From Capability Index to Maturity Model: International Institutional Strategies for Innovation in Engineering Education

Dr. Jose Texier, LACCEI

Assistant Director of "The Latin American and Caribbean Consortium of Engineering Institutions" (LACCEI). Computer Engineer UNET (2002, Venezuela). Master of Computer Science, University of the Andes (2008, Venezuela). PhD in Computer Science from the National University of La Plata (2014, Argentina). Invited Professor and Researcher Universidad Nacional de Chilecito (2014-2023, Argentina). Ex professor UNET (2003-2015). The research areas are framed in Digital Libraries / Institutional Repositories / Open Science, Compilers and Interpreters, Natural Language Processing: *. Orcid: http://orcid.org/0000-0003-0176-6625 *. Google Scholar: https://scholar.google.com.ar/citations?user=kUQ1boMAAAAJ&hl=en&oi=ao *. ENTER (EngineeriNg educaTors pEdagogical tRaining): 2311001032

Dr. Maria Mercedes Larrondo-Petrie, Florida Atlantic University

Dr. Larrondo Petrie has a Ph.D. in Computer Engineering and is a Professor at Florida Atlantic University. She is the pro-bono Executive Director of LACCEI (Latin American and Caribbean Consortium of Engineering Institutions), a Titular Member of the Pan-American Academy of Engineering. and directs the Organization of American States' OAS Center of Excellence of Engineering for the Americas. She serves on Standards Development Working Groups for the Institute of Electrical and Electronic Engineers (IEEE). Awards she has received include: the Global Engineering Deans Council and the International Federation of Engineering Education joint Duncan Fraser International Engineering Education Award in 2016, the IEEE's Edwin Jones Service award, the American Society of Engineering Education's International Engineering Educator Award, the Society of Women Engineers' Outstanding Women in Engineering of 2019, and the Society of Hispanic Professional Engineers' National Faculty Advisor of the Year in 2018. The U.S. National Academy of Engineering invited her to be part of their Indo-US Collaboration for Engineering Education initiative, and she was appointed US-Mentor to the State of Gujarat, India. Her research interests focus on global engineering education, designing next generation learning systems, modeling complex systems, and designing for security. Her research publications earned her an h-index of 27, an i-index of 60, a g-index of 31 and have received over 2100 citations. She was awarded more than four million dollars in research grants over her career.

Prof. Cuauhtemoc Godoy P.E., Polytechnic University of Puerto Rico
Dr. Renetta Garrison Tull, University of California, Davis

Renetta Garrison Tull, Ph.D., is the Vice Chancellor for Inclusive Excellence at the University of California Davis, and she is a past convenor for the University of California's system-wide (10 campus) Council of Vice Chancellors for Equity and Inclusion. Tull's undergraduate and doctoral degrees in electrical engineering and speech science are from Howard University and Northwestern University, respectively. She has had past faculty roles at UW-Madison, the University of Maryland College Park, and UMBC. At UC Davis, she is an Adjunct Professor in the Department of Electrical and Computer Engineering in the College of Engineering, and a faculty affiliate in the Interdepartmental Program on Human Rights Studies. As Vice Chancellor, her divisional portfolio includes the Davis-based Office of Campus Community Relations, and the Office for Advancing Mentoring and the Professoriate. The Sacramento headquarters houses the Office for Health Equity by Design for Inclusive Excellence, serving the medical school, nursing school, and medical center. Inclusive Excellence also covers medical clinics around California, and UC Davis' locations in the Bay Area and other parts of the state. Her portfolio also includes the Avanza initiative; the Police Accountability Board; the Center for Reducing Health Disparities; the Center for the Advancement of Multicultural Perspectives on Science; the Center for the Advancement of Multicultural Perspectives on Social Sciences, Arts, and the Humanities; and the Truth, Community Healing, and Transformation Center. She credits the success of Inclusive Excellence to talented teams and a supportive university environment. She is proud to be the Executive Sponsor for the UC Davis Principles of Community university-wide campus climate campaign, which highlights the key phrase, "We affirm the dignity inherent in all of us."

Before joining UC Davis in California, Tull was in Maryland at the University of Maryland Baltimore County (UMBC) and served as Assistant Dean for Graduate Student Development (GSD), Associate Vice Provost for GSD and Postdoctoral Affairs, and Associate Vice Provost for Strategic Initiatives. She later had a detail with the University System of Maryland (USM, 12 institutions), serving as the Director for USM Pipeline Professional Development Programs, and she had Co-PI and PI roles on National Science Foundation (NSF) grants within the LSAMP, Alliances for Graduate Education and the Professoriate, and ADVANCE programs. At Davis, she is PI for the NSF-funded PROMISE Engineering Institute (PEI - UC Davis and UMBC). PEI has developed an intergenerational mentoring engineering leadership network which has engaged engineering graduate students and senior leaders from UC Davis, UMBC, UC Irvine, UC Berkeley, UCLA, Stanford, University of Maryland College Park, Virginia State University, Rice University, George Mason University, and North Carolina A&T.

An international speaker on global inclusion in STEM, Dr. Tull, a member of Tau Beta Pi, has shared Humanitarian Engineering principles and work connected to the United Nations' Sustainable Development Goals at the United Nations Headquarters, and on every continent (except Antarctica). Through the Latin and Caribbean Consortium for Engineering Institutions (LACCEI), she has given bilingual talks across Latin America on topics related to engineering for all.

Tull was a finalist for the Global Engineering Deans Council/Airbus Diversity Award (announced in Italy and acknowledged in Dubai). In addition, she has received the ABET Claire L. Felbinger Award for Diversity, the Student Platform for Engineering Education Development Global Mentoring Award, and the Electrical and Computer Engineering Department Head Association's (ECEDHA) Diversity Award. She was a PI for Puerto Rico's ADVANCE Hispanic Women in STEM, she is the past President for LACCEI, and the current Vice President of Transformative Initiatives for the International Federation of Engineering Education Societies (IFEES). Tull is currently leading the "Alianza" project for LACCEI in partnership with the Organization of American States; she sits on the Board of Directors of the American Geophysical Union (AGU), one of the world's largest Earth and space science organizations; and recently, she has been invited to serve on engineering expert teams in Chile and China. Tull was a co-author for UNESCO Engineering Report II, and she participated in the UN Women CSW66 side event on "Role of Women in STEM in Addressing Climate Change" where she joined global leaders on the importance of women in engineering for climate action, disaster risk reduction, and sustainable development. She is an author of a chapter of "Rising to the Top," an IFEES book on global women in engineering, and was a co-author for the National Academies' "Impact of COVID-19 on the Careers of Women in Academic STEMM," and "The Science of Effective Mentoring in STEMM. She is also co-author for the "Matilda y las Mujeres en Ingeniería" series, and her book chapter with a collaborative team of authors from several continents, "Models for International Collaborations to Nurture Students into Global Engineers," in the Springer book, "Academic Leadership in Engineering Education: Learnings and Case Studies from Educational Leaders Around the Globe," was launched in Australia. Tull enjoys her work as a global education policy strategist and champion for equity. She often travels with her husband of more than 30 years, Dr. Damon Tull, with whom she collaborates on work such as "The Success Equation," and "Dark Matters: Metaphorical Black Holes…", which creatively couples math, physics, and social science.

Laura Romero, Tecnologico de Monterrey
Fernando José Zorto-Aguilera, National Autonomous University of Honduras

Professor of the Department of Mechanical Engineering and Director of the Research Institute of Applied Science and Technologies of the National Autonomous University of Honduras. Vice-President of Iniciatives of LACCEI.

Christian Chacua, Harvard University

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Abstract: The capacity of institutions to generate, adapt, and transfer productive knowledge is increasingly linked to differences in economic development among regions. In this context, universities with established engineering programs play a strategic role in strengthening innovation ecosystems and supporting regional and international economic development.

The objective of this study is to develop and apply a Capability Maturity Model (CMM) to assess and promote institutional innovation and international collaboration capacity in engineering education. The fundamental research question guiding this study is as follows: How can a CMM be utilized to assess and guide the progression of universities with established engineering programs toward higher levels of research, innovation, knowledge transfer, and international engagement within global knowledge ecosystems?

Methodologically, the study adapts the traditional CMM framework for application in higher education, employing it to analyze engineering universities across several countries in the Americas. Initial validation focuses on the technological output and research dimension of the Capability Index using standardized indicators of scientific publications, citations, patents, and international collaboration obtained from OpenAlex and Espacenet. The emphasis on international engagement highlights the role of global knowledge networks and cross-border collaboration as drivers of institutional maturation in engineering education.

The results indicate a notable concentration of institutions at intermediate maturity levels, particularly at Level 3 (Defined), suggesting that a considerable number of universities have implemented standardized research processes but have not yet transitioned to data-driven management and innovation-intensive performance. It is noteworthy that only a single institution attains Level 5 (Optimized), thereby underscoring the rigorous nature of these maturity thresholds.

From a discussion perspective, these findings suggest that the main challenge for most institutions is not initiating research activity, but rather strengthening its quality, regional and cross-border impact, and the mechanisms that translate knowledge into innovation outcomes. The model facilitates strategic prioritization by identifying institutional bottlenecks and transition pathways, particularly from Level 3 to Level 4.

The study's findings indicate that the proposed EECMM (Engineering Education Capability Maturity Model) functions as a diagnostic and strategic planning instrument, rather than a competitive ranking mechanism. It offers a structured framework to guide the development of institutional capacities and inform policy and investment decisions in engineering education and globalized innovation systems.

Keywords: Engineering Education; Capability Maturity Model; EECMM, Institutional Innovation; Research; Development; Technology Transfer; Economic Complexity; Triple Helix; Higher Education Institutions

Introduction

Differences in economic development across world regions are increasingly associated with the ability of economies to generate goods and services of high productive complexity [1]. Such complexity depends largely on the extent to which nations and their institutions can develop, adapt, and apply specialized knowledge that enables meaningful participation in global value chains.

According to the economic complexity framework developed by Ricardo Hausmann and César Hidalgo, the accumulation of practical and theoretical knowledge within a society—beyond physical infrastructure or natural resource endowments—constitutes a decisive determinant of competitiveness [2]. Economic growth is driven by innovation through new ideas, creative processes, and forms of knowledge that materialize as devices, methods, or significant improvements in the products economies generate and export [1], [3].

In this context, technology, capital, institutions, digitalization, and the skills required to create new products do not diffuse uniformly across productive sectors [4], [5] or in the geographic space [6]. Productive know-how therefore extends beyond technical expertise and includes the institutional capacity to apply knowledge efficiently and sustainably, fostering both regional and global entrepreneurship and innovation as central drivers of economic growth [7].

Historically, although innovation and entrepreneurship often disrupt existing equilibria, both have proven to be powerful engines of development. The virtuous relationship between innovation, entrepreneurship, and growth has enabled societies to overcome demographic constraints and limitations in food and energy resources, creating new opportunities for development and sustained employment growth [8], [9].

Within this framework, engineering education plays a strategic role. Universities are not only responsible for educating highly qualified professionals, but also act as key agents in the creation, adaptation, and transfer of knowledge and technology, directly influencing a country's innovation capacity. To fulfill this role, higher education institutions must continuously update their curricula to incorporate technological advances, evolving production paradigms, and labor market trends.

Such adaptation is essential to equip students with the competencies required to address contemporary socioeconomic challenges. However, curricular reform alone is insufficient. These changes must be accompanied by transformations in organizational structures and external collaboration mechanisms, promoting closer and more effective engagement with scientific, technological, and industrial actors.

The experiences of countries such as South Korea, Japan, Singapore, and Taiwan demonstrate that sustained investment in research and development (R&D), together with coherent institutional strengthening policies, enables the creation of high value-added products and technologies, reinforcing their position within the global economic system [10], [11], [12]. In contrast, in many developing regions—including Latin America—universities face structural challenges that limit their innovation capacity and constrain their contribution to industrial development. Despite numerous initiatives aimed at promoting innovation, the region continues to play a marginal role in global innovation activities [13]. This gap underscores the need for systematic approaches to assess and strengthen the institutional capacities of universities to adapt, create, and transfer technological knowledge with tangible economic impact.

Multiple studies suggest that developing economies must reduce their dependence on imported technologies to address productive and social challenges. Increasing national productivity and competitiveness requires strengthening endogenous innovation capabilities. International experience shows that the establishment of reliable innovation ecosystems—based on sustained interaction among firms, universities, and supporting institutions—can generate virtuous cycles with positive societal impact [14].

This study expands on previous work presented at another conference [15] by shifting from a capabilities-based assessment approach to a Capability Maturity Model. The proposed model classifies levels of institutional development in universities with established engineering programs and systematically integrates research, innovation, and entrepreneurship as measurable dimensions of institutional maturity. In doing so, it strengthens the articulation between academia, industry, and government under the Triple Helix framework, which conceptualizes innovation as the result of strategic collaboration among universities as knowledge generators, industry as agents of application and commercialization, and government as providers of regulatory frameworks and public policy support.

This study aims to propose a methodological tool that enables the assessment and strategic guidance of institutional innovation in engineering education. Accordingly, the research question guiding this study is as follows: How can a Capability Maturity Model be utilized to assess and guide the progression of engineering universities toward higher levels of research, innovation, knowledge transfer, and international engagement within global knowledge ecosystems?

Theoretical Framework

The design of the Capability Maturity Model (CMM) is grounded in several complementary theoretical frameworks that explain how universities generate, apply, and transfer knowledge within innovation systems.

First, the work of Lall et al. emphasizes that technological development does not occur in isolation, but is strongly shaped by economic context and public policies that promote research and innovation. From this perspective, innovation processes in developing countries differ substantially from those in advanced economies, where mature technologies are often adopted with limited success. Within this framework, higher education institutions constitute essential components of national capabilities, as their role extends beyond teaching to include the creation and diffusion of knowledge applicable to the productive sector [16], [17], [18], [19].

Building on this foundation, the Triple Helix model of university–industry–government relations was developed in the 1990s by Henry Etzkowitz and Loet Leydesdorff [20], and later expanded by Meyer et al. [17]. This framework conceptualizes the transition from a dominant industry–government dyad characteristic of industrial society to an increasingly triadic relationship among universities, industry, and government in the knowledge-based economy [17], [19], [21]. The core premise of the Triple Helix model is that the potential for innovation and economic development lies in a more prominent role for universities and in the hybridization of institutional functions across the three spheres, leading to new organizational and social arrangements for the production, transfer, and application of knowledge.

Meyer et al. [17] further describe this dynamic interaction as a foundational mechanism for innovation generation, emphasizing that universities must not only produce knowledge, but also act as catalysts for technology transfer and entrepreneurial processes, actively participating in regional economic development. This perspective encompasses not only the concept of creative destruction as a natural dynamic of innovation, but also creative renewal occurring within each institutional sphere—university, industry, and government—as well as at their intersections. Over the past two decades, a substantial body of theoretical and empirical research on the Triple Helix has emerged, providing a comprehensive framework for analyzing complex innovation dynamics and informing innovation and development policies at national, regional, and international levels. This literature can broadly be interpreted from two complementary perspectives [17], [22].

Complementarily, Powers et al. examine how universities adapt to market demands through the commercialization of research outcomes, a phenomenon commonly referred to as academic capitalism. This process includes the creation of spin-off companies, patenting activities, and revenue generation through licensing, reflecting the growing relevance of university–industry linkages. More recent studies have further explored this phenomenon [19]. In parallel, other authors analyze how collaboration between universities and firms can serve as a key driver of innovation, highlighting the critical role of government support and innovation policy in strengthening these partnerships [23].

As a result, the Triple Helix model continues to evolve in response to new socioeconomic contexts, emphasizing the need for intensified interaction not only between universities and industry, but also with government actors to foster economic and social development. These recent contributions underscore the sustained and multifaceted relevance of universities within the broader landscape of academic capitalism and innovation [24], [25].

Finally, Hidalgo et al. [2] contribute the perspective of economic complexity, which argues that a nation's development depends on the diversity and sophistication of its productive capabilities. From this viewpoint, universities play a direct role in increasing regional and international productive complexity by strengthening scientific, technological, and innovation capacities, thereby positioning themselves as key actors in economic development processes [26].

Drawing on these theoretical foundations, the proposed CMM is structured around five dimensions that reflect the critical institutional capabilities of a university:

1. Economic capabilities, which relate investment in R&D to regional productive development;
2. Legal agility, which measures the institution's ability to protect intellectual property and facilitate technology transfer;
3. Scientific and technological output, which evaluates knowledge generation and its social and industrial impact;
4. Human resources with scientific impact, which assess academic talent and the quality of human capital engaged in research activities; and
5. Entrepreneurship and technology transfer, which analyze the creation of spin-offs, incubators, and institutional mechanisms that support innovation.

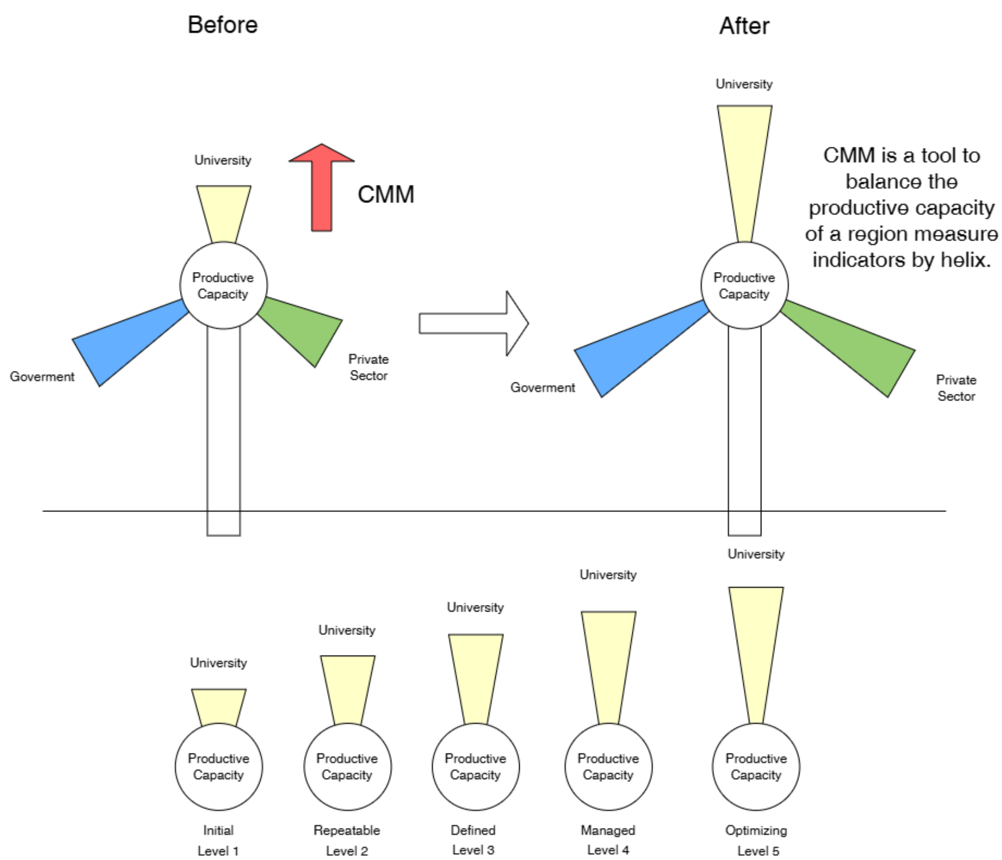

Figure 1. Visual of theoretical framework. Source: Own.

Together, these five dimensions constitute a robust theoretical framework for analyzing institutional maturity from a systemic perspective, recognizing that innovation is not an isolated event, but rather the outcome of cumulative processes of learning, collaboration, and knowledge management.

In this sense, the Capability Maturity Model does not merely quantify the level of development of engineering universities, but also guides their strategic evolution toward higher levels of technological autonomy and sustainability, strengthening their role within national and international innovation ecosystems.

Figure 1 synthesizes the theoretical articulation between productive capacity, the Triple Helix model, and the proposed Capability Maturity Model. For productive capacity to be driven by innovation and generate economic development, sustained interaction among universities, industry, and government is essential. However, these helices frequently operate with asymmetric or limited capabilities, constraining systemic advancement. The proposed CMM specifically addresses the university helix by strengthening institutional maturity levels, thereby enhancing its contribution to regional productive capacity and improving the overall balance within the innovation ecosystem.

Design of the Capability Maturity Model

The Capability Maturity Model (CMM) [27] is a process improvement framework composed of five maturity levels, originally developed to assess the capability of software engineering organizations to achieve planned and predictable outcomes. The model was formalized in the early 1990s through the work of Paulk et al. [27], within the context of the Software Engineering Institute, as a means to evaluate and improve software development processes. As process capability increases, outcomes become more measurable and predictable, and the causes of low quality or productivity can be systematically controlled or eliminated.

Over time, the CMM framework has evolved and been applied beyond software engineering to a wide range of organizational contexts, including academia. Baig et al. [28] extended CMM to improve the process of teaching and learning. Charlotte [29] applied it to improve online course design. Duarte et al. [30] focused on adapting the model to improve the overall efficiency and responsiveness of the business processes in Higher Education Institutions (HEIs). The Engineering Education Capability Maturity Model (EECMM) was developed to guide HEIs engineering programs through processes of accreditation and improving quality assurance, moving from national to international program accreditation [31], [32], [33]. In this broader context, the model has proven to be a useful instrument for assessing institutional maturity and establishing structured pathways for continuous improvement.

In this study, the EECMM framework is adapted and extended as the foundation for an institutional capacity-strengthening approach aimed at measuring and improving the capability of engineering universities and, by extension, the productive sectors embedded in their regional and national contexts. This adaptation positions the CMM as a bridge between institutional performance in engineering education and broader innovation and development objectives.
The proposed model seeks to encourage collaborative engagement among universities, governments, and the industrial sector to support applied research, provide incentives and support for faculty and researchers involved in technological projects, and establish the infrastructure, internal policies, and administrative procedures required to manage research funding and project outcomes effectively.

Accordingly, the EECMM framework defines a progressive structure of five maturity levels (Table 1), where each level represents a degree of institutional maturity. Organizations or institutions typically begin at Level 1 (Initial) and advance toward higher levels as they strengthen their objectives, processes, infrastructure, and management practices

Across maturity levels, internationalization evolves from emerging collaborative activity (Level 3) to strategically managed cross-border integration (Level 4), and ultimately to structurally embedded global leadership (Level 5). This progression reinforces international engagement as a key mechanism of institutional maturity within engineering education.

Table 1. Capability Maturity Model Levels. Source: Own.

Level	Description
Level 1 – Initial	Processes are ad hoc and reactive. Quality and productivity are highly variable, and outcomes depend on individual effort. The loss of key personnel results in the loss of knowledge and organizational capability. Progress requires the definition of goals, objectives, and basic control mechanisms to measure and monitor current performance.
Level 2 – Repeatable	Basic project management infrastructure and systems are established. Processes begin to be controlled through realistic planning based on prior experience. Policies and procedures are developed to enable the replication of successful outcomes.
Level 3 – Defined	Standardized processes are institutionalized and consistently applied in research and innovation management. International collaboration increases, though it remains primarily project-based rather than strategically embedded.
Level 4 – Managed	Quantitative management ensures predictable R&D&I performance. Internationalization is strategically managed through sustained cross-border collaboration and structured participation in global research networks.
Level 5 – Optimized	Continuous improvement is institutionalized through change management and innovation leadership. International engagement is structurally embedded, with global visibility and centrality in international knowledge networks.

Figure 2 illustrates how to raise the level of capability maturity. An institution at Level 1 starts applying project management practices to develop a disciplined process to attain Level 2, where the outcomes are repeatable but may depend on individuals in the organization. If these individuals leave, the level cannot be maintained because the institutional knowledge of how to achieve results leaves with them. By applying engineering management practices and adopting standard, consistent processes, the institution rises to Level 3, where others can follow the defined process to achieve consistent results. By applying quantitative management practices, predictable processes can be developed to attain Level 4. At this level, change management can be applied to practice continuous improvement processes to attain Level 5, where the institution is optimizing the results achieved.

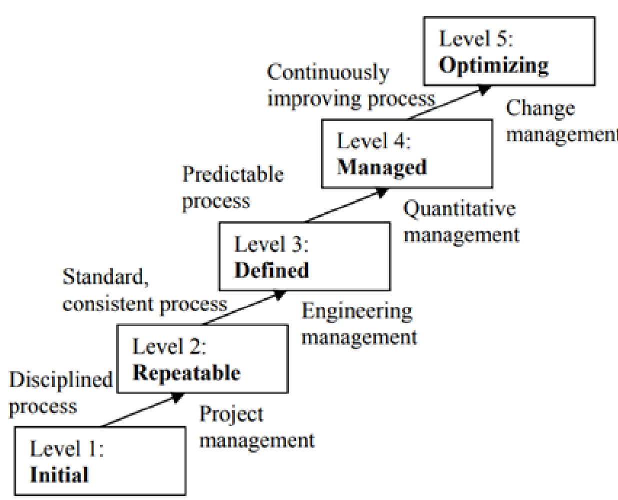

Figure 2. Five Levels of the Capability Maturity Model. Source: Own.

The adapted CMM aims to identify the processes, activities, and infrastructures that must be in place for institutions to progress from one maturity level to the next, particularly in the domains of applied research and technology transfer.

The model provides a reference framework for designing institutional capacity-building programs for universities and developing countries, especially in Latin America and the Caribbean. In this sense, the Capability Maturity Model functions not only as a measurement instrument, but also as a guide for institutional development, supporting the strategic evolution of universities toward higher levels of efficiency, innovation, and collaboration within their respective knowledge and innovation ecosystems.

Case Studies: Overview

To validate the Capability Maturity Model, the model was applied to a sample of 58 universities with established engineering programs drawn from diverse institutional contexts across North America, South America, Central America, and the Caribbean (the Americas). These case studies enable an assessment of the model's flexibility, scalability, and international validity by capturing a wide range of organizational maturity levels, resource availability, and degrees of industry engagement.

The heterogeneity of the sample provides an appropriate empirical basis to test whether the EECMM can effectively differentiate institutional maturity levels while remaining applicable across distinct higher education systems and innovation ecosystems.

Selected Universities

LACCEI is a non-profit organization with a network of over 250 universities, but for this study, we focused on only 58 active member universities. We classify them according to their geographic context: North America, South America, Central America, and the Caribbean. A summarized list of institutions is provided in Appendix 1 [34]. In this study, the term "engineering universities" refers to universities with established engineering programs (faculties or schools of engineering) and structured research activity in engineering-related fields.

North America

In the United States, the sample includes internationally recognized research-intensive institutions such as Clemson University, Florida Atlantic University, Marquette University, University of California Davis, North Carolina State University, Vaughn College of Aeronautics and Technology, University of Maine, and the Ana G. Méndez University System. These institutions represent mature research ecosystems characterized by a combination of basic research, applied research, and technological innovation.

Mexico is represented by Tecnológico de Monterrey, Universidad de Monterrey, Universidad Autónoma de Chihuahua, and Universidad Popular Autónoma del Estado de Puebla, institutions with a strong orientation toward industry–academia collaboration and technology-based entrepreneurship.

South America

The largest concentration of institutions in the study corresponds to South America, reflecting the diversity of university ecosystems and varying levels of research maturity.

Argentina is represented by Universidad Tecnológica Nacional, a federally structured institution with a strong focus on engineering and technology.

Chile contributes Universidad Andrés Bello and Universidad de la Frontera, both with established trajectories in applied research and engagement with the productive sector.

Colombia exhibits a particularly high level of institutional representation, including Universidad Nacional de Colombia, Universidad El Bosque, Universidad Mariana, Universidad EIA, Universidad Cooperativa de Colombia, Universidad Tecnológica de Pereira, Universidad de Pamplona, Universidad de los Llanos, Politécnico Grancolombiano, Universidad Nacional Abierta y a Distancia, Universidad de América, Universidad La Gran Colombia, and Universidad Tecnológica de Bolívar. This group reflects a highly diverse higher education system composed of both public and private institutions actively engaged in research, advanced training, and knowledge transfer.

Ecuador is represented by Escuela Politécnica Nacional, Escuela Superior Politécnica del Litoral, Escuela Superior Politécnica del Chimborazo, Universidad de Guayaquil, and Universidad Bolivariana del Ecuador, which are key institutions in the country's scientific and technical education system.

Peru contributes a broad and heterogeneous set of universities, including Pontificia Universidad Católica del Perú, Universidad Nacional de Ingeniería, Universidad Tecnológica del Perú, Universidad Privada del Norte, Universidad Ricardo Palma, Universidad César Vallejo, Universidad Peruana de Ciencias Aplicadas, Universidad Privada San Juan Bautista, Universidad de Ingeniería y Tecnología, Universidad de Ciencias y Humanidades, and Universidad Católica Santo Toribio de Mogrovejo.

Venezuela is represented by Universidad Simón Bolívar, historically recognized for its emphasis on science, technology, and engineering.

Central America and the Caribbean

In Central America, Costa Rica contributes Universidad Latina de Costa Rica and Universidad Fidélitas, both with growing orientations toward applied research and internationalization. Honduras is represented by Universidad Nacional Autónoma de Honduras and Universidad Tecnológica Centroamericana, while Panama is represented by Universidad Tecnológica de Panamá.

In the Caribbean, the sample includes Polytechnic University of Puerto Rico, as well as Universidad Tecnológica de Santiago and Universidad Central del Este from the Dominican Republic, reflecting the progressive development of academic and research capacities in the region.

Methodological Approach for the Initial Analysis

To ensure computational efficiency and analytical clarity in this initial validation stage, each university was evaluated using only the research and technological production dimension of the Capability Index. The selected indicators (Table 2) include: total number of publications, total citations, total patents, and international collaboration rate.

This initial validation focuses exclusively on the research and technological output dimension of the Capability Index as a first-stage empirical application of the Engineering Education Capability Maturity Model (EECMM). Subsequent phases will progressively incorporate the remaining structural and institutional dimensions of the model (*including legal agility, human capital with scientific impact, and entrepreneurship and technology transfer*) to achieve a more comprehensive maturity assessment.

Data were collected via automated queries to OpenAlex (publications/citations) and Espacenet (patents) using their free API services. A custom script was developed to (i) resolve each university to a unique institutional entity, (ii) execute reproducible queries with consistent parameters, (iii) paginate results when required, (iv) validate and normalize key fields, and (v) deduplicate records before computing indicators. OpenAlex outputs were used to compute total publications (work count), total citations (sum of cited-by counts), and international collaboration (share of works with cross-country co-authorship), with collaboration calculated over the last 100 papers to reflect current networking capacity. Espacenet outputs were used to compute total patents by aggregating retrieved patent records linked to each institution through applicant/assignee matching, applying name-variant harmonization and deduplication to minimize repeated counts caused by multiple publications of the same invention in different offices.

Each indicator was normalized on a 0–1 scale following the Capability Index met[15]logy [13], which assesses institutional capacity in engineering education. The weighting scheme (35–25–20–20) was retained to preserve theoretical consistency and construct continuity, assigning greater structural relevance to research intensity (publications and citations) while incorporating innovation (patents) and international collaboration as complementary performance dimensions.

Table 2. Operationalization of the variables according to their dimension. Source: Own

Dimension	Variable (Indicator)	Weight (Wi)	Normalization Type
Scientific Production	Total of publications	35%	Logarithmic
Scientific Impact	Total citations	25%	Logarithmic
Innovation	Total patents	20%	Logarithmic
Strategic Synergy	International collaboration (%)	20%	Linear

To correct statistical asymmetry caused by large-scale institutions (outliers), logarithmic normalization was applied to three indicators. This approach evaluates maturity in terms of orders of magnitude and prevents the undervaluation of highly efficient mid-sized institutions. The logarithmic normalization function applied was:

$$X_{norm} = \frac{ln(X+1)}{ln(X_{max}+1)} \quad \text{Eq.1}$$

Where x represents the raw value for the analyzed variable, and X_{max} is the maximum observed value within the global sample. The constant 1 ensures appropriate handling of zero values. For the international collaboration variable, linear normalization was applied due to its percentage-based and more homogeneous distribution:

$$S_{norm} = \frac{S}{S_{max}} \quad \text{Eq.2}$$

Where S is the percentage of international collaboration of the institution in its last 100 papers, and S_{max} is the maximum value of international collaboration observed in the sample. The final weighted score (Q) for each institution was calculated using a weighted sum of the previously normalized variables, according to the equation:

$$Q = \sum_{i=1}^{n} (w_i * X_{norm,i}) \quad \text{Eq.3}$$

The Q value corresponds to a normalized composite index in the range [0-1], where values close to one (1) indicate greater institutional maturity across all dimensions of the research, development, and innovation ecosystem. A limitation of the proposed metric is that normalization relies on sample-specific maxima (X_{max} and S_{max}), which may affect comparability across different samples or years. Additionally, logarithmic scaling compresses differences among high-performing institutions and the weighted additive structure allows compensability between dimensions, potentially masking critical weaknesses (e.g., low patenting offset by high publication volume).

Institutional Maturity Levels and Profiles

Based on the composite score Q, each university was assigned to a maturity level from Initial (Level 1) to Optimized (Level 5), representing progressive stages of research capacity development (see Table 3). The classification strictly follows the "Score Range (Index)" intervals defined in Table 3, where predefined thresholds are distributed equitably across the normalized scale (0–1) to reflect the conceptual logic of staged maturity rather than statistical percentiles. Accordingly, Level 4 corresponds to Q values between 0.60 and 0.79, signaling sustained internationalized R&D&I performance, while Level 5 includes institutions with Q > 0.80, denoting consolidated global impact and integration into international knowledge networks.

From these maturity levels, five institutional profiles can be identified:

A. Teaching-centered universities primarily focus on undergraduate education, with incipient research activity that is often individual and unsystematic. At this stage, defining a clear research strategy and allocating seed funding for the creation and consolidation of research groups are critical.
B. Universities with emerging research maintain a strong emphasis on teaching—particularly at the master's level—while developing a nascent research ecosystem. Active research groups are typically present, with participation in indexed conferences and early publication efforts. The main strategic challenge at this level is increasing publications in indexed scientific journals to improve citation impact.
C. Universities with active research exhibit consolidated research programs and consistent scientific outputs. Regular publication in recognized scientific databases, and significant international collaboration are common. Strategic emphasis at this stage should focus on enhancing visibility and citation impact.
D. Research-intensive universities place research at the core of institutional growth. These institutions display high volumes of scientific production and impact, enabling access to competitive national and international research funding. At this level, patents, spin-offs, and technology transfer mechanisms begin to emerge. The strategic objective is to consolidate regional leadership and strengthen global positioning.
E. Finally, global research leader universities operate at the frontier of knowledge, with a strong presence in large-scale international research networks. These ecosystems often include highly influential researchers, extensive and strategic international collaboration, and leadership in addressing global challenges through high-impact scientific, technological, and societal contributions.

Table 3. Institutional maturity levels for higher education institutions under the EECMM. Source: Own

Level	Level Name	Description	Score Range (Index)
1	Initial (Ad hoc)	Research activities are uncoordinated and depend on individual initiatives.	Index < 0.19
2	Managed (Emerging)	Basic research management exists, primarily oriented toward local or national impact.	0.2 – 0.39
3	Defined (Consolidated)	Standardized research processes with growing international activity.	0.40– 0.59
4	Quantitatively Managed (International)	High international visibility, patent activity, and citation impact.	0.6– .79
5	Optimized (World Class)	Global leadership in research volume, impact, and network centrality.	Index > 0.8

Results of the Initial Analysis

Based on the application of the composite index `Q`, calculated through the weighted aggregation of normalized indicators for scientific production, impact, innovation, and international collaboration, the 58 universities were classified across the five EECMM maturity levels.

The Q index ranged from 0.2434 to 0.8006, with a mean of approximately 0.542 and a median close to 0.519, indicating that the center of the sample is located at Level 3 (Defined). This concentration suggests that many institutions have established standardized research processes but still have room to transition toward data-driven management models (Level 4), particularly in terms of technological innovation outcomes and sustained international positioning.

Table 4. Number of universities by CMM level. Source: Own

CMM Level	Number of Universities	Percentage (%)
Level 1 (Initial)	0	0.00
Level 2 (Managed)	4	6.90
Level 3 (Defined)	34	58.62
Level 4 (Quantitatively Managed)	19	32.76
Level 5 (Optimized)	1	1.72

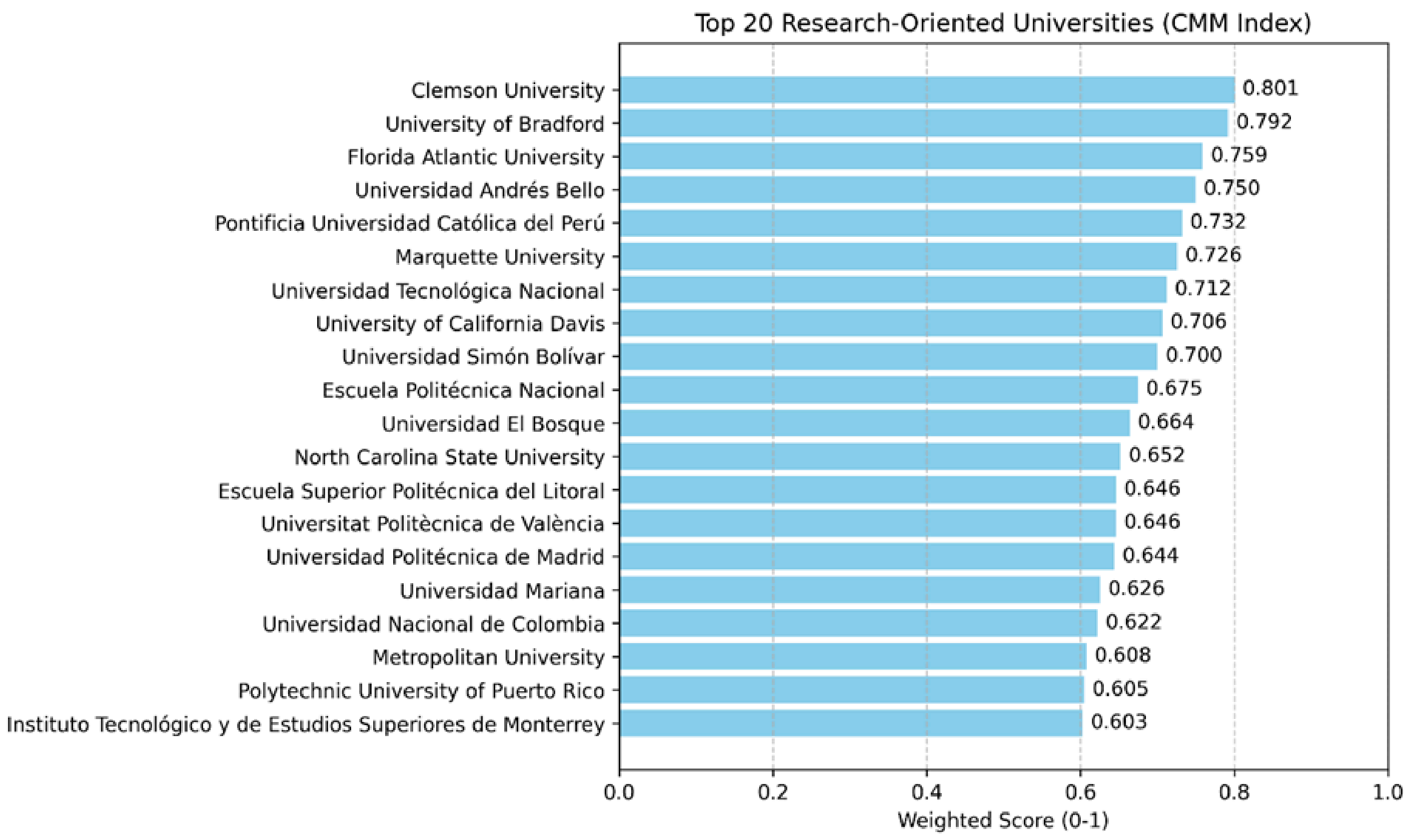

Figure 3. Top 20 universities across CMM maturity levels. Source: Own.

No institutions were classified at Level 1, while the majority were concentrated at Level 3. In percentage terms, 6.9% of universities were classified at Level 2, 58.62% at Level 3, 32.76% at Level 4, and 1.72% at Level 5 (Table 4).

Figure 3 highlights a leading group of institutions with high composite scores, located near the upper boundary of Level 4 and the threshold of Level 5 of the Capability Maturity Model. In first place, Clemson University is observed with a composite score of $Q=0.8006$, being the only institution classified at Level 5 (Optimized). It is followed by the University of Bradford ($Q=0.7921$), Florida Atlantic University ($Q=0.7588$), and Universidad Andrés Bello ($Q=0.7497$), all of which are classified at Level 4.

Within this same level, institutions from Latin America and Europe also stand out, including Pontificia Universidad Católica del Perú, Universidad Tecnológica Nacional (Argentina), Universidad Nacional de Colombia, Universitat Politècnica de València (*part of the Las Americas consortium network*), and Universidad Politécnica de Madrid (*part of the Las Americas consortium network*). This pattern suggests that the proposed model is sensitive to capturing institutional maturity across heterogeneous ecosystems, provided that verifiable outcomes exist in scientific production, impact, innovation, and collaboration networks. The complete ranking of the 58 universities analyzed is presented in Appendix 2 [34].

Discussion of Results

The results of the initial analysis indicate that the majority of the evaluated universities are concentrated at intermediate maturity levels, with a significant predominance at Level 3 (Defined). Although the sample is limited to 58 active LACCEI member universities, its geographic diversity (spanning North America, South America, Central America, and the Caribbean) provides a heterogeneous empirical context for testing the structural logic of the EECMM. The objective of this initial application is not statistical generalization to all engineering institutions in the Americas, but rather conceptual and methodological validation of the maturity framework across diverse institutional ecosystems. This concentration suggests that many institutions have already established standardized research processes and are experiencing growth in international collaboration.

In contrast, Level 4 groups institutions that already exhibit more robust signals of maturity, not only in terms of scientific production and impact, but also through observable innovation outcomes and international performance. These characteristics are effectively captured by the model through the integration of publications, citations, patents, and international collaboration into the composite index Q. This multidimensional structure is essential to avoid reductive interpretations based solely on publication volume.

Importantly, while the composite index Q allows ordered comparison among institutions, the purpose of the model is not to function as a traditional ranking system. Unlike global league tables that primarily reward output volume, the EECMM is structured around developmental stages that emphasize institutional progression and structural capability building. This distinction is critical to interpret the results as maturity diagnostics rather than reputational hierarchies. The EECMM works like a roadmap to improve the capability of the university to interact with the other actors of the Triple helix model and this interaction will be useful for developing feasible solutions in the society.

The framework proposed in this study explicitly links maturity levels with institutional profiles, enabling the derivation of practical implications. For example, for institutions classified at Level 3, the discussion suggests that the primary bottleneck is no longer the initiation of research activities, but rather the enhancement of quality, visibility, and impact. This includes consolidating strategic international collaborations and strengthening mechanisms that translate knowledge into innovation outcomes, such as patents, technology transfer, and spin-offs. This interpretation aligns with the progression described by the institutional profiles and with the characterization of Level 4 as a stage in which quantitative management and innovation outputs become visible and measurable.

From a public policy perspective, the model also aligns with the need to articulate university–government–industry collaboration to finance applied research and strengthen infrastructure, internal policies, and administrative procedures required to manage research funding and outcomes effectively. Consequently, a useful interpretation of the ranking is not purely competitive, but rather strategic: it supports investment prioritization. Institutions at Level 3 with high potential may accelerate their transition to Level 4 if capacities for data-driven management and technology transfer are reinforced. Thus, the model provides a structured pathway for institutional progression.

The fact that only one institution reaches Level 5 in this initial analysis is consistent with the definition of that level as representing global leadership in research volume, impact, and centrality within international networks. From a discussion standpoint, this suggests that the selected threshold ($Q>0.8$) functions as a demanding criterion for distinguishing truly exceptional performance, avoiding the artificial inflation of the number of "world-class" institutions.

As with any composite index, the Q core depends on the quality and coverage of the underlying data sources, as well as on modeling decisions such as weighting schemes and normalization methods. Although logarithmic transformation mitigates scale-related biases, several limitations remain: (i) innovation measured through patents may underrepresent disciplines or transfer models that are not patent-oriented; (ii) international collaboration measured through the "last 100 publications" may bias institutions with low recent output or highly specialized disciplinary profiles; and (iii) the cross-sectional comparison captures a snapshot of performance rather than modeling longitudinal trajectories over time.

Overall, these findings support the usefulness of the adapted CMM for engineering education as a diagnostic and planning tool, particularly in the context of developing countries, where institutional agendas often require clear prioritization of capacity-building actions. The international diversity of the sample further supports the cross-context robustness of the model, indicating that its maturity structure captures institutional development patterns beyond country-specific conditions. The initial analysis suggests that the primary practical value of the model does not lie in identifying "winners," but rather in clearly distinguishing maturity levels and guiding concrete transition strategies—especially from Level 3 to Level 4, where metric-driven management, strategic internationalization, and traceable innovation outcomes become decisive.

It is important to acknowledge that the proposed composite metric is inherently influenced by the normalization and aggregation choices adopted for this initial validation. Because the indicators are normalized using sample-specific maxima (X_max, S_max), the resulting scores are not strictly invariant to changes in the comparison set: adding or removing institutions—particularly extreme outliers—may shift the relative positioning of the entire sample and affect cross-study or longitudinal comparability. Although logarithmic normalization mitigates statistical asymmetry and reduces the dominance of very large institutions, it also compresses differences among high-performing universities, potentially understating performance gaps at the upper end of the distribution. In addition, computing international collaboration from each institution's most recent 100 papers introduces heterogeneous time windows across universities, which may favor high-output institutions (shorter, more current windows) and dilute comparability for lower-output institutions (longer, historically mixed windows). Finally, while patent output was measured using patent families to reduce duplicate counting across jurisdictions, patenting intensity varies substantially across disciplines, national innovation systems, and institutional IP strategies, and assignee name variants or ownership structures (e.g., subsidiaries or spin-offs) can lead to under- or over-attribution. These limitations do not invalidate the index, but they highlight that the reported maturity levels should be interpreted as relative, sample-conditioned profiles of research and technological output, motivating future work on sensitivity analyses (weights and cutoffs), field- and age-normalized impact measures, and harmonized time windows to strengthen robustness

Future Work

Future work will focus on consolidating and extending the validation of the Engineering Education Capability Maturity Model (EECMM) from methodological, empirical, and applied perspectives. First, the remaining dimensions of the Capability Index (legal agility, human capital with scientific impact, and entrepreneurship and technology transfer) will be progressively incorporated to enable a more comprehensive and balanced assessment of institutional maturity in engineering universities.

Second, longitudinal analyses will be developed to examine institutional trajectories over time and to assess the effects of public policies, institutional strategies, and funding instruments on progression across maturity levels.

To strengthen content validity and methodological robustness, an expert validation using the Delphi method will be conducted, complemented by internal consistency analysis using Cronbach's alpha (α). These steps will support refinement of the model structure and provide additional evidence of reliability as a measurement instrument. Additionally, formal sensitivity analyses will be performed to evaluate the stability of institutional maturity classifications under alternative weighting schemes, normalization methods, and threshold definitions.

Within the proposed framework, the integration of the CMM into the Institutional Capability Mapping System will be explored to support continuous monitoring of research, innovation, and technology transfer through automated indicators, monitoring dashboards, and links to institutional repositories and open science platforms. Finally, future studies will consider applications of the model to specific industrial sectors and to national and regional analyses, incorporating contextual factors (social, cultural, and governance-related) to more accurately capture the diversity of innovation ecosystems in engineering education.

Conclusions

This study presents the Engineering Education Capability Maturity Model (EECMM) as an evolution of the Capability Index toward a structured maturity-based framework for assessing and guiding institutional development in engineering education. By integrating scientific production, impact, innovation outcomes, R&D&I performance, and international collaboration into a staged progression model, the EECMM moves beyond isolated output metrics and provides a systemic perspective on institutional capacity building.

The empirical application to 58 engineering universities across diverse national contexts in the Americas demonstrates the model's ability to differentiate maturity levels within heterogeneous higher education ecosystems. The predominance of institutions at Level 3 (Defined) indicates that standardized research processes are increasingly institutionalized; however, significant structural efforts remain necessary to achieve quantitatively managed, innovation-intensive, and internationally integrated R&D&I performance associated with higher maturity stages.

Methodologically, this study contributes by operationalizing institutional maturity progression in engineering education through a composite yet development-oriented index. Rather than functioning as a conventional ranking mechanism, the EECMM serves as a diagnostic and strategic roadmap, identifying transition thresholds and guiding institutional progression—particularly from Level 3 to Level 4, where data-driven R&D&I management, strategic internationalization, and traceable innovation outputs become decisive.

The international composition of the sample reinforces the cross-context applicability of the model and highlights the importance of cross-border collaboration as a catalyst for institutional maturation within global knowledge ecosystems. By providing an empirically grounded and progression-oriented framework, the EECMM contributes to international engineering education by supporting comparative analysis, institutional benchmarking, and strategic capacity development across diverse national contexts, thereby strengthening the productive capacity of regions, countries, and continents.

Future phases incorporating additional institutional dimensions, expert validation, and longitudinal analysis will further strengthen the methodological robustness of the model and extend its applicability as a replicable framework for analyzing institutional maturity and designing capacity-building strategies at university, national, and international levels.

Disclaimer on Language Editing

Some sections of this manuscript were originally drafted in Spanish and subsequently revised with the assistance of artificial intelligence tools to improve clarity, grammar, and academic English. The authors retain full responsibility for the content, interpretations, and conclusions presented.

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