical and current trends of how laboratories were (are) typically integrated into the engineering curriculum. Second, we synthesize the scarce amount of literature on faculty attitudes toward the integration of laboratories into undergraduate engineering education. Third, we explore the literature on faculty professional development to identify factors that could be associated with instructional decisions and approaches to teaching laboratory classes. Finally, we discuss implications of these findings for the design of professional development programs that would foster the effective use of laboratory classes in engineering education.

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II. THE INTEGRATION OF LABORATORIES INTO ENGINEERING EDUCATION

A. Historical perspective

The use of laboratories in engineering education in the U.S. dates to the times of the first engineering courses. The Mann Report [7], a historical document that describes important characteristics of engineering education since its introduction to the U.S., helps us understand some of the traditions in laboratory work that still persist today. According to this report, since the first engineering education program, laboratory work was used as a supplement to lectures, and as a place where students “reproduced standard reactions, measured known constants, verified theories, visualized principles, and acquired skill in manipulating delicate instruments” [7, p. 37]. In addition, Mann described pedagogical approaches adopted in engineering education laboratories in 1918. He wrote,

> When a class entered the laboratory, each member received a number directing him to the apparatus and written directions for making the required measurements and recording the results. In this way, Professor Pickering was able to care for a class of twenty-five students at one time, because, as he himself tells us, the written directions prevented the students from making serious mistakes (p.37).

Although Mann seemed to be an enthusiast of the ideas of Professor Pickering, he also described a few weaknesses of such an approach. He wrote,

> In the laboratory work, the methods and aims defined by Professor Pickering in 1869 are still dominant everywhere. About one-third of his original experiments are still in use, and the new ones that have been introduced have as their objects the verification of some known law, the visualization of some known fact, or the determination of some known constant. When the same experiments are used year after year, as is the case at most schools, the students soon discover that the number of failures and low grades in physics can be materially reduced if the results of the physics experiments are carefully preserved from year to year and judiciously used as occasion may require. Projects of the form ‘Which of these S electric motors is the best for the price?’—a question that cannot be answered without making the experiment—are almost never used. The prevailing type is measure the efficiency of this electric motor. In other words, physics instruction, like that in chemistry, aims to stock the student's mind with information as a preparation for solving real problems should they ever arise (p. 40).

In his final recommendations, Mann suggested that laboratory work must be used in a more applied fashion, through problems and projects linked to real world situations.

B. Current trend: Technology integration

The integration of laboratories into engineering education has an important space in the academic literature and community. Recent publications range from descriptive approaches in which the authors aim to present an experimental apparatus [8]–[10], to more refined educational research in which the authors aim to investigate the learning effectiveness of a specific type of laboratory activity [11], [12]. There are also articles exploring pedagogical approaches to laboratory education [13]–[15]. Finally, another common trend in the literature are studies that aim to investigate characteristics, affordances and differences between different types of laboratory including remote, virtual and physical labs [5], [6], [16]. These studies reveal how advances in technology have enabled laboratory settings to transform. Physical labs are now competing with remote and virtual labs.

C. Instructional designs in the lab

In a recent systematic literature review, Coutinho [17], found that 22 out of 23 articles describing laboratory activities reported “the development of conceptual understanding” as the main learning objective, while only a few articles mentioned different learning objectives such as developing instrumentation and design skills. Coutinho also found that 60% of the reported laboratory activities rely on “cookbook” or well-structured instructions that students follow, but researchers have found that this approach has limited pedagogical efficiency [3] regarding developing engineering skills among undergraduates. Finally, Coutinho also reported that knowledge tests are the most used way of assessing students’ learning in the lab. These tests, although having many strengths, cannot accurately measure many kinds of complex knowledge and skills such as design, teamwork, and communication skills [18].

As noted above, the findings from recent research about laboratory education, including the use of lab activities as a complement of lectures, the use of well-structured instructions were students have no space for creativity, and the lack of real world problems, are the same as those discussed by Mann, one hundred years ago.

III. FACTORS AFFECTING FACULTY APPROACHES TO TEACHING IN THE LAB

Studies such as the ones described by Mann [7], Sheppard and colleagues [1], and Coutinho [17] help researchers identify key issues of laboratory practices in engineering education, but do not provide sufficient evidence of the implicit factors that inform faculty decisions about laboratory practices. In fact, the studies reveal the “overt side” of current laboratory education practices such as pedagogical approaches, common learning objectives, and assessment instruments. On the other hand, we have few or no clues about the factors that inform faculty decisions about instructional designs of laboratory activities. In this section, we will explore some of these factors, and indicate how they may affect faculty decisions about instructional designs.

First, we must notice that there is a scarcity of studies exploring this topic, especially in engineering domains. For this reason, most of the discussion presented in this section comes from the literature on teaching and teachers' professional development.

A. The nature of the teacher's knowledge

In a seminal work, Shulman [19] explored different perspectives on teacher knowledge. To better describe the nature of the teachers' knowledge, Shulman proposed a framework with three categories: (a) subject-matter content knowledge, (b) pedagogical content knowledge, and (c) curricular knowledge. Subject-matter content knowledge referred to the teacher's knowledge about the subject-matter. Pedagogical content knowledge referred to the knowledge about the best ways to teach content. Curriculum knowledge referred to the knowledge of design curriculum. In further studies Shulman acknowledged the importance of the pedagogical content knowledge "because it identifies the distinctive bodies of knowledge for teaching." [19, p. 8].

Building on Shulman's notion of pedagogical content knowledge, Mishra and Koehler [20] proposed a new framework that takes into account the influence of the technology on the teaching process. Mishra and Koehler argued that subject matter, pedagogy, and technology play an intertwined role in the teaching process, and thus, cannot be analyzed as three separate bodies of teacher knowledge. The authors saw the teacher knowledge as the interplay between the technology, pedagogy, and content, as illustrated in Figure 1.

This framework is particularly interesting for analyzing faculty attitudes toward laboratory since it allows researchers to understand, within the scope of laboratory education, "the connections, interactions, affordances, and constraints between and among content, pedagogy, and technology" [20, p. 1025].

As noted by the arrowed lines in Figure 1, the analysis of the interactions between these three bodies of teacher knowledge allows researchers to identify and explore four new types of knowledge important in teaching. Indeed, pedagogical content knowledge (PCK), technological pedagogical knowledge (TPK), technological content knowledge (TCK), as well as technological pedagogical content knowledge (TPCK) plays a fundamental role on teachers' performance [21]–[24]. In the following paragraphs, we will define these different types of knowledge and discuss potential implications for laboratory education.

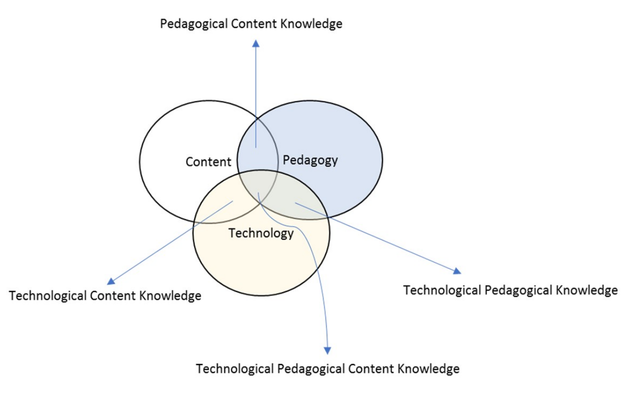

Fig. 1. The TPaCK model as adopted from [20].

Pedagogical Content Knowledge (PCK) results from the interplay between pedagogical knowledge and content knowledge. Indeed, teaching requires a kind of knowledge that goes beyond the expertise in a disciplinary domain and beyond the general knowledge about classroom dynamics and learning theories. Pedagogical content knowledge encompasses a body of knowledge that helps teachers to design effective learning experiences for specific content. It includes not only the knowledge about how to represent concepts, principles, and phenomena related to a particular domain but also the knowledge about threshold concepts, misconceptions, as well as students' characteristics. In other words, good teachers need to know the best ways to teach the subject matter in a way that supports students' learning. Regarding laboratory use, teachers must be able to understand the complexities of the subject matter and identify instructional approaches that best fit with the intended learning outcomes of the laboratory activities.

Technological Content Knowledge (TCK) results from the interplay between content and technology and refers to the knowledge about how content and technology are interrelated. In a lab, a teacher with a high technological content knowledge knows the subject matter and knows how the lab equipment can be used to represent or observe the subject matter. It does not necessarily mean that the teacher knows how to use the lab equipment in a way that facilitates students' learning the subject matter.

Technological Pedagogical Knowledge (TPK) refers to the knowledge of the different educational technologies and how they can be used in teaching. In laboratories, technological pedagogical knowledge refers to the knowledge of the laboratory equipment and tools, as well as the expertise in the ways that equipment is used to create meaningful learning experiences. It does not necessarily mean that the teacher has expertise on the subject matter.

Technological Pedagogical Content Knowledge (TPCK) is a body of knowledge that integrates the teachers' knowledge of content, pedagogy, and technology to support the development of meaningful learning experiences related to the content. In other words, a teacher with strong TPCK considers factors such as students' characteristics (e.g., prior knowledge), educational technologies (e.g., virtual labs), and the complexities of the content (e.g., threshold concepts) to design pedagogical practices that foster students' learning of the subject matter.

In conclusion, to design activities that support the achievement of course or laboratory learning goals, teachers must be knowledgeable of the characteristics and affordances of the equipment, tools, pedagogical approaches, and use them in a way that supports the development of students' skills.

B. Institutional context and policies

Institutional and departmental contexts play a strong influence on the way faculty shape their behaviors, values, and beliefs [25]–[28]. Factors such as the type of institution, institutional policies and rewarding systems, as well as institutional constraints directly affect faculty decisions about teaching.

The *type of institution* may indicate whether the faculty place emphasis on research or teaching, and thus informing their decisions about the time spent on teaching activities, and also about pedagogical approaches [26], [29]. Indeed, as reported by Fairweather [27], colleges and universities have historically favored research over teaching. In addition, an institution's orientation to research usually drives institutional policies related to recruitment, promotion and tenure decisions [29], [30]. This orientation eventually prevents educational innovation since less importance is given to the scholarship of teaching and learning [30]. For example, Lattuca and colleagues [29] found that faculty who perceive institutional emphasis on research over teaching tend to use more instructor-centered approaches rather than student-centered pedagogies. To overcome this problem, different scholars [31], [32] are proposing policies that reward the scholarship of teaching and learning as a way to fostering educational innovation.

Faculty reward systems relate to important faculty outcomes such as motivation, performance, and choice of pedagogies [29], [30], [33]. Reward systems reflect cultural aspects that pervade an institution and indicate a set of values, beliefs and assumptions about professional work within the organization. The importance of faculty reward systems on educational outcomes was well expressed by Lagowski [34], a well-known American chemist, who claimed that "reforms in the teaching of chemistry will not get very far if the faculty-reward system is not changed" (p. 537). In fact, as reported by Borrego, Froyd and Hall [35] faculty "are unmotivated to adopt engineering education innovations when they perceive that teaching innovation is marginalized in promotion and tenure considerations and that their colleagues are skeptical of assessment evidence" (p.203).

More recently, Lund and Stains [36] explored factors that influence STEM faculty decisions to adopt educational innovations. They found that 40% of the faculty reported that the departmental reward systems influenced the way they teach. Although these latter results do not address laboratory activities directly, we hypothesize that departmental reward systems that do not value laboratory activities may also influence faculty decisions about teaching in the laboratories.

Institutional constraints, including funding, class sizes, space, time and instructional staff may also influence faculty decisions about teaching practices [26], [35], [37], [38]. For example, Hora [26] revealed that some faculty indicated that the use of active learning strategies, such as small group discussions, becomes "untenable" depending on the class size. Alternatively, one department chair reported difficulties to support annual software updates [35]. In addition, laboratory space and safety create barriers to the use of new pedagogies such as artifact dissection [39]. We propose that similar constraints create barriers to the appropriate use of laboratories in engineering education settings. Magana and Coutinho [38] explored opportunities and barriers for integrating modelling and simulation at undergraduate engineering programs. The findings reveal that although faculty see the laboratory as a strategic place to integrate those computational methods, the lack of time was one of the most cited barriers.

TABLE I. COMMON STAKEHOLDERS IN ENGINEERING EDUCATION

Stakeholder	Role in Faculty Teaching decisions	Reference
Peers, chairs, and deans	Supporting professional development, creating environments that foster educational innovation, fostering faculty interpersonal networks	[32], [40], [41]
Students	Providing feedback and evaluations, resistance	[42], [43]
Scholars in the field	Publishing books, research, and reports that support the scholarship of teaching. Attending conferences, promoting workshops and participating in interpersonal networks	[32], [40]
ABET	Formulating policies (e.g., EC2000)	[43], [44]
ASEE	Promoting professional development, community of practice, dissemination of educational innovations	[40], [44]
NAE	Promoting professional development, creating systematic assessments of engineering education state and culture	[44]
Industry	Supporting professional development, supporting policy development, evaluating students outcomes	[42], [44], [45]
Professional societies	Promoting professional development, fostering design competitions, sponsoring honors for educational innovation	[32], [45]
Funding agencies	Supporting programs that foster the scholarship of teaching	[42], [43]

The *type of faculty appointment* is also identified in the literature as having consequences on instructional practices [46]. For example, O'Meara et al. [30], in an extensive work on the life and work of American college and university faculty, raised concerns about the teaching practices of part-time and non-tenure-track faculty. O'Meara and colleagues reported that faculty in non-tenure-track appointments usually adopt less effective teaching practices, including lower use of technology, fewer collaborative learning tools, and less time-intensive instructional practices. The report does not discuss what are the consequences of such faculty appointments on laboratory activities. We may hypothesize, for example, that non-tenure-track faculty would adopt traditional ("cookbook") approaches to laboratory education. On the other hand, as most of these faculty are primarily in teaching roles, it is possible that they dedicate time to design and conduct more engaging learning activities. Thus, to solve this apparent contradiction, research is necessary to investigate how faculty appointments effects laboratory activities.

C. The role of society

The faculty is not alone in their decision-making processes. Indeed, although instructors make the teaching decisions [32], [40], these decisions result from a complex set of interrelations between the faculty and the environment [47], including different stakeholders. In engineering programs, these stakeholders may include ABET, ASEE, NAE, industry and NSF, among others. In Table 1, we summarize the most common engineering education stakeholders and the main role they may play in faculty decisions about teaching.

Peers, chairs, deans and students are the faculty's most influential stakeholders. They are part of the main environment where faculty work and teach, and directly impact faculty decisions. Campbell and O'Meara [25] found that faculty enhance their agency if peers and department chairs value their work and recognize it. In addition, faculty shape their teaching practices through interactions with colleagues [48]. Students are at core of the teaching activity. Their reactions, behaviors and outcomes influence the way one teaches. In fact, several studies reported students' resistance and student feedback as important factors in how faculty choose to teach [35], [43], [49].

Scholars in the field of engineering education play a significant role on faculty professional development whether acting as role models or just by sharing applied knowledge. Faculty who engage in the scholarship of teaching and learning through more constant interactions with the engineering education community tend to use more active learning strategies. For example, Lattuca, Bergom, & Knight [29] revealed that faculty who read academic works on teaching and learning as well as those who published articles, papers, or even books are more likely to use active learning pedagogies instead of using lectures.

Beyond the above mentioned stakeholders, Jamieson and Lohmann [32] described the roles that important community stakeholders must play to foster educational innovation in engineering education. The authors suggest that organizations beyond departmental and institutional structures, such as ASEE, NAE, professional engineering societies, ABET, industry, and funding agencies, may serve as important sources of faculty beliefs and attitudes.

ABET is an accreditation agency that develops policies that support the use of best practices in engineering education and foster educational innovation. ABET policies intend not only to orient institutions but also to influence faculty decisions about course design and teaching practices. In a study to investigate the impact of the EC2000 on both student learning outcomes and organizational and educational practices of accredited engineering programs, Lattuca, Terenzini, and Volkwein [50] found that at least 50% of the faculty reported the adoption of active learning methods and improved assessment strategies. Jamieson and Lohman [32] posited that ABET must "promulgate exemplary teaching and learning tools and techniques" (p. 67) and place more emphasis on assessment of strengths and potential areas for improvement in order to foster educational innovations. Moreover, ABET might modify Criterion 6, addressing faculty competencies, to support continuing development in education and educational scholarship [51].

ASEE, as an organization that aims the advancement of education in engineering and engineering technology, plays an essential role on promoting best educational practices in engineering education, fostering communication and the sharing of ideas between members, and creating a community of practice that support educational innovations. Faculty may interact with ASEE in order to support their professional development and keep up to date about educational technologies and practices. Specifically, ASEE has a division focused on experimentation and laboratory-oriented studies that aims to promote innovations in laboratory instruction.

Jamieson and Lohman [32] provided a series of recommendations to increase the influence of The National Academy of Engineering (NAE) and professional engineering societies on engineering education programs. They stated that NAE must acknowledge the innovation efforts of faculty at beginning stages of the career, create an engineering education section, offer engineering education workshops, and collaborate with ASEE and funding agencies to periodically assess "the state of engineering education and the state of the culture for scholarly and systematic innovation in engineering education" (p. 70). Professional engineering societies must support student chapters in engineering education, promote professional development for future faculty, create education-focused groups, organize publications and events, and sponsor honors for educational innovation.

Industry represents the market and engineering employers. They are important "consumers" of the engineering education process. Thus, their feedback about the quality of the engineers graduating from our institutions impacts educational policies regarding engineering education. Indeed, as reported by Lattuca, Terenzini, and Volkwein [42], the EC2000 aimed to reduce the mismatch between industry needs and abilities of the engineering graduates. Beyond the influential role on policy-making, industry also fosters the use of innovative approaches in engineering education. Lattuca et al. [29] revealed that industry partnership and working in industry positively related to faculty's use of student-centered techniques.

The role of funding agencies in promoting disciplinary and interdisciplinary knowledge is well-known [52], [53]. However, additional effort, from the engineering education community, is necessary to promote advancements in educational innovation, especially in terms of creating conditions for technology diffusion [35]. Borrego, Froyd and Hall [35] investigated the diffusion of engineering education innovations among chairs of engineering departments in the U.S. and found that 28% of them reported becoming familiar with educational innovations through the word of mouth, while 23% reported the role of presentations on their campus and participation in conferences such as ASEE. Interestingly, chairs rarely learn of innovations from articles and books (8%) or professional societies (3%). Based on these data, Borrego and colleagues concluded that department chairs may be not engaging with engineering education literature. Although the data refer to chairs of departments, we expect similar, or worse, results from faculty. Thus, research is necessary to investigate the sources of information that influence faculty decisions about teaching practices, and in what ways community might support their professional development.

D. Faculty beliefs

In their review of the literature regarding facilitating change in STEM education, Henderson, Beach, and Finkelstein [54] identified two actors in the educational system who are the primary targets of change strategies: individuals and environments. In other words, change efforts are directed toward the beliefs and actions of the instructor or toward the environment in which the instructor operates. The assumption made when the environment is targeted is that a change in the environment will lead to a change in the instructor's actions, which is the same position we took in the previous sections. However, the work of Henderson and colleagues identifies an additional factor affecting faculty decisions that we have yet to explore: faculty beliefs about teaching and learning.

While Henderson, Beach, and Finkelstein [54] found that instructors' beliefs are often targets for when a change in action is desired, the research literature does not agree on the strength of the relationship between beliefs and actions [55]. A portion of researchers find that a substantial relationship between beliefs and actions exists [56], [57], but others detail inconsistencies in this relationship [58], [59]. For example, an instructor's beliefs can be student oriented, but his (her) actions can be instructor oriented. An important consideration of this inconsistency, however, is that when an inconsistency occurs the teacher's actions always seem to be more instructor oriented than their espoused beliefs.

The implications of this relationship between beliefs and actions for the engineering laboratory context are twofold. First, instructors with student-centered orientations to teaching laboratories will likely be the ones who adopt innovative pedagogies. However, the second implication is that an instructor's student-centered orientation to teaching does not *guarantee* the use of innovative pedagogies. Gess-Newsome [57] suggested that faculty will not adopt change or strive to make changes successful unless they are dissatisfied with their current actions or beliefs. Therefore, for laboratory instructors to adopt innovative ways of teaching, they must become dissatisfied with the traditional "cookbook" style of instruction. This dissatisfaction could stem from a change in beliefs, e.g., as the result of transformative learning [60], or from environmental factors as discussed in previously. Indeed, faculty attitudes toward laboratory is a result on a confluence of factors internal and external [26].

IV. Conclusion and Implications

Engineering laboratories play an important role in developing the epistemology and ontology of engineering students. However, the full potential of laboratory experiences often is not realized and students are relegated to "cookbook" laboratory exercise. Furthermore, the laboratory experience should go beyond the development of conceptual understanding by promoting other competences and skills such as the ones proposed by [38] and [61]. While previous work has explored factors that could improve the effectiveness of lab, this work is unique in that it presents possible influencers of faculty decisions regarding laboratory pedagogies.

Through a literature review of faculty knowledge, institutional context and policies, the role of society, and instructor beliefs, we find that faculty decisions are influenced by a myriad of stakeholders and context details. Faculty's own knowledge of the content, how to teach the content, and how to use technology for learning can influence their instructional actions. Institutional values, reward systems, and resources can dictate what pedagogical techniques, risks, or reform efforts are employed. External stakeholders such as industrial employers of students, accreditation services, professional societies, and funding agencies can guide what is valued and/or required in engineering laboratory curriculum. Finally, the individual beliefs and values of the instructors may impact their actions when teaching laboratory classes. Thus, to better understand the role instructors may play in efforts to improve the effectiveness of engineering classes, we must consider a myriad of internal and external factors that influence instructors' decisions.

V. Future Research

This work presents initial findings from a literature review on the faculty decision making process regarding laboratory instructional approaches. A further step will be to conduct a qualitative study to explore the lived experiences of engineering faculty working in different higher education institutions. This qualitative study will contribute to a better understanding of how the different sources of influences affect the nature of the students' learning experiences in engineering education laboratories.

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REFERENCES

[1] S. D. Sheppard, K. Macatangay, A. Kolb, and W. M. Sullivan, *Educating Engineers: Designing for the Future of the Field*. San Francisco: Jossey-Bass, 2008.

[2] L. D. Feisel and A. J. Rosa, "The Role of the Laboratory in Undergraduate Engineering Education," *J. Eng. Educ.*, vol. 94, no. 1, pp. 121–130, 2005.

[3] P. C. Wankat and F. S. Oreovicz, *Teaching engineering*. New York: Knovel, 1993.

[4] J. J. Duderstadt, *Engineering for a changing world: A roadmap to the future of American engineering practice, research, and education*. Ann Arbor: Millenium Project, University of Michigan, 2008.

[5] J. Ma and J. V. Nickerson, "Hands-on, simulated, and remote laboratories: A comparative literature review," *ACM Comput. Surv.*, vol. 38, no. 3, p. 7–es, 2006.

[6] R. Heradio, L. De La Torre, D. Galan, F. J. Cabrerizo, E. Herrera-Viedma, and S. Dormido, "Virtual and Remote Labs in Education: a Bibliometric Analysis," *Comput. Educ.*, vol. 98, pp. 14–38, Jul. 2016.

[7] C. R. Mann, *A study of engineering education. Prepared for the Joint Comittee on Engineering Education of The National Engineering Societes. N0. 11*. New York: Merrymount Press, 1918.

[8] P. Avitabile, "Integrating dynamic systems materials into a mechanical engineering curriculum through innovative use of web-based acquisition and hands-on application and use of virtual graphical user interfaces Part 3: Dynamic systems - Analytical and experimental syst," *Exp. Tech.*, vol. 32, no. 1, pp. 17–23, 2008.

[9] P. J. Axaopoulos, K. N. Moutsopoulos, and M. P. Theodoridis, "Engineering education using a remote laboratory through the Internet," *Eur. J. Eng. Educ.*, vol. 37, no. 1, pp. 39–48, Mar. 2012.

[10] M. S. Ayas and I. H. Altas, "A virtual laboratory for system simulation and control with undergraduate curriculum," *Comput. Appl. Eng. Educ.*, vol. 24, no. 1, pp. 122–130, Jan. 2016.

[11] M. del R. Uribe, A. J. Magana, J.-H. Bahk, and A. Shakouri, "Computational simulations as virtual laboratories for online engineering education: A case study in the field of thermoelectricity," *Comput. Appl. Eng. Educ.*, vol. 24, no. 3, pp. 428–442, 2016.

[12] M. D. Koretsky, K. Christine, and E. Gummer, "Student learning in industrially situated virtual laboratories," *Chem. Eng. Educ.*, vol. 45, no. 3, pp. 219–228, Jun. 2011.

[13] T. de Jong, "Technological advances in inquiry learning," *Science (80-.).*, vol. 312, no. 5773, pp. 532–533, 2006.

[14] T. de Jong, "Learning and instruction with computer simulations," *Educ. Comput.*, vol. 6, pp. 217–229, 1991.

[15] T. de Jong and W. R. van Joolingen, "Scientific discovery learning with computer simulations of conceptual domains," *Rev. Educ. Res.*, vol. 68, no. 2, pp. 179–201, 1998.

[16] J. E. Corter, J. V. Nickerson, S. K. Esche, C. Chassapis, S. Im, and J. Ma, "Constructing reality: A study of remote, hands-on, and simulated laboratories," *ACM Trans. Comput. Interact.*, vol. 14, no. 2, p. 7–es, Aug. 2007.

[17] G. S. Coutinho, "Instructional designs in the lab: A systematic review. Department of Engineering Education. Purdue University. Unpublished," West Lafayette, IN, 2016.

[18] J. W. Pellegrino, N. Chudowsky, and R. Glaser, *Knowing what students know: The science and design of educational assessment*. Washington, DC: National Academies Press, 2001.

[19] L. S. Shulman, "Knowledge and teaching: Foundations of the new reform," *Harv. Educ. Rev.*, vol. 57, no. 1, pp. 1–21, 1987.

[20] P. Mishra and M. J. Koehler, "Technological pedagogical content knowledge: A framework for teacher knowledge," *Teach. Coll. Rec.*, vol. 108, no. 6, pp. 1017–1054, 2006.

[21] A. J. Magana, S. P. Brophy, and G. M. Bodner, "Student Views of Engineering Professors Technological Pedagogical Content Knowledge for Integrating Computational Simulation Tools in Nanoscale," *Int. J. Enginnering Educ.*, vol. 28, no. 5, pp. 1033–1045, 2012.

[22] J. M. Rosenberg *et al.*, "Context and Technological Pedagogical Content Knowledge (TPACK): A Systematic Review," *J. Res. Technol. Educ.*, vol. 47, no. 3, pp. 186–210, 2015.

[23] I. Sahin, "Development of survey of technological pedagogical and content knowledge (TPACK)," *TOJET Turkish Online J. Educ. Technol.*, vol. 10, no. 1, pp. 97–105, 2011.

[24] R. Groth, D. Spickler, J. Bergner, and M. Bardzell, "A Qualitative Approach to Assessing Technological Pedagogical Content Knowledge," *Contemp. Issues Technol. Teach. Educ.*, vol. 9, no. 4, pp. 392–411, 2009.

[25] C. M. Campbell and K. A. O'Meara, "Faculty Agency: Departmental Contexts that Matter in Faculty Careers," *Res. High. Educ.*, vol. 55, no. 1, pp. 49–74, 2014.

[26] M. T. Hora, "Organizational factors and instructional decision-making: A cognitive perspective," *Rev. High. Educ.*, vol. 35, no. 2, pp. 207–235, 2012.

[27] J. S. Fairweather, "The mythologies of faculty productivity: Implication for institutional policy and decision making," *J. Higher Educ.*, vol. 73, no. 1, pp. 26–48, 2002.

[28] R. T. Blackburn, J. P. Bieber, J. H. Lawrence, and L. Trautvetter, "Faculty at work : Focus on research , scholarship , and service," *Res. High. Educ.*, vol. 32, no. 4, pp. 385–413, 1991.

[29] L. R. Lattuca, I. Bergom, and D. B. Knight, "Professional development, departmental contexts,

and use of instructional strategies," *J. Eng. Educ.*, vol. 103, no. 4, pp. 549–572, 2014.

[30] K. O'Meara, A. L. Terosky, and A. Neumann, "Faculty Careers and Work Lives," *ASHE High. Educ. Rep.*, vol. 34, no. 3, pp. 1–22, 2008.

[31] E. L. Boyer, *Scholarship reconsidered. Priorities of the professoriate*. Jossey-Bass, 2015.

[32] L. Jamieson and J. Lohmann, *Innovation with Impact: Creating a Culture for Scholarly and Systematic Innovation in Engineering Education*. Washington, DC: ASEE, 2012.

[33] K. O'Meara, "Inside the panopticon: Studying academic reward systems," in *Higher education: Handbook of theory and research*, no. March 2011, Springer Netherlands, 2011, pp. 161–220.

[34] J. J. Lagowski, "Reforming the facuty-reward system. (Editorial)," *J. Chem. Educ.*, vol. 71, no. 7, p. 1994, 1994.

[35] M. Borrego, J. E. Froyd, and T. S. Hall, "Diffusion of Engineering Education Innovations: A Survey of Awareness and Adoption Rates in U.S. Engineering Departments," *J. Eng. Educ.*, vol. 99, no. 3, pp. 185–207, 2010.

[36] T. J. Lund and M. Stains, "The importance of context: an exploration of factors influencing the adoption of student-centered teaching among chemistry, biology, and physics faculty," *Int. J. STEM Educ.*, vol. 2, no. 1, p. 13, 2015.

[37] A. M. Rodríguez, "A Theoretical Analysis of Factors Influencing the Decision of Faculty to Use Educational Technologies in the Context of Institutions of Higher Education," vol. 4, no. 1, pp. 147–164, 2017.

[38] A. J. Magana and G. Silva Coutinho, "Modeling and simulation practices for a computational thinking-enabled engineering workforce," *Comput. Appl. Eng. Educ.*, vol. 25, no. 1, pp. 62–78, 2017.

[39] K. D. Beddoes, B. K. Jesiek, and M. Borrego, "Identifying opportunities for collaborations in international engineering education research on problem- and project-based learning," *Interdiscip. J. Probl. Learn.*, vol. 4, no. 2, pp. 6–34, 2010.

[40] M. Besterfield-Sacre, M. F. Cox, M. Borrego, K. Beddoes, and J. Zhu, "Changing engineering education: Views of U.S. faculty, chairs, and deans," *J. Eng. Educ.*, vol. 103, no. 2, pp. 193–219, 2014.

[41] M. Borrego, M. J. Foster, and J. E. Froyd, "What is the state of the art of systematic reviewin engineering education?," vol. 104, no. 2, pp. 212–242, Apr. 2015.

[42] L. R. Lattuca, P. T. Terenzini, and J. F. Volkwein, "Engineering change: A study of the impact of EC2000," *Int. J. Eng. Educ.*, vol. 20, no. 3, pp. 318–328, 2004.

[43] E. Seymour, K. DeWelde, and C. Fry, "Determining progress in improving undergraduate STEM education: The reformer's tale," *... Diffus. Transform. Eng. Educ. ...*, pp. 1–30, 2011.

[44] L. Jamieson and J. Lohmann, "Innovation with impact, Executive summary," 2012.

[45] L. R. Lattuca, "Influences on Engineering Faculty Members ' Decisions about Educational Innovations : A Systems View of Curricular and Instructional Change. A White Paper Commissioned for the Characterizing the Impact of Diffusion of Engineering Education Innovations For," *Charact. Impact Diffus. Eng. Educ. Innov.*, pp. 1–16, 2011.

[46] C. J. Bland, B. a. (Bruce A. Center, D. a. Finstad, K. R. Risbey, and J. Staples, "The Impact of Appointment Type on the Productivity and Commitment of Full-Time Faculty in Research and Doctoral Institutions," *J. Higher Educ.*, vol. 77, no. 1, pp. 89–123, 2006.

[47] R. G. Baldwin and R. T. Blackburn, "The Academic Career as a Developmental Process," *Journalof High. Educ.*, vol. 52, no. 6, pp. 598–614, 1981.

[48] A. Oleson and M. T. Hora, "Teaching the way they were taught? Revisiting the sources of teaching knowledge and the role of prior experience in shaping faculty teaching practices," *High. Educ.*, vol. 68, no. 1, pp. 29–45, 2014.

[49] I. Forum, J. E. Froyd, and A. Provost, "Propagation and Realization of Educational Innovations in the System of Undergraduate STEM Education," 2011.

[50] L. R. Lattuca, P. T. Terenzini, and J. F. Volkwein, *Engineering change: A study of the impact of EC2000. Executive summary.* Baltimore, MD: ABET, 2006.

[51] ABET Engineering Accreditation Commision, "Criteria for accrediting engineering programs: Effective for during the 2016-2017 accreditation cycle.," 2015.

[52] C. Lyall, A. Bruce, W. Marsden, and L. Meagher, "The role of funding agencies in creating interdisciplinary knowledge," *Sci. Public Policy*, vol. 40, no. 1, pp. 62–71, 2013.

[53] B. Bozeman and C. Boardman, "The NSF Engineering Research Centers and the University–Industry Research Revolution: A Brief History Featuring an Interview with Erich Bloch," *J. Technol. Transf.*, vol. 29, pp. 365–375, 2004.

[54] C. Henderson, A. Beach, and N. Finkelstein, "Facilitating change in undergraduate STEM instructional practices: An analytic review of the literature," *J. Res. Sci. Teach.*, vol. 48, no. 8, pp. 952–984, 2011.

[55] Z. Fang, "A review of research on teacher beliefs and practices," *Educ. Res.*, vol. 38, no. 1, 1996.

[56] V. Richardson, J. Sikula, T. Buttery, and E. Guyton (Eds.), "The role of attitudes and beliefs in learning to teach.," *Handb. Res. Teach. Educ.*, pp. 102–119, 1996.

[57] J. Gess-Newsome, S. a. Southerland, A. Johnston, and S. Woodbury, "Educational reform, personal practical theories, and dissatisfaction: The anatomy of change in college science teaching," *Am. Educ. Res. J.*, vol.

40, no. 3, pp. 731–767, 2003.
[58] P. E. Simmons *et al.*, “Beginning Teachers: Beliefs and Classroom Actions,” *J. Res. Sci. Teach.*, vol. 36, no. 8, pp. 930–954, Oct. 1999.
[59] R. Kane, S. Sandretto, and C. Heath, “Telling half the story : A critical review of research on the teaching beliefs and practices of university academics,” *Rev. Educ. Res.*, vol. 72, no. 2, pp. 177–228, 2002.
[60] J. A. W. Siddiqui and R. S. Adams, “Transformation of engineering education: Taking a perspective for the challenges of change,” vol. 3636518, p. 309, 2014.
[61] A. J. Magana, “Modeling and Simulation in Engineering Education: A learning progression (in press),” *J. Prof. Issues Eng. Educ. Pract.*