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Engineering design: complexity in its teaching

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Abstract

The trend toward increasing the design component in engineering curricula is part of an effort to better prepare graduates for engineering practice. The objective of the article is to review and contrast some methodological strategies of engineering design teaching at the university level to analyze the psychological theories in teaching practice and the temporal location of these courses within 5 years of the program. The results of the bibliographic review made allowed us to infer psychological postures, preferably cognitive and constructivist, and the location of design courses in the first semesters of engineering curricula. However, engineering design courses are recommended throughout the degree (taking as a reference some results of the Saber PRO tests) in which students participate in applied projects, and get closer to the industry, as more favorable strategies for the adaptation of future engineers to the particular demands of the national productive sector.

Keywords: engineering design; the teaching of design; design methodologies; design learning.

Diseño en ingeniería: complejidad en su enseñanza

Resumen

La tendencia hacia el aumento del componente de diseño en los planes de estudios de ingeniería es parte de un esfuerzo por preparar mejor a los graduados para la práctica de la ingeniería. El objetivo del artículo es revisar y contrastar algunas estrategias metodológicas de la enseñanza del diseño en ingeniería a nivel universitario para identificar las teorías psicológicas subyacentes en la práctica docente y la ubicación temporal de esos cursos dentro de los cinco años de la carrera. Los resultados de la pesquisa permitieron identificar posturas psicológicas principalmente cognitiva y constructivista y la ubicación de cursos de diseño en primeros semestres de los currículos de ingeniería. Sin embargo, se recomienda cursos de diseño en ingeniería a lo largo de la carrera (tomando como referencia algunos resultados de las pruebas Saber Pro) en los que los estudiantes participen en proyectos aplicados, y se acerquen a la industria, como estrategias más propicias para la adaptación de los futuros ingenieros a las demandas particulares del sector productivo nacional.

Palabras clave: diseño en ingeniería; enseñanza del diseño; metodologías del diseño; aprendizaje del diseño.

1. Introduction

The input of this article are the reports on engineering design by various national and international authors that include basic concepts, experiential methodological initiatives used by teachers in the teaching of design, curricular proposals from university institutions, and government entities; In addition, the results of the Saber Pro tests in the last 20 years in Colombia, examined in three different periods, show unflattering results in the educational field of engineering design.

2. Framework

2.1 Engineering design

When reviewing the literature, some definitions of engineering design are found: Villamil & García affirm that engineering design is a process that implies the conception of systems, equipment, and components to satisfy a need; therefore, it is a creative act dedicated to selecting, combining, converting, restricting, modifying, manipulating, and shaping ideas, scientific results and physical laws into

useful products or processes [1]. On the other hand, Dym, et al. say that engineering design is a systematic and intelligent process, in which the designer generates, evaluates, and specifies concepts for devices, systems, or processes, which work according to the needs of the client while satisfying a specific set of constraints [2]. Engineering education is concerned with developing an understanding of the principles, methods, and ways of thinking that underlie engineering, and preparing students and engineers for productive engineering careers.

2.2 Design thinking – how designers think

Some conceptions of how designers think are: Wordpress [3] mentions that "they have taught us to think logically, to understand from analysis, breaking down events into parts and then rejoining them (synthesis), and in some cases, this works, but not when we try to apply it indiscriminately; as it occurs, for example, in the system design process. For his part, Garcia [4] affirms that design goes beyond defining, analyzing, and synthesizing, it continues with the evaluation of alternatives, the preliminary design or blueprint, the detailed design, the development of models, and the tests. As can be inferred, the role of the designer in engineering is complex, so their training must consider the "ability to design a system, component, or process to satisfy desired needs, within realistic restrictions such as economic, environmental, social, policies, ethics, health and safety, manufacturability, and sustainability" [5].

It is a fact that questioning is essential for design: designers need to ask themselves questions throughout the process. However, it is not always followed in traditional teaching approaches, which employ guided probing, and the use of proven principles to arrive at a verifiable solution. The question "... is a statement without truth-value since it cannot be stated whether it is true or false. The question explores something uncertain, but at the same time presupposes a level of knowledge of what is unknown, because otherwise, it could not even be formulated" [6]. The foregoing corroborates what Aristotle affirmed that the kinds of questions we can ask are as many as the kinds of things we know, knowledge resides in the questions we can ask and the answers we can give, then there is a hierarchy [2]; that is, certain types of questions need to be asked and answered before others are asked.

For Morales [7] and Dym et al. [2] engineering design involves two types of questioning, deep reasoning questions that seek to converge on an answer or a truth value, characteristic of convergent thinking, and questions called generative design questions, divergent in nature, and have multiple alternatives of known answers, true or false, or multiple possible unknown answers. Convergent questions operate in the knowledge domain, while divergent questions operate in the concept domain; this connotation has strong implications in the teaching of conceptual design because concepts do not need truth value while knowledge does. Dym et al [2] state that "design thinking can be seen as a series of transformations from the concept domain to the knowledge domain; however, teaching divergent questioning in design thinking is not yet clearly recognized for inclusion in engineering curriculum because, for example, it is not

acceptable for a student to answer a final exam question in an engineering science course with multiple possible concepts that have no truth value." At this point, it is worth considering the reflection of Morales [7] when citing the article by Ulrich Kraft published in 2005 in the journal *Scientific American Mind*, they believe that: "students are machines of invention, we are born with the creative capacity, but it is the convergent thinking education (existing in the left side of the brain) which kills and castrates our creativity, ending divergent thinking (housed in the right side of the brain)". It will be necessary to rethink how engineering is currently taught in Colombia.

2.3 When to start the study of engineering design?

Some educational institutions began to introduce the concepts of engineering from high school, which gave rise to a teaching model called "engineering infusion" [8]. In this model, students and teachers begin to "try out" engineering design-based teaching methods before moving on to university education. Gero & Danino [9] refer to the case of 12th-grade students who must complete various engineering tasks to motivate them to enter university, encourage them to develop thinking skills about systems, and train them in teamwork. In the same way, Hynes et al. [8] state that society is recognizing the need to improve secondary education, and one way to achieve this is by introducing engineering design concepts before college; the purpose is not to get to build something (a common mistake), but rather to teach students to organize thoughts to improve decision making to develop high-quality solutions to problems. Daugherty, et al. [10] focus their study on the review of the background, problems, approaches, challenges, and proposals to define the conceptual basis of engineering at an appropriate level for science education at the secondary level, from the teaching of scientific concepts and processes through the artifact design; They consider that very little is still known about how to improve the introduction of engineering concepts in the science curriculum, although they highlight the efforts made for this purpose. While Custer, et al. [11] seek to find methods to implement engineering concepts within science, the National Science Foundation [12], within the Engineering Education program, proposes a teacher professional development plan so that engineering design is used as a tool for teaching science in high school through multidisciplinary design units based on science and research, as well as preparing primary school teachers to teach science through engineering design.

From the previous review a challenge arises that imposes the teaching of design: how far does the mastery of science go? And how far does the domain of engineering go? Science and engineering in design education pursue different objectives because engineering is not exactly applied science: science generates knowledge and engineering provides procedures and technical systems for specific tasks. Hence, it must be considered that the proposals based on the design for the teaching of science will find the barrier of the epistemological differences between science and engineering because engineering demands an intermediate form of knowledge between the abstract and the concrete.

The engineering curricula emphasize a model called

engineering sciences, in which solid foundations in natural sciences and mathematics are taught in the first semesters. However, upon entering the workforce, industrialists perceive recently graduated engineers as incapable of practicing in the industry. Some authors (Hjalmarson & Lesh [13] and Lesh & Sriramm [14]) justify mathematics in the first semesters for the guidance it offers students in the design of processes and resources, and in the application of scientific principles to technological problems. Experience shows another result: a "disconnection" of new students with their professors from the engineering program itself, up to two years after entering the program. To remedy this deficiency, design and/or introductory courses appeared in engineering, which serve to "introduce" students to the work of engineers, while learning the basics of the design process from project development.

Brousseau, et al. [15] propose a course at the beginning of engineering programs with an introductory pedagogical approach to the real world of engineering problems. On the other hand, Stacey, et al. [16] suggest courses that emphasize the need to improve the connection between design and engineering science, for which they propose the pedagogical tool "design case study" which addresses a world design theme relating it to various concepts learned in the course. Bazylak & Wild [17] reviewed the best practices and teaching methods in first-year engineering design courses at 40 universities in Canada and the United States. Among their findings, they discovered six recurring themes in engineering design teaching methods, namely: large-scale projects, small-scale projects, case study analysis, reverse engineering projects, design, and integration tools and methods. For each case, they present the analysis from the point of view of the professors to be a valuable source of information for those who develop first-year engineering design courses. Burton & White [18] presented the results of a project developed at the University of Alaska Fairbanks: this consisted of investigating the importance of teaching design in the first year of Civil, Electrical, and Mechanical engineering programs accredited by ABET. The results were: design education is important because it helps to motivate and excite students for higher-level engineering science courses, introduces design concepts and projects from the beginning, promotes teamwork, and introduces engineering tools.

For introductory engineering courses, the literature reports a diversity of proposals. McClaren & Boyle [19] propose one in which design activities and project teamwork are conducted in parallel; at the end of the course a result is presented by each team about the work done. Likewise, Labun [20] reports in his study that at the University of British Columbia Okanagan School of Engineering, first-year students take a 3-credit engineering communication course, replacing the traditional 3-credit language course that other freshmen take. Hirsch, et al. [21] describe an interdisciplinary project-based course at Northwestern University in engineering and communication design, arguing that this interdisciplinary approach enhances communication and design instruction, and gives students an appreciation for math and science courses. sciences that are required as pre-and co-requisites for engineering courses. Sleeman & Sorby [22] highlight that design-based introductory engineering courses have a positive effect on student retention rates, as 70% of first-year students perceive

better comfort and learning through projects with teamwork. In this same perspective, Knight, et al. [23] report an increase in the retention rate of up to 20%, over eight years, in 5,070 students who took the introductory engineering course. Although these courses seem to offer academic advantages, especially to mitigate desertion and be a source of motivation for new students, Richards & Carlson [24] state that "these courses are unusual and are only taken into account by a relatively small number of teachers, who have not generally dedicated themselves to this pedagogical vision, because they do not find it easy or comfortable due to the amount of effort involved and the kinds of activities required to do so." In the case of Colombia, Buitrago & González [25], the Planning Office of the National University of Colombia, Medellín Campus [26], Rueda & Mantilla [27] and Rojas [28] reviewed some case studies on desertion in Engineering programs of some educational institutions in the country and found no relationship between the presence of design courses in the first semester and student dropout in the first semesters of their program. They claim that it is not clear if the instruments used for assessing student dropout inquired about the relationship between its cause and the presence of courses to raise interest in their profession or coursework that would allow them to discover and explore the connections between humanities, basic sciences, and engineering. The documentary review in the national academic context (and in general in Spanish) yields few publications about the presence and implementation of design courses at the beginning of engineering programs. These are more evident in higher semesters, for which more publications are found.

The design courses seen in higher semesters differ from the previous ones in their scope; they go beyond the design itself, they get to contemplate, in some cases, the production plan, intellectual property rights, and the business model. They aim to bridge the gap between the ways of thinking that engineers and entrepreneurs have as well. In this perspective, Silva & Faria [29] suggest designing courses focused on the training of innovative engineers with an entrepreneurial profile, who go beyond being product developers or problem solvers, but can identify the problem and fix it. Upon completion of a senior design course, the future engineer is expected to be able to: identify customer needs and translate them into product specifications; understand the product as a whole from early design sketches to the final stages of production and marketing; join a multidisciplinary work team to design innovative products that are relevant to market needs; and apply structured methodologies for product development that reduce uncertainty, risk, and the elapsed time from the generation of the idea to the launch of the product on the market. Refaat [30] proposes a course at the end of the program that favors the education and training of future engineers in the recognition and development of modern technologies for the industry, so that they can commercialize it and introduce it into the market. This implies knowing how to prepare development plans with milestones and allocation of resources for the distinct phases of product development, as well as being capable of establishing general and specific objectives, and knowing how to communicate them to all interested parties, understanding their role and the role of the work team. As can be seen, it is a challenge for the professor to develop a design course in the last semesters of engineering with the scope.

2.4 Design teaching strategies

Dym, et al. [2] consider the teaching of engineering design to be a "Pandora's box" due to the controversial content of the topics it involves, which becomes evident only when accreditation times approach. They also highlight that there is a lack of recognition by some academic leaders about the intellectual complexity and resources that a good education in design demands, whose appreciation was already partially exposed early in [18], indicating that to induce the design from the first year of the degree requires space, resources, equipment, and in some cases support from the industry. This last requirement is especially corroborated by Tomiyama, et al. [31] indicating that to teach design methodologies and theories more effectively, in addition to understanding the theoretical aspects, teachers should be competent in the use of these methodologies to design products and/or systems, since practical experiences are very important in the effective teaching of design, and these are only possible when there is a close collaboration between academia and industry.

The influence that the classical approach has on engineering education and therefore on design education is the modification of the set of base experiences that a student could have when facing a design problem. Koen [32] defines the exercise of design as a complex repertoire of behaviors. These can be understood in turn as the execution of a set of tools and methodologies developed by the student or the engineer to approach the exercise of design. This considers that the repertoire of behaviors that make up the design methodology of an engineer differs from the behaviors of other engineers from other countries, from diverse backgrounds, or different experiences. Therefore, teaching engineering should be about developing a strategy for changing the student's repertoire of design behaviors toward those that are acceptable to a professional engineer.

For approximately two decades, organizations such as ABET (Accreditation Board for Engineering and Technology) have promoted the inclusion of design in engineering [5]. In this perspective, Burton & White [18] report the actions of professional associations such as the American Society of Mechanical Engineers (ASME), The Institute of Electrical and Electronics Engineers, Inc. (IEEE) and the American Society of Civil Engineers (ASCE), which have adopted teaching objectives following the recommendations of ABET. Other institutions such as MIT (Massachusetts Institute of Technology) have implemented the CDIO (Conceive-Design-Implement-Operate) methodology, in which design appears as a key step in professional training [33,34], and even the teaching of design from the secondary education level, as found in [8]. Ramos [35] proposes to apply reverse engineering for teaching design. This consists of starting from the analysis of an existing product in the market to identify and know the details of its design, manufacture, and operation to improve it without copying it. With this strategy and using modern design tools such as the 3D scanner, it is possible, for example, to capture the geometry of existing objects to incorporate their characteristics in the design of a new product [36]. Another option is concurrent engineering as a cohesion mechanism in teamwork [37].

Problem-based learning (PBL) can also be used, which according to Savery [38] is a student-centered instructional (and curricular) approach that enables students to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem. In Fernández & Duarte [39], the use of the PBL methodology for the formation of competencies in engineering students in Colombia is reported, in the development of a project with eighth-semester students. The results showed improvements in the skills related to the solution of real problems, as well as in the management of projects through the preparation and socialization of the report (Saber-Pro results).

Another strategy widely used in design courses in the final semesters is Project-Based Learning which, according to Ferrara [40], fosters the development of analytical, scientific, mathematical, and technical skills, as well as communication, creativity, leadership, and organization, required by engineers. Cohen & Katz [41] emphasize the teaching of engineering design from its practical part through Project-Based Learning. In these scenarios, virtual reality and online collaborative platforms could be used to build information models for group class projects. In times of pandemic, it was possible to explore the diversity of teaching platforms available in the market; this advance could be used to increase the choice of final design projects available to students, and thus take advantage of the flexibility of the platforms to pose significant challenges to multidisciplinary teams of students, according to their learning profiles. Roncero [42] recommends applying the knowledge acquired throughout the aeronautical engineering program to a project that allows them to design and build an airplane, following the specifications and instructions proposed by the instructor.

In general, the strategies used in these courses should be aimed at getting students involved in the real world of product design and development, since there is a shortcoming as recognized by Dunn-Rankin, et al. [43], noting that in many universities the curriculum does not include courses that teach students the essential professional knowledge necessary to become a true design engineer. Therefore, in their work, they propose the creation of a specific engineering design program in the industry. According to García [44], academic mobility is considered a key element to improve professional training in engineering, so in addition to the aspects of cognitive, curricular, technical, and methodological training, it is necessary to favor an approach to the industrial reality, to adapt to the needs of the country.

In the Colombian context, Misas [45] recognizes the need for a compromise between academia and industry; however, there is a lack of effort to do the corresponding thing, implementing, for example, teaching-learning strategies based on the practice of product design and development within companies. To make the required reforms in engineering curricula, leaving the classroom, to explore, and to learn how design is conducted in professional practice is essential to design strategies that allow adapting each of the elements found in the design practice in R&D departments in the industry. Currently, methodologies based on engineering design are considered business ideas for some companies, as [46] stated, or they are applied as tools within the processes of innovation and technological development of companies as found in [47,48].

Although the current world economy revolves around value-added products and services achieved from R&D processes and engineering design within an environment of innovation, such conditions have led to engineering education being diversified for training to be relevant for today's demands. In this perspective, Luryi, et al. [49] expose the conclusion of the development of the project How to introduce the enterprising spirit in engineering education? Entrepreneurship must be a compulsory course for all engineering programs, and the dynamics of the course must involve work in multidisciplinary teams. At the same time, these students must have the ability to collaborate and work with people from different disciplines and be able to seek innovation. In this perspective, some engineering programs in Colombia have been developing different approaches to improve these required skills, for example through hackathons. Fostering high-tech entrepreneurship is a growing focus of business agency activities in a growing number of developed economies. Developing countries need to foster entrepreneurial cultures to fuel their economic growth and improve the quality of life for their people.

The essence of engineering designs and design is behavior, that is, something the engineer does [32]. Consequently, the teaching and learning of design must be reviewed (because of behavior) from the psychological theories that underlie their pedagogical practices. Learning is understood as behavioral and mental change because of experience; it differs from person to person depending on their learning style and the situation. All teachers have certain ideas, somehow explicit, about how to teach, and that their teaching model necessarily underlies a conception of how to learn. Education and psychology do not interact with each other in isolation; the

processes that govern the behavior of engineering students go hand in hand with the different educational trends, from behavioral education to current educational models. Below is a summary of the psychological theories contextualized for the teaching of engineering design, in Table 1.

3. Materials and methods

The subject investigated is in engineering education, specifically on engineering design, and is based on the interpretative theories of Habermas (1976) and the complex thinking of Edgar Morin (1999). The epistemological position of these approaches alludes not only to the conscious, holistic, multidimensional, and complex nature of the educational phenomenon, but also to the fact that as these are understood as objective-subjective processes, they are contextualized, structured, and reflected from different perspectives.

The methodological design followed in this article is divided into two stages: a preliminary review, to identify methodologies followed in the teaching of engineering design (qualitative data), and temporary location of design courses in the engineering career (qualitative data). the second stage of the study performed analysis, and classification of the findings found in the first stage, to identify predominant psychological theories in these teaching methodologies, and preferred location of the courses in the 5 years of the program. The results of the Saber PRO tests will also be analyzed in three periods within the last 20 years of Colombian history: the first period (2004 – 2009), has the average results obtained by the students in the problem-

Table 1.
Psychological theories underlying the teaching of engineering design.

Psychological theories	Engineering design conception	Instruction alfocus	How engineering designis learned	How engineering design shouldbe taught	Types of results obtained	Refer ence
<i>Behaviorists (early twentieth century): Skinner, Thorndike, Tolman, Watson</i>	Design is behavior: it must be taught in a manner consistent with behavior modification theory.	Curriculum-focused (correct behaviors)	Learning by stimulus, doing repetition tasks followed by positive and negative reinforcement.	Plans learning, establishes activities, checks for expected behavioral modifications, and focuses on positive and negative reinforcement.	Quantitative results: rewarding correct behavioral actions, reinforcing, and stimulating their recurrence; oral methodologies.	[32]
<i>Cognitive (late 1950s)</i>	Design knowledge is not something direct, fixed, or immediate, but is negotiated through previous experience and logical judgments.	Curriculum-focused (appropriate information)	Absorbing, processing information received and storing it in memory. Duplicate knowledge structures (knower)	The teacher considers the organization and cognitive reorganization in the perceptual field and plans the activities, accordingly, also enabling active learning; oral methodologies.	Quantitative results: skills and capabilities that are acquired after learning techniques, assimilating specific and general knowledge, and inspecting successful experiences from the past.	[50]
<i>Constructivism (1970's and 1980's): Piaget, Bruner, Ausubel</i>	Design is a process that transforms information from conditions, needs, and requirements into a description of a structure that satisfies them.	Student center (meaning ful processin g)	Adapting through processes of interpretation, assimilation, and accommodation; in this way, students' mental structures are organized.	Motivating the learner to discover principles on their own, being a guide or mediator, helping learners to become involved and positively linked to knowledge: cognitive scaffolding.	Qualitative results (knowledge structure)	[51]
<i>Social learning (1977): Bandura</i>	The design is collaborative work in interdisciplinary teams, face-to-face or virtual environments.	Peer-centered (Behaviora l modeling)	Observing and imitating in a social context (vicarious learning). Learning by doing (active learning)	Facilitating modeling and social interaction: team and peer work: sensory perception methodologies.	Qualitative results	[52]
<i>Social constructivism (end of the 20th century): Vygotsky, Rogoff and Lave</i>	Design as a psychological development based on the person themselves	External factors(zone of proximal development)	Interacting in real engineering situations: knowledge is a product of the context and culture in which it is formed.	Facilitating contextualized activities in collaboration with peers: practical methodologies.	Qualitative results (contextual knowledge)	[53]
<i>Experiential learning: CarlRogers</i>	Design is changing behavior generated by experience.	External factors (experience)	Getting to know significant engineering design experiences and engaging in design experiences.	Facilitating practical, youth-driven design experiences: practical methodologies	Quantitative results	[54]

Source: The Authors.

Note: All psychological schools and theories of teaching and learning are well-intentioned about the idea of being human at a certain moment in history.

solving component - ECAES tests (today Saber Pro) in 8 engineering fields (systems-telematics and related, chemistry and related, administrative and related, biomedical and related, industrial, electronics-telecommunications and related, mechanical and related). In the second period, (2016 – 2017), the average results obtained by the students in eleven specific competencies evaluated in the Saber PRO tests will be analyzed. Finally, the third period (2019 – 2020) contains the results obtained by students in the general component – quantitative reasoning Saber Pro tests in seven engineering programs. The reason it was decided to do the analysis was the coincident findings of the three categories: Problem-solving, specific design skills and contributions of basic sciences through quantitative reasoning for engineering design found in the literature review, specifically in [2,4,5,16-21,23,40].

4. Results

Despite changes in curricular objectives, teaching methods, and assessment of design-based engineering curricula worldwide, much more is still required. Table 2 shows the summary of literature review on engineering design conducted in this research.

One of the affirmations reiterated in the revised authors is "design concepts are learned by solving problems". However, there is no clear and explicit notion of what is meant by problems, they could be a type of problem called paper and pencil exercises, and not real problems. In this perspective, a cross-sectional and comparative analysis will be made of the Saber-Pro tests for the period between 2004 and 2009, in which 142,300 students were evaluated through twelve specific exams (Decree 1781 of 2003

Table 2.
Psychological theories underlying the teaching of engineering design.

Author	Psychological position	Temporal presence of engineering design subjects.	
		Freshman year	Senior year
Dym, C et al., Stacey, L et al., Bazylak, J., & Wild, P., Burton, J., & White, D., Maclaren, A., & Boyle, J., Labun, C., Hirsch, P. et al., Knight, D. et al.	Cognitive (PBL, reverse engineering)	x (in 3- and 5-semester courses, positively impact student retention rates)	
Anonym	Constructivist		x
Garcia, G., Ferrara, J.	Cognitive (PBL)		x
Hynes, M. et al., Gero, A., & Danino, O., Daugherty, J. et al., Custer, R. et al., Maclaren, A., & Boyle, J., Dunn-Rankin, D. et al., Luryi, S. et al.	Constructivist	x (design education, including from secondary school level through infusing engineering, grade 12, through multidisciplinary research-based design units, etc.)	
Brousseau, J., El Ouafi, A., & Loubert, S.	Situated learning	x	
Sleeman, K., & Sorby, S.	Social constructivism	x (have a positive impact on student retention rates)	
Richards, L., & Carlson, S.	Behaviorist	X (in introductory courses they mitigate attrition and are a source of motivation for new students.)	
Tomiyama, T., Gu, P., Jin, Y., Lutters, D., Kind, C., & Kimura, F.	Cognitive ("mathematically based methods", "methodologies to achieve specific design objectives" and "process methodologies").	x	
Oliveros, A., Vásquez, S., Hurtado, M., & Córdoba, J.	Behaviorist		x
Ruth, D., & Britton, M., Dunn-Rankin, D., Bobrow, J., Mease, K., & McCarthy, J.	Experiential learning	x	
Ramos, D., Creaform, Savery, J., Roncero, S.	Cognitive (Reverse Engineering)		x

Source: The Authors.

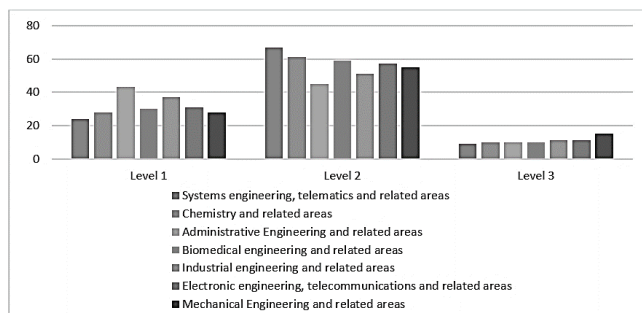


Figure 1. Percentage distribution of the results obtained by some university engineering programs in the problem-solving component of the ECAES tests (2004-2009)

Source: The Authors

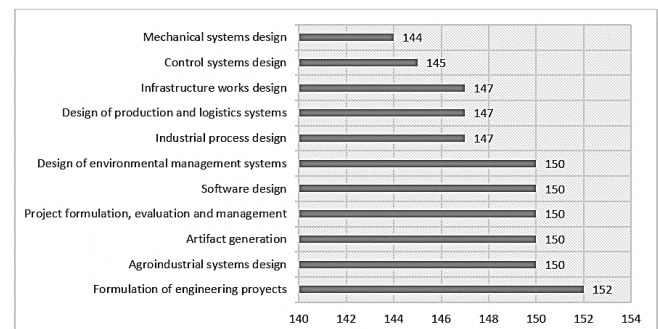


Figure 2. Average results of the specific design skills obtained by the students in the Saber Pro tests, 2016 and 2017.

Source: The Authors

regulated and defined the Quality Exams of Higher Education "ECAES", today Saber Pro to evaluate the quality of the educational public service in Colombia). Fig. 1 shows the average results of the specific problem-solving component. The specific competence of Troubleshooting includes the ability to interpret information, identify the relevant aspects of a problem (non-specialized) and identify and evaluate solution strategies and their results.

According to the results, a greater development of the competence to solve problems with medium complexity is evident in the students (analyzes and logically classifies information, analyzes, and reorganizes patterns presented in a standard way, isolates and applies key information to solve well-defined problems, demonstrates an adequate level of numerical performance to oversee routine problems). When comparing the results of the engineering programs in the category of problem solving with high complexity (analyzes and classifies information deeply and systematically, analyzes and synthesizes complex data, applies strategies to solve problems that involve abstract and complex relationships, demonstrates a prominent level of numerical performance), the mechanical engineering program stands out over the other programs.

There seems to be confusion between engineering design activities and other problem-solving activities, such as planning, which undoubtedly use similar processes. For example, the different problem-solving activities in the different disciplines include structuring the problem, producing different solutions, selecting a viable solution, and fully developing it. However, the presence of these components does not make the activity an engineering design activity.

On the other hand, in 2016 and 2017, 40 common specific competences were built for twenty reference groups and 4,400 students were evaluated; Fig. 2 shows the average results of eleven reference groups in engineering. The specific competences were previously chosen by each Higher Education Institution; the test consisted of between 30 and 60 questions per module and was answered in a period of 2 to 4 hours. The specific design component evaluated the student's abilities to analyze the notion of a technical artifact as a product of the process, to apply formal methods to the solution of an engineering design problem, to solve a proposed engineering design problem, to build functional prototypes as a solution of proposed problems and document the design information obtained throughout the process of solving the engineering design problem.

The score obtained in most of the specific skills modules was 150 points, which implies an intermediate level of development of the design skill. Skills for the formulation of engineering projects are highlighted and deficiencies in the design of mechanical and control systems are evident. The average overall engineering score was 153/180.

A design implies a specific problem in a specific context, which requires declarative knowledge and procedural knowledge (knowing how to do following predetermined procedures) specific to the context and according to the specialty. Not all engineering specialties in Colombia seem to have an identified engineering design object; consequently, it is unfeasible to try to analyze all the engineering specialties from a generic design test, because

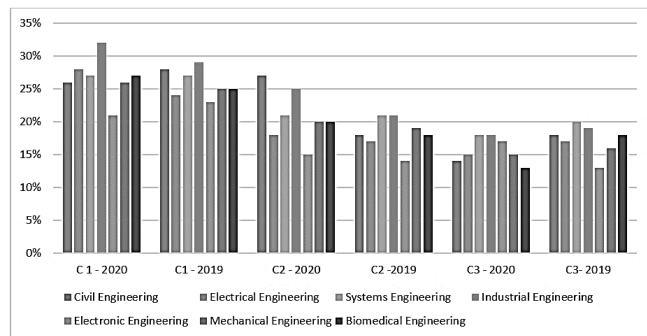


Figure 3. Average results of the general competition: Useful quantitative reasoning for design obtained by students in the Saber Protests, 2019 and 2020.

Source: The Authors

there will be a bias: while the cases were very complex for most of the engineering specialties, they are trivial for others, as a result in a clear benefit for the specialties handled by the respective context.

Within the framework of the SABER PRO tests of 2019 and 2020 in which 246,000 students in Colombia presented; the results obtained by the students in the general quantitative reasoning competence are shown in Fig. 3. Quantitative reasoning assesses the development of skills to understand and transform quantitative information presented in different formats; formulate and execute plans to solve problems involving quantitative information or mathematical objects; and justify, argue, or validate mathematical procedures and strategies used to solve problems.

The results obtained by the students of industrial and civil engineering are highlighted, which evidences the development of skills in mathematical procedures and strategies used to solve problems, planning and implementation of strategies that lead to adequate solutions, and transformation of quantitative and schematic information into different formats.

5. Analysis of results

Design courses in the first semesters of engineering studies differ from higher-level design courses in their focus on conceptual design methods and less on discipline-specific artifacts [32]. Currently in Colombia, advanced design courses for university students appear after 75% of the curriculum, so it is not measurable by the SABER PRO test in its current location as defined by law.

Most of the authors reviewed are inclined to introduce engineering design in the first semesters to motivate students, enhance individual creativity, avoid dropout, become familiar with design tools, and understand the team design process participating in the development of an applied project. However, the integration of existing interdependent design courses (it is not about creating new courses in the already full curriculum and loaded with academic credits) that are transversal and appear at three different moments throughout the career, within the nuclei of basic sciences, basic engineering, and applied engineering is a proposal by the authors of this article. The suggestion is to take a new curricular approach to design, and more effective teacher

preparation to teach, as well as officialization through national evaluations (Saber Pro Tests), and accreditation processes. Under this paradigm, it is desirable to provide the student with possibilities that allow them to establish a learning path and application of engineering design, in which they explore different methodologies to design, that adapt to the context of the problem they seek to solve, and that, in turn, receive feedback from the teacher in charge to direct and organize your ideas. Students should also receive training in how to recognize and develop modern technologies, bring technologies into market, and practice industry-proven commercialization processes within an academic setting.

As future work, it is recommended to combine in engineering design: knowledge (both how to design and the object of design), participation in interdisciplinary groups, and synthesis as a determining stage in the design process.

6. Conclusions

- The literature review allows classifying the teaching of engineering design as a complex educational process - to the extent that there are great abstractions around the idea of design-, for which many resources are required, and which are not always available in engineering programs. The complexity is identified in the cognitive, curricular, technical, and methodological aspects, and even in the adaptation to the forms of work currently required by global management systems in the industry.
- According to the studies reviewed, design courses fit better in the first semesters of the curriculum of engineering programs. Although it remains to be defined how to include it authentically and appropriately according to the educational purpose of the specialty.
- Criteria such as those of ABET and methodologies such as MIT's CDIO should be considered in the engineering curriculum, because they manage to give design courses a focus by considering the development of projects that present "real problems" and that are sponsored by companies. This favors a more adequate and realistic professional preparation for engineers while improving the focus of engineering curricula.
- The turnaround in how to design and implement alternative methodologies for teaching engineering design entails a change in thinking not only for the teacher but also for the students, since it takes the protagonists out of their comfort zone and requires their thinking and using emotional intelligence. On the other hand, for the teacher, it means capturing the student's academic attention with a new and different model than the one they are normally used to. For this reason, the role of the teacher should not only be reinvented from the pedagogical point of view, but also the technological and disciplinary point of view.
- It is assumed that the student who follows courses in basic sciences and engineering sciences supplemented by professional courses, in which small designs are made within the framework of academic exercises, frequently with a single correct solution, develops the skills to design. However, the growing emphasis in the international framework to explicitly promote design

skills seems to indicate that the strategy described above is insufficient.

- The demands imposed by the teaching of engineering design in Colombia today cannot be ignored. Therefore, higher education institutions are invited to rethink their curricula to give them more relevance and diversify their engineering design teaching strategies according to global trends, bringing students closer to the industrial reality.

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