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ADAPTING AND IMPLEMENTING CDIO AND COMPETENCY-BASED LEARNING APPROACHES TO MECHANICAL ENGINEERING EDUCATION

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Abstract. *The CDIO framework encompasses a tailored approach designed teaching and learning for a mechanical engineering undergraduate program, taking into account various aspects. It was developed based on an extensive survey of the knowledge, skills, and psychological traits currently required of mechanical engineers. Alternatively, competency-based learning is a methodology employed in several courses within the Brazilian Army, connecting diverse areas of knowledge. Instead of solely focusing on theoretical aspects, it aims to prepare individuals for professional action by leveraging knowledge, resources, attitudes, values, and skills within specific real-life situations. In this approach, students are exposed to a curriculum composed of integrated modules, which facilitate the development of new practical, technical, cognitive, and socio-emotional abilities. The teaching approach revolves around problem-based scenarios. Within this context, it is possible to observe the synergy between these two methodologies. The convergence of these two curriculum construction systems has enabled the creation of a hybrid methodology for mechanical engineering, combining the CDIO and Competency-based learning methodologies. It is worth noting that aligning this hybrid methodology with the Curriculum Guidelines for engineering education in Brazil poses an additional challenge. Therefore, this paper aims to compare the key concepts and sequence of actions required to construct an innovative curriculum that incorporates both approaches. This comparison seeks to facilitate the understanding of the ongoing reforms implemented in the mechanical engineering undergraduate program.*

Keywords: *Constructive alignment, CDIO approach, Competency-based learning, Teaching-learning innovation.*

1. INTRODUCTION

Competency-based learning has become a significant aspect of advancing professional education due to the prevalence of complex and uncertain situations within the engineering work environment. Consequently, an undergraduate course that fosters an interdisciplinary approach and nurtures teamwork abilities has become indispensable. Merely possessing a solid scientific foundation is no longer sufficient for engineering professionals, although it remains crucial. Engineers must now seamlessly integrate theory with practical application by employing effective knowledge transfer strategies within real-world scenarios.

With this objective in mind, starting from the 1990s, the CDIO Initiative introduced a pedagogical approach centered on competencies. This methodology entails a systematic construction of the curriculum and proposes a range of instructional techniques based on the identification of the engineer's core competencies: conceiving, designing, implementing, and operating. These competencies are accompanied by a collection of skills, knowledge, and attitudes. This mapping process was conducted on a large scale, taking into account the professional realities of various countries within the job market.

In Brazil, the implementation of competency-based learning in the field of mechanical engineering was initially regulated through the National Curriculum Guidelines (DCNs) for undergraduate engineering programs in 2002. These guidelines aimed to equip professionals with the necessary skills and knowledge aligned with the societal needs and labor market demands. They emphasized an engineer's profile that emphasized humanistic values, interdisciplinary thinking, and reflective practices.

This emphasis on a comprehensive approach was further strengthened in 2019 when the Brazilian Ministry of Education introduced new DCNs for undergraduate engineering courses. These updated guidelines mandated explicit formulation of systematic curriculum planning, as well as the implementation of effective teaching, learning, and assessment practices. Compliance with these guidelines is required both within the framework of the Course Pedagogical Project (PPCs) and in the curricular documents of mechanical engineering courses.

Given this context, it is vital to describe the pedagogical strategies being implemented to meet the requirements of the new DCNs in mechanical engineering education in Brazil. It is crucial to explore the logic behind the construction, innovation, and adaptation of existing methodologies, while considering the unique characteristics of each engineering discipline, the organizational culture of the engineering school, and the needs of teachers and students.

From this perspective, this study examines the development of the curriculum construction methodology at the Military Institute of Engineering (IME). It encompasses the integration of components derived from the CDIO framework, the updated DCNs for mechanical engineering programs in Brazil, and the competency-based learning utilized by the Brazilian Army. This process of customization was carried out through a collaborative partnership between the Department of Science and Technology of the Brazilian Army (DCT) and the IME. The implementation was overseen by a group of IME implanters, comprising five experienced professors in engineering education known as the G-5, along with the coordination of the G-20 team, consisting of twenty professors responsible for overseeing the ten undergraduate courses at the IME. Additionally, the process involved the guidance of two pedagogical advisors, one from the DCT and one from the IME. The coordinator of the mechanical engineering course was in the G-20 group.

Consequently, the curriculum construction methodology at the IME's mechanical engineering incorporates concepts and procedures derived from three distinct approaches: the CDIO framework, the updated guidelines for the engineering courses (DCNs), and the competency-based learning approach employed by the Brazilian Army. These methodologies provide fundamental insights into the principles of teaching and learning, suggesting sequential procedures for curriculum development and assessment, as well as recommending didactic activities.

2. APPROACHES TO MECHANICAL ENGINEERING CURRICULUM DEVELOPMENT

2.1 CDIO Approach

The development of the CDIO approach by the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (CDIO, 2022) was prompted by two key factors. Firstly, there was a significant surge in technical knowledge within engineering and its related fields. Secondly, it was recognized that engineers should possess a range of personal and interpersonal attributes and skills to effectively collaborate in teams and deliver products and systems.

To establish the CDIO Syllabus (Crawley et al., 2014), which outlines the desired qualities and characteristics of an engineer, the CDIO Initiative conducted an extensive mapping exercise of the knowledge, skills, and competencies required by engineers across different engineering disciplines and countries.

As such, the CDIO Syllabus sets forth the fundamental professional requirements necessary for the practice of engineering, taking into account professional engineering norms and guidelines, as well as other relevant considerations from industry professionals. It is adaptable to diverse professional contexts, allowing for customization based on organizational cultures and explicitly outlining different levels of excellence in task performance. The Syllabus can also be utilized in personnel selection, staff training processes in companies, and professional development programs within higher education engineering courses. It encompasses a broad spectrum of professional activities, including the conceptualization, design, implementation, and operation of products and systems.

The development of the undergraduate engineering curriculum and the establishment of learning outcomes often stem from the utilization of the Syllabus as a foundational framework. This Syllabus places a significant emphasis on engineering sciences and scientific research within the field. It encompasses three primary components: technical knowledge and cognitive skills, personal and professional skills, and interpersonal skills.

Regarding individual skills, the Syllabus encompasses professional-oriented capabilities such as problem-solving, scientific exploration, and systemic thinking. Additionally, it emphasizes the importance of effective oral and written communication, proficient utilization of information and communication technologies, and adherence to professional ethical standards. Furthermore, the Syllabus also highlights certain personal characteristics such as initiative, perseverance, creative and critical thinking, intellectual curiosity, commitment to self-improvement, and a positive attitude towards teamwork.

To ensure effective curriculum implementation, the CDIO Initiative advocates the utilization of the CDIO Standard as a best practice (Ulloa et al., 2014). The CDIO Standard entails the preparation of the course to achieve the desired learning outcomes through the adaptation of suitable teaching-learning methodologies, the incorporation of practical laboratory experiences, and the assessment of student learning.

2.2 New Brazilian Curriculum Guidelines for engineering education (DCNs)

Formed by specialists from academic, professional, and business sectors well-versed in the core themes of the guidelines, the new DCNs were meticulously crafted under the coordination of the National Council of Education. This collaborative effort involved five thematic subcommittees, guided by overarching coordination, to produce a comprehensive support document (BRAZIL, 2019a). Among its objectives, the DCNs aim to address the prevalent issue of high dropout rates in undergraduate engineering courses in Brazil. To achieve this, they propose a fresh teaching and learning model for engineering education, different from the traditional approach of lectures and textbook exercises,

which have been partially attributed to students' subpar academic performance in the National Student Performance Examination (ENADE) for Brazilian engineering courses.

The new DCNs serve as a legal framework for engineering education, emphasizing the well-recognized components of CHA—knowledge, skills, and attitudes—as the building blocks of competencies required for future engineers. Furthermore, the guidelines explicitly endorse an active learning approach, placing the student at the forefront of the teaching and learning process (CNI et al., 2020).

At its core, this document seeks to foster closer collaboration between engineering programs, the job market, productive sectors, and professional councils. This necessitates the development of flexible study programs that continually evolve and incorporate integration activities. In essence, the objective is to design a curriculum that mirrors the real-world working conditions of engineers, in stark contrast to traditional theoretical curricula that compartmentalize knowledge.

The new DCNs, in essence, adopt a different approach by reversing the conventional relationship between content and profile. Instead of beginning with the available institutional content and striving to achieve the desired graduate profile, the focus is placed on the egress profile and the Course Pedagogical Project is built to obtain this pre-established profile (CNI et al., 2020).

This shift in perspective brings about a transformation in teaching strategies, favouring project-based pedagogy and the formulation of clear learning outcomes. The sole emphasis on transmitting textbook knowledge is replaced by a pedagogical approach that emphasizes the process of learning and the development of students' abilities and skills. Consequently, the new DCNs embody pedagogical logics that prioritize active learning methods.

Within the pedagogical framework of the DCNs, detailed requirements are outlined for the Course Pedagogical Project (PPC). The PPC should encompass the competencies to be developed, both general and specific, and should be aligned with teaching and learning activities as well as complementary endeavours. Didactics and assessment are integrated, bridging theory and practice in the context of application. These elements are essential for skill development through active methods, with a focus on teamwork and the simulation of real work situations, both in the classroom and through industry-school collaborations.

Furthermore, the new guidelines propose various activities to promote integration and interdisciplinary approaches. Scientific research projects, academic competitions, interdisciplinary and transdisciplinary initiatives, extension projects, volunteer work, technical visits, team-based projects, prototype development, mentoring, participation in junior companies, incubators, and other entrepreneurial activities are all recommended (BRAZIL, 2019b). According to the methodology, the curriculum construction process can be carried out through the following steps (CNI et al., 2020):

- Identify a set of undergraduate learning outcomes (general and specific).
- Define specific skills associated with the competencies.
- Structure the learning outcomes linked to the specific skills.
- Select teaching contents that facilitate the achievement of the learning outcomes.

The DCNs highlight various forms of learning spaces and activities, including face-to-face, virtual, remote, mobile, and collaborative formats, in synergy with both public and private institutions. As for assessment, the new DCNs prioritize continuous evaluation and pedagogical principles that go beyond the sole focus on obtaining a degree. Assessment methods are diversified and can include monographs, exercises, dissertations, seminars, oral presentations, reports, projects, and practical activities, among others, fostering individual and collaborative learning and encouraging intellectual production among students (CNI et al., 2020).

Additionally, the DCNs define content in terms of factual, conceptual, and procedural knowledge, encompassing cognitive abilities such as remembering, understanding, applying, evaluating, analysing, and creating. The curriculum construction strategies recommended include the correlation between general course objectives and graduate profiles, the establishment of frameworks connecting overall course objectives with specific objectives within tracks and curricular components, the breakdown of each objective (competence) into its constituent parts (skills, knowledge, and attitudes), the creation of frameworks linking different assessment instruments to specific components and their respective cognitive dimensions, and the alignment of each competence with the corresponding evaluation instruments used (CNI et al., 2020).

2.3 The Brazilian Army curriculum construction methodology

The implementation of competency-based education in the Brazilian Army was influenced by the methodology of SENAI (National Industrial Learning Service), with important adaptations to incorporate the transverse axis, which encompasses the skills, attitudes, and values inherent to the engineering profession. The development of this transverse axis involved a brainstorming process with professionals of varying levels of experience in their respective fields.

Certain adaptations were made based on pre-existing elements prior to the implementation of competency-based education in the Brazilian Army. For instance, the psychological characteristics of graduates were previously described in the Professional Profile document, which was retained and integrated with the competency mapping process, resulting in the creation of the Functional Map. The Functional Map includes a selection of components from the transverse axis.

The Professional Profile still outlines the desired personality traits of graduates, as it did before, but now it is inferred based on the description of work activities provided in the Functional Map. The elements of the transverse axis are incorporated throughout the curriculum, influencing the design of the curriculum, teaching methods, and evaluation processes. Additionally, the Brazilian Army's methodology includes the completion of an Integrated Plan of Disciplines (PID), which outlines the necessary content for interdisciplinary activities. The Discipline Plan (PD) is developed concurrently with the PID, establishing the specific disciplines and their intersections. The elements of the transverse axis are also integrated into the PID and PD (BRASIL, 2022).

Three types of disciplines exist within this methodology:

- Competence-focused disciplines.
- Disciplines aimed at developing existing skills, attitudes, and values in the transversal axis.
- Fundamentation and instrumentalization disciplines, which establish the foundations of disciplinary knowledge and facilitate the acquisition of practical technical knowledge across various disciplines and different work activities.

Ultimately, the Course Pedagogical Project (PPC) serves as the document that consolidates pertinent information from the Professional Profile, Integrated Plan of Disciplines (PID), and Discipline Plans (PD). Within the PPC, you will find the General Table of School Activities, which outlines the distribution of subject workloads and integration activities. Additionally, the PPC embraces constructive alignment (Biggs, 1996) as a means of advancing the undergraduate course. It highlights faculty training characteristics, the evaluation methodology for the program, and potential improvements.

When it comes to the pedagogical methodology employed by the Brazilian Army, emphasis is placed on active teaching and learning methods centered on the student. These methods encompass various types of academic group activities, project-based learning, and problem-solving approaches. Additionally, the methodology proposes systematic planning and evaluation of learning content, categorized as factual, conceptual, procedural, and attitudinal. Each category corresponds to distinct teaching and learning processes, necessitating diverse didactic and evaluation procedures (Coll et al., 2020). Furthermore, the educational evaluation component encompasses various instruments, including tools for assessing and scaling student performance based on predetermined criteria (BRAZIL, 2020).

3. THE CHALLENGE OF METHODOLOGICAL INTEGRATION

Figure 1 illustrates the concept of constructive alignment, which is evident in all the approaches discussed in this work. The new DCNs outline the requirements that must be fulfilled in the Course Pedagogical Project (PPC) to cater to the needs of engineering graduates from Brazilian universities. Essentially, the PPC should explicitly state the desired learning outcomes, detail the academic activities necessary to achieve these objectives, provide adequate teacher training, and incorporate suitable assessment methods for each selected activity type. The academic activities encompass various elements such as lectures, active learning, extracurricular engagements, teamwork, and utilization of laboratory facilities.

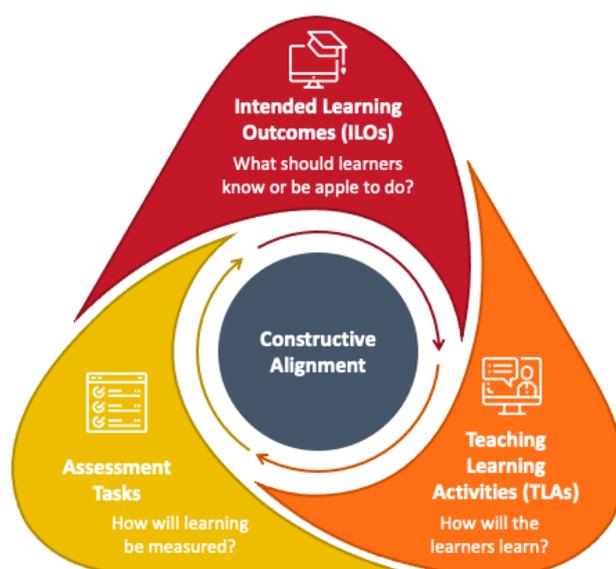


Figure 1. Constructive alignment (Biggs, 1996).

However, it is worth noting that the DCNs do not present a specific methodology for curriculum construction. Periodic evaluations conducted by the Brazilian Ministry of Education assess whether the Course Pedagogical Project (PPC) aligns with the DCNs. If the PPC fails to comply with the NCGs, the undergraduate course may lose its accreditation to graduate new professionals.

On the other hand, the CDIO approach utilizes the CDIO Standards as a curriculum construction methodology. The content specified by the DCNs closely corresponds to the subjects addressed by the CDIO Standards (Rezende et al., 2022).

The curriculum construction methodology employed by the Brazilian Army encompasses the documentation of steps leading to the finalization of the Course Pedagogical Project (PPC). In Brazil, this is crucial as the PPC serves as an evaluative document in accordance with education laws. The Brazilian Army methodology proved highly beneficial during the development of the PPC, as it facilitated the consolidation of guidelines from the CDIO Standards, requirements set forth by the new DCNs, and contributions from all participants involved in the curriculum construction process.

Table 1 provides a concise summary of the synergies observed among the curriculum construction topics featured in the new DCNs, CDIO Standards, and the Brazilian Army methodology.

Table 1. Alignment of the new DCNs propositions, CDIO Standards and documents in Brazilian Army methodology for the PPCs.

Propositions for PPCs by DCNs	CDIO Standards	Brazilian Army methodology
Induction of innovative institutional policies	CDIO as context	Course Pedagogical Project (PPC)
	Program evaluation	Course Pedagogical Project (PPC)
Focus on teaching through skills development	Integrated curriculum	Integrated Plan of Disciplines (IPD)
	Learning outcomes	Professional Profile Competences + Transverse Axis
Emphasis on managing the learning process	Introduction to engineering	Integrated Plan of Disciplines (PID)
	Integrated learning experiences	Integrated Plan of Disciplines (PID)
	Learning assessment	Discipline Plan (PD)
	Engineering workspaces	Discipline Plan (PD)
Relationship strengthening with different organizations	Design-implement experiences	Integrated Plan of Disciplines (PID)
Innovative teaching methodologies	Active learning	Discipline Plan (PD)
Valuing faculty training	Enhancement of faculty competence	Course Pedagogical Project (PPC)
	Enhancement of faculty teaching competence	Course Pedagogical Project (PPC)

The selection of knowledge, skills, and attitudes that engineering students should possess upon graduation is another aspect of integrating the methodologies.

The curriculum design process commenced with a thorough examination of the CDIO Syllabus, which was compared with the learning outcomes mandated by Brazilian education laws, engineering firms, and society. In the realm of engineering higher education, the learning outcomes must align with the DCNs for engineering courses as stipulated by Brazilian law (Brazil, 2019b). To practice the engineering profession, the Federal Council of Engineering and Agronomy (CONFEA, 2005) defines the activities, abilities, and responsibilities expected of engineers. Notably, there exists a strong similarity between the knowledge, skills, and attitudes outlined by the National Curricular Guidelines of Engineering Undergraduate Programs (Brazil, 2019b) and those set forth by the Federal Council of Engineering and Agronomy (CONFEA, 2005). Thus, Table 2 establishes correlations between the requirements specified by the National Guidelines and CONFEA and the skills and knowledge proposed in different sections of the CDIO Syllabus.

Table 2. Correlation of competences between the Brazilian aspects and the CDIO Syllabus.

Competencies established by the DCNs and by CONFEA		<i>CDIO Syllabus</i>
Apply mathematical, scientific, technological, and instrumental knowledge to the engineering	➔	Disciplinary knowledge and reasoning
Design and conduct experiments and interpret results	➔	Personal and professional skills and attributes
Planning, supervise, elaborate, and coordinate engineering projects and services		
Identify, formulate, and solve engineering problems		
Develop and/or use new tools and techniques		
Understand and apply professional ethics and responsibility		
Assume the posture of permanent search for professional updating		
Communicating effectively in written, oral, and graphic forms	➔	Interpersonal skills: teamwork and communication
Work in multidisciplinary teams		
Conceive, design, and analyze systems, products, and processes	➔	Conceiving, designing, implementing, and operating systems in the enterprise, societal and environmental context – the innovation process
Supervise the operation and maintenance of systems		
Evaluate the impact of engineering activities in the social and environmental context		
Evaluate the economic feasibility of engineering projects		

In Table 2, it is evident that the CDIO Syllabus effectively addresses the requirements outlined by Brazilian education laws and the demands of engineering work in companies (CONFEA requirements). Notably, the Brazilian Army methodology encompasses military engineer skills that bear significant resemblance to the CDIO Syllabus; however, further elaboration on this topic will not be provided in this paper.

Considering the CDIO Syllabus as a contemporary research framework that meets the needs of modern mechanical engineers, the faculty of the IME mechanical engineering course decided to adopt it as a basis for selecting skills and attitudes, while making the necessary adaptations. to meet specific contents of military engineering. Thus, as mentioned earlier, these knowledge, skills and attitudes will be incorporated into the Professional Profile document.

4. FINAL CONSIDERATIONS

In this case, the curriculum construction methodology underwent a customization process, incorporating elements from the Brazilian Army methodology, the new DCNs, and the CDIO approach. The Brazilian Army's methodology played a predominant role in the process due to its simplicity and its focus on curriculum construction. This allowed for a implementation of the teaching reform in mechanical engineering undergraduate course, meeting the tight deadlines set by the Brazilian Ministry of Education and the competency-based learning requirements of the Brazilian Army.

One significant innovation introduced by the IME was the inclusion of skills, which were drawn from the CDIO and the new DCNs, and integrated into the Transversal Axis. These skills were then incorporated into the Integrated Plan of Disciplines (PID) and the Discipline Plan (PD), providing clear guidance on how to develop them within the framework of teaching and evaluation.

It is worth noting that the IME methodology, although focused on curriculum construction, took into account the analysis of existing curricula in mechanical engineering programs. Criticisms of these curricula were considered during the transposition process to the new educational framework. Many pedagogical training sessions were conducted for mechanical engineering program faculty ensure that the reform went beyond superficial changes in terminology and challenged the traditional selection of content based on established practices. This facilitated the acceptance of active learning and interdisciplinary approaches among professors, leading to spontaneous experimentation with these pedagogical approaches across different programs.

In conclusion, the curriculum construction methodology that is being implemented in the undergraduate course in Mechanical Engineering at IME represents a significant step towards a more comprehensive and innovative approach to teaching and learning in engineering, in line with the demands of the Ministry of Education and the Brazilian Army.

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