Lean Engineering Education Model: Building A Multidisciplinary Engineering Skillset For Professional Life

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Abstract

Engineering professionals represent the core of the growth and transformation of society; thus, they must be equipped with multidisciplinary knowledge and a complete skillset with both technical and interpersonal skills. Nevertheless, the current higher education approach based on traditional teacher-centered methodologies focuses on technical and theoretical knowledge, resulting in underprepared graduated engineers. This study aims to establish a framework to address the industry needs of engineering students with a comprehensive, multidisciplinary set of competencies through the application of the Lean philosophy in the academic field. Based on an exploratory research methodology, the Lean Engineering Education model is developed with the integration of Lean principles into active teaching and learning strategies including gamification, project-based learning, and case-based teaching. Lean tools such as voice of the customer analysis, root cause analysis, and PDCA (i.e., Plan, Do, Check, Act) cycles are used. This study demonstrates that Lean principles and tools can be applied to the teaching, learning, and assessment processes in engineering education. The strategic implementation of the model within a classroom can be expected to enhance the teaching and learning processes while fostering the development of a multidisciplinary engineering skill set. This paper extends the existing research that primarily focused on the implementation of the Lean philosophy into administrative processes in the academic context. Thus, this study represents an initiative toward the improvement of the educational system.

Keywords: Active Learning, Lean Philosophy, Multidisciplinary, Student-Centered Learning, Teaching Methodologies

1. Introduction

The fundamental premise of this study is that engineering education is the engine of growth and transformation of society with a multiplier effect on all aspects of development. Engineering professionals are at the heart of technological, economic, and social innovation processes, endowing their education with an exceptional level of importance (Sheppard et al., 2009). Technical instruction has been subject to exponential growth globally, giving rise to Engineering Education, the academic branch focused on teaching concepts and knowledge related to the practice of engineering as a professional career (Valencia, 2010). Nevertheless, engineering is going through a crisis due to the focus on the technical element of the profession and the lack of relationship with areas of knowledge such as humanities and arts, resulting in a deficiency of soft skills and abilities for performance in working life (Valencia, 2010).

Factors such as accelerated globalization, technological development, and the fifth industrial revolution, require higher education to continuously evolve to meet the changing needs of society (Alves et al., 2017). Today's complex and volatile world requires "a new type of engineer, an entrepreneurial engineer, who needs a broad range of skills and knowledge above and beyond a strong scientific and engineering background" (Creed et al., 2002). In essence, engineering professionals must be equipped with interdisciplinary knowledge and practice-oriented soft skills for the 21st century, including (1) critical, whole-system, and problem-solving thinking, (2) effective communication skills, (3) strong ethical sense, (4) leadership and collaborative teamwork, and (5) continuous learning and knowledge building disposition (Parker et al., 2019; ABET, 2021; Voogt & Roblin, 2010).

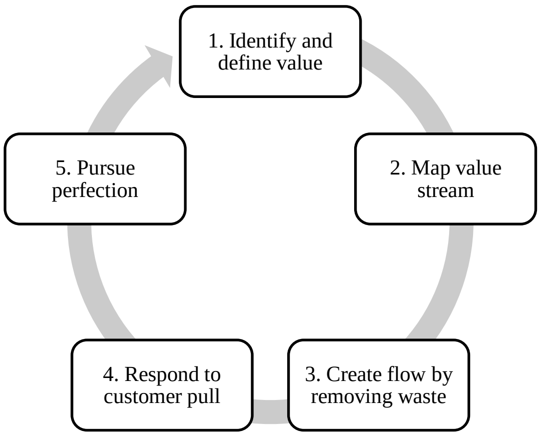
According to the Accreditation Commission for Engineering Technology (2021), university degree programs are responsible for developing students' ability to apply knowledge as practicing professionals. However, there is increasing discussion of the ineffectiveness of traditional teacher-centered education in failing to develop students' critical thinking skills and their ability to solve problems as professionals (Berkel & Schmidt, 2005). Indeed, it has been established that current engineering education does not prepare graduates for engineering practice within the professional sector effectively (Brawner & Miller, 2003). Emerging literature indicates the benefits of learner-centered forms of instruction, where the student is an active participant in the learning process (Bransford et al., 2000). With increased emphasis on hands-on, project-based, and problem-solving learning, an immediate boost in student capabilities in engineering can be expected (Chiang & Lee, 2016).

As Naik (2004) states, to effectively promote the development of technology and face industry, it is essential to have highly qualified and competent human capital, and thus, engineering education is key. As a consequence, this study aims to establish a framework to address the gap between the demand for fully trained engineering graduates and the educational capacity to provide them. In order to do this, the Lean Engineering Education model is developed through the application of Lean principles and tools to the teaching and learning processes in a higher education engineering classroom. Integrating Lean principles and concepts into the aforementioned processes is challenging and thus, a new research area. Considering this, the present study sought to answer the following research question: To what extent can the Lean principles and tools be integrated into the teaching and learning processes in a Higher Education classroom?

2. Methods

To answer the research question on the implementation of the Lean philosophy into academic processes, this paper follows an exploratory research methodology. Qualitative in approach, the research design is based on the procedural application of each of the five key principles of the Lean philosophy. As shown in Fig. 1, the Lean principles are: (1) identification of value, (2) mapping of the value stream, (3) creation of flow, (4) implementation of pull production and (5) pursuit of perfection (Womack & Jones, 1996). The following section briefly presents each principle and indicates its use and application within the context of education.

Figure 1. Five Lean principles



Source: Andino, Quito (own figure).

3. Results: Lean Engineering Education Model

3.1 First Lean Principle: Customer Value

Lean Thinking is a quality management and improvement approach that defines quality as the ability to meet customer demands (Womack and Jones, 1996), thus, defining value from a customer's perspective is the starting point in the Lean process. Identifying the customer in academic settings can be challenging as there seem to be multiple stakeholders in the education process. The literature review demonstrates that most studies that highlight the implementation of quality tools to enhance the performance of higher education institutions include three customer groups for education: (1) students, (2) academic staff, and (3) employers of the private or public sector (Owlia & Aspinwall, 1998; Jiang et al., 2007; Nygaard et al., 2008). In the present case, the aforementioned three groups are considered customers as they interact directly with education services.

An analysis of the voice of the customer (VOC), employed to describe customer needs and expectations (Griffin & Hauser, 1991), is performed to specify customer value. The student outcomes (SOs) outlined by ABET (2021) describe the desired learning objectives capturing a specific set of hard and soft skills. Tab. 1 summarizes the alignment of the ABET's SOs with the corresponding soft skills and competencies.

3.1 Second Lean Principle: Value Stream Analysis

Mapping the "value stream" includes all the activities and processes involved in the procurement, processing, and delivery of a product or service (Womack and Jones, 1996). The higher education process can be compared to a manufacturing process, in which raw materials are processed via a series of steps to produce and deliver finished goods. Accordingly, higher education institutions are part of the process where new students become intellectual graduates with a set of skills that are later employed in the industry. To understand the process variables, a version of the SIPOC (i.e., Suppliers, Inputs, Process, Outputs and Customers) diagram from the engineering education global view perspective is provided in Fig. 2.

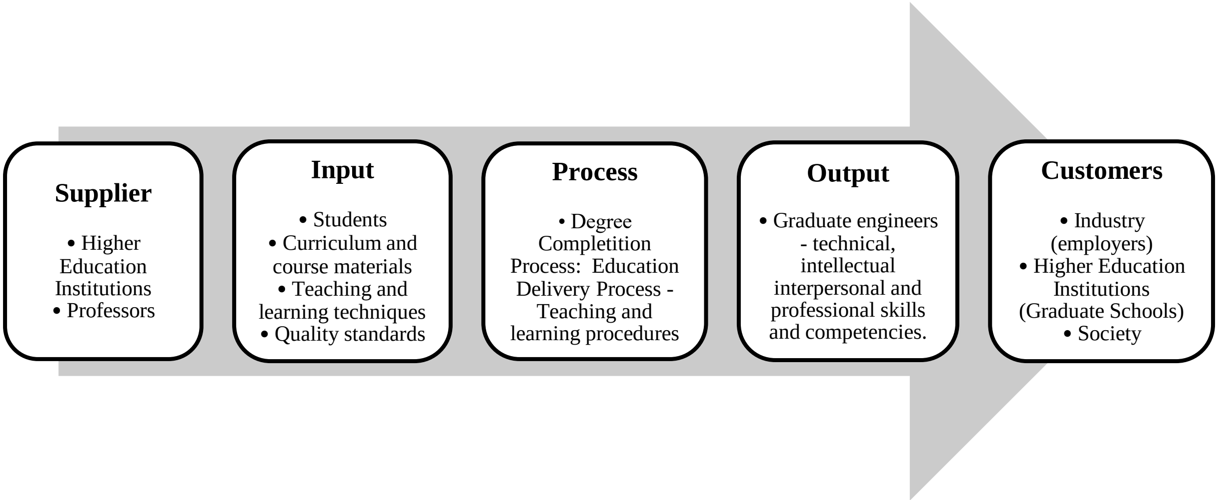
Table 1: Alignment of ABET SO's and Soft Skills

Item	ABET's Student Outcomes*	Skills and Competencies
1	an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	Logical thinking Problem-solving skills
2	an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social,	Innovative thinking Problem-solving skills

	environmental, and economic factors.	
3	an ability to communicate effectively with a range of audiences.	Communication skills
4	an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.	Critical reasoning Integrity
5	an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.	Leadership Teamwork Collaboration
6	an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	Critical reasoning Organizational skills
7	an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.	Life-long learning

Source: ABET, 2021.

Figure 2: SIPOC of Engineering Education process



Source: Andino, Quito (own figure).

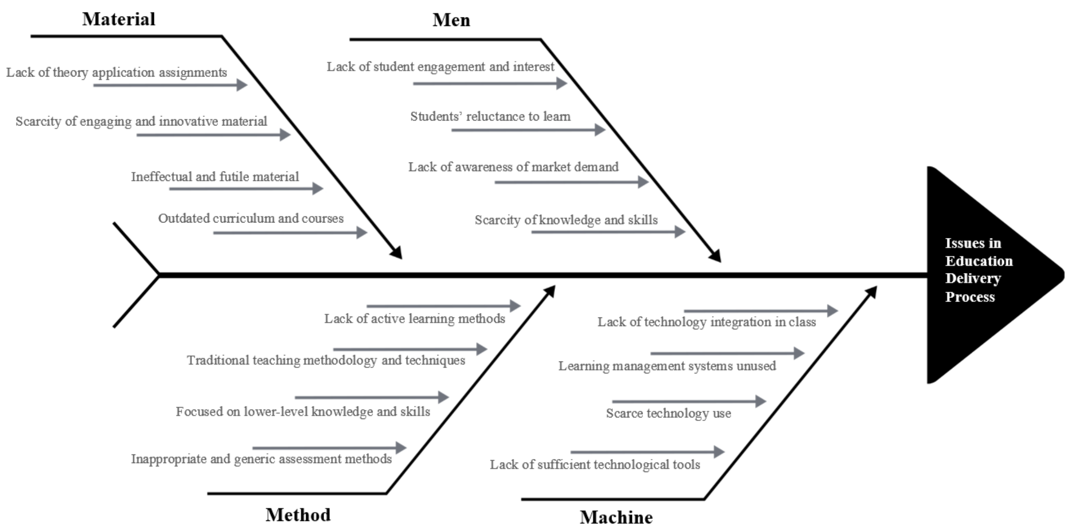
The idea behind the value stream analysis is to examine the business process to determine steps that do create value and eliminate the ones that do not (Alves et al., 2017). In Lean terminology, a product that does not satisfy customer expectations is referred to be defective and must be reworked to comply with the specifications (Womack & Jones, 1996). Mapping this concept in the academic field enables us to visualize that new workforce is being generated without the appropriate knowledge and skills, thus, not meeting industry requirements.

Additionally, since minimizing waste is one of the main goals of Lean Manufacturing, waste must be defined in the higher education system of processes. As established by Womack and Jones (1996), waste is any human activity that consumes resources but creates no value. In a Lean manufacturing study focused on waste, Douglas et al. (2015) determined that examples of educational waste include teaching topics already taught in other courses, excessive review of prerequisite materials, unnecessary and redundant introductions, spoon-feeding, and teaching obsolete topics. In general, waste in education typically happens when time, resources, and effort are expended, but the final results do not meet the standards set by key performance indicators (i.e., students do not acquire new knowledge or required skills). Hence, considering the core idea behind Lean is maximizing customer value while minimizing waste (Womack & Jones, 1996), to produce high-quality graduates, efforts to minimize waste must be undertaken throughout the process with careful consideration of stakeholders' views.

3.3. Third Lean Principle: Flow

After the waste has been removed from the value stream, one must ensure that the remaining activities flow smoothly with no interruptions, delays, or bottlenecks (Womack & Jones, 1996). Hence, the focus is on organizing a continuous flow through the process, which in the academic field refers to a smooth and leveled workload without waste pushing back students, faculty, and society (Alves et al., 2017). In general, with enhanced flow, the delivery of service improves, and the level of productivity increases. To identify the root causes of common issues, delays, and bottlenecks that impact the education delivery process and determine the need for corrective actions, a root cause analysis is conducted through the construction of a cause-effect diagram shown in Fig. 3.

Figure 3: Cause and Effect Diagram



Source: Andino, Quito (own figure).

3.4. Fourth Lean Principle: Pull System

In a pull system, customer demand triggers the services, delivery, and content intending to produce the value that is needed by the customer to avoid overwork, overproduction, and waste (Womack & Jones, 1996). As previously established, engineering students are required to have a complete skill set with both technical (i.e., hard skills) and interpersonal competencies (i.e., soft skills) in order to perform appropriately in the industry. In light of this, it can be said that the demand for a high-quality education is present and must be addressed.

3.5. Fifth Lean Principle: Pursue Perfection

The management of non-value-adding elements and waste is a process of continuous improvement, thus, there is no end to reducing time, cost, space, mistakes, and effort. Hence, the fifth Lean principle is focused on enhancing the activities that generate the most value for the customer and sustaining the process with continuous improvements (Womack & Jones, 1996). In this case, this principle is supported by the integration of the PDCA (i.e., Plan, Do, Check, Act) cycle, a four-stage iterative process for constant improvement of a product or service by potential solutions testing, results analysis, and process enhancement (Chakraborty, 2016). In this case, the planning process of the first stage must consider the proposed learning outcomes and the teaching methodologies to achieve them. The second stage covers the development of the classroom, which should focus on student-centered methodologies and active learning techniques, such as gamification, project-based learning, and case-based teaching. In the third stage, the evaluation of the methodology takes place through assessments, tests, surveys, observations, and other review methods. Based on the evaluation results, corrective actions are taken to improve the performance of the methodology and provide the desired results in an efficient and effective manner.

A key summary of the application of Lean principles in the education framework is provided in Tab. 2.

Table 2: Lean Principles and Tools in the Education Framework

Lean Principle	**Lean Tools Applied**	**Education Framework**
Identify Customer Value	Voice of Customer (VOC) Analysis	Mastery of knowledge (hard-skills) complemented by interpersonal competencies (soft-skills) Ability to integrate and apply knowledge and skills in the workplace and industry
Map Value Stream	SIPOC Diagram Waste Identification	Proper course planification considering expected outcomes, teaching strategies and assessment methods Application of student-centered teaching methodologies where students have an active role in the learning process.
Flow	Cause and Effect Diagram	Continuous assessment Monitoring the learning process Timely and continuos feedback
Pull System	PDCA cycle	Taking into account customer's needs and interests to design and develop the teaching and learning processes.
Pursue of Perfection	PDCA cycle	Active learning and student-centered methodologies, including gamification, project-based learning, and case-based teaching.

Source: Andino, Quito (own figure).

4. Discussion

In this study, the Lean Engineering Education model was built and proposed to develop the complete and comprehensive skill set that engineering students need to succeed in their professional life. In the development of the model, Lean principles and tools were integrated into the teaching and learning processes within a classroom in the Higher Education environment.

Lean Education is the application of Lean thinking to education both in administration processes and academic activities (Alves et al., 2017). Evidence suggests that Lean methodology has been successfully implemented in a vast variety of institutions to improve business processes and deliver greater value to end-use customers (Balzer, 2016). However, there is a scarcity of research that shows Lean philosophy can be effectively employed in key processes that take place within classrooms in programs at institutions of Higher Education

(Vukadinovic et al., 2017). This study shows how each of the five Lean principles can be integrated to enhance teaching and learning processes.

Based on the first Lean principle of defining customer value, it was determined that the customer in the academic setting includes three groups: (1) students, (2) faculty, and (3) the industry, as they interact directly with education services. An analysis of the voice of the customer (VOC) was performed based on the student outcomes (SOs) outlined by ABET (2021) to identify the soft skills and competencies considered valuable by the customers. The key interpersonal abilities include logical and innovative thinking, problem-solving skills, critical reasoning, leadership, teamwork and collaboration, organization, knowledge-building disposition, and communication skills. These findings align with a multi-year project conducted by Hundley (2015) that, reflecting the voice of industry, developed a series of competencies needed by engineers in order to effectively live and work in a global context. The “Attributes of a Global Engineer” included personal skills (e.g., critical and creative thinking, individual and cooperative reasoning, initiative and willingness to learn), interpersonal skills (e.g., teamwork abilities), and cross-cultural skills (e.g., understanding of political and social perspectives and ethical and business norms, possession of a multidisciplinary and global perspective) (Hundley, 2015).

To achieve desired student outcomes and the development of interpersonal competencies, the proposed approach was based on active and student-centered learning methodologies. An extensive literature review was performed on the outcomes in regard to student performance and attitude development of active teaching methods.

With the application of the second and third Lean principles, waste was defined in the Higher Education system. It was established that waste includes unbalanced workload, over-assessment, delayed evaluation and late grading, poor knowledge acquisition, learning not relevant to industry requirements, and students as passive spectators. Furthermore, a cause-effect diagram was constructed to determine the root causes of these issues and bottlenecks that impact the education delivery process and recognize the need for corrective actions. Several comprehensive studies on waste management in higher education institutes (Braun & Campos, 2020; Douglas et al., 2015; Fagnani & Guimarães, 2017) identified issues in both academic and administrative processes, including excessive movement of people, overproduction of materials, excessive inventory, and waste of human resources. Nevertheless, as Céspedes et al. (2021) established, if Lean concepts are implemented in earnest, the elimination of waste can be expected making the learning process more responsive to industry needs.

Finally, based on the fifth principle of pursuing perfection, this study implemented the PDCA cycle as the base of the framework. In line with previous work (Knight & Allen, 2012), the PDCA cycle of continuous improvement seems to be a systematic approach to incrementally move closer to a particular goal. This assumption is reinforced by other previous studies on the application of PDCA cycles in different industries. For instance, Maruyama (2016) applied the PDCA cycle on leadership education on graduate students of engineering, resulting in seven years of continuously improved quality of the education program in which students achieved their learning goals. Chakraborty (2016) conducted a case study on the implementation of the PDCA cycle in an automobile manufacturing company and concluded that this data-based framework drives continuous and ongoing efforts to achieve measurable improvements in the efficiency, effectiveness, performance, accountability, and outcomes in any process. In synthesis, through the application of Lean tools, this study provides the framework to identify underlying factors that influence educational outcomes and, ultimately, modify the procedures in order to deliver the best learning outcomes.

5. Conclusion

This study demonstrates that Lean principles and tools can be applied to the teaching, learning, and assessment processes in engineering education. This framework allows faculty to identify industry needs in terms of student skills and competencies necessary in the workplace. Not only that but the proposed model has the potential to mitigate issues concerning content delivery, knowledge acquisition, abilities development, and assessment methods. The strategic implementation of the model within a classroom can be expected to enhance the teaching and learning processes while fostering the development of a multidisciplinary engineering skill set. By engaging the students in the learning process through active and student-centered methodologies, positive results can be expected in regard to the targeted learning outcomes. The paper extended the existing research that primarily focused on the implementation of the Lean philosophy into administrative processes in the academic context. Thus, this study represents an initiative toward the improvement of the education system.

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