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ORIGINAL PAPER

Experiential learning at Lean-Thinking-Learning Space

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Abstract

This research paper presents a proposal for a learning model that extends the availability of resources for training and development of professional skills in the field of Lean Manufacturing. This research arises due to the lack and current limitations of effective teaching models for the development of professional competencies. The importance of this educational innovation proposal lies in being a unique reference frame of its type. This offers cutting-edge methods for optimization and process improvement tools, while developing general and disciplinary competencies in the area of industrial engineering. The notion of learning is presented in a context of real-world experiences to develop relevant competencies in real businesses settings for manufacturing and services. This work presents a literature review on competency-based education, experiential learning and challenge-based learning. Therefore, a background explanation of the proposed learning model and a learning space called Lean-Thinking-Learning Space are elaborated. Additionally, an experiment carried out to measure the development of competencies is showed in terms of comparing the teaching results of a course in two different learning spaces; namely, a traditional classroom and the proposed experiential learning space. The results of this investigation reflect an increase of 29% in the level of attainment of competencies observed in the experiential learning space proposed in this research work.

Keywords Competency-based education · Challenge-based learning · Educational innovation · Experiential learning · Industrial engineering · Higher education

1 Introduction

Currently, companies and organizations demand that graduating professionals have competencies that allow them to solve large complex problems, have a value-based approach to decision-making and to be strong in self-awareness, self-leadership and teamwork in order to interact and address the resolution of engineering problems and social concerns with an entrepreneurial mentality and work/product design methodologies [1]. On the other hand, Vries and Navarro [2] mention that students do not recognize the relevance of their studies, because they do not see a direct relationship between what they learn and what will be required of them in their future professional careers.

The above consideration is not something that arises in the final stages of their studies; rather, it is a problem throughout their professional education from admission to graduation [3]. This lack of connection between studies and required future competencies that can be eradicated by generating appropriate learning activities that transfer knowledge to students and produce their pertinent learning [4].

In Mexico, according to the comments of Salvador Jara, the Sub-secretary of Higher Education of the Federal Secretary of Public Education (SEP), the manufacturing and services industries require each year about 30 thousand engineers trained to meet the needs of companies related to the automotive industry, but only 20 thousand young engineers graduate in a year [5]. Because of this, Mexican higher education must improve its performance in meaningful ways to successfully face current and future challenges.

Considering the aforementioned problem, two important areas to improve in higher education are: (a) education must simultaneously teach and train young people; i.e., go beyond traditional teaching to unify education and training for work;

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and (b) the teaching–learning process must develop skills and competencies for the needs of the 21st century, such as, creativity, innovation, flexibility and adaptability. This is about not only technical competencies but also personal competencies that graduates need to develop during their higher education. This is because some of the most demanded competencies by the productive sector are socio-emotional intelligence, teamwork, perseverance and leadership [6].

Along the same lines, the Engineering Accreditation Commission (EAC) of the Accreditation Board for Engineering and Technology (ABET) recognizes the importance of developing specific competencies in graduates which have been defined directly by employers working together around the world and which focus on the needs of the current working environment [2]. ABET runs accreditation evaluations for engineering academic programs all over to world to validate their contributions to quality education, the discipline and society in general.

Accordingly, this present research work proposes, as a starting point, the following research questions:

Q1 How to develop an experiential learning space for the development of relevant, personal and disciplinary competencies that make an impact on the improvement and optimization of design processes and products in professional practice?

Q2 Could the teaching of improvement and process optimization centered around an interactive learning challenge within a flexible and experiential space contribute to the development in future engineering graduates the abilities that are highly demanded in industry, as defined by student outcomes "c" declared by ABET: "The ability to design a system, component or process to meet the desired needs within realistic limitations such as economic, environmental, social, ethical, health and safety, manufacturing and sustainability?" [2].

Therefore, this document looks at Competency-Based-Education (CBE), Experiential-Learning (EL) and Challenge-Based-Learning (ChBL) and their relationship to interactive learning spaces, as a starting point. Later, a detailed explanation is provided about the proposed learning model called, "Lean-Thinking-Learning Space (LTLS)." Next, this work continues with the experimentation and findings of the proposed model of the learning space and its implementation. Finally, conclusions and proposed future work are presented for guiding the next steps of this work.

2 Literature review

CBE has been intensively introduced at different educational levels since the 1980s. Since that time, important efforts have been made to define conceptual frameworks and establish key competencies for the strengthening of educational systems and their evaluation at the international level. Examples can be found in the works of Tunning [7], Tunning Latinoamerica [8], the European Commission in Key Competencies for Lifelong Learning [9], the OECD in the DeSeCo project (Definition and Selection of Competencies) [10], and The Future of Education and Skills 2030 project [11], among others. The benefits of CBE are that the student's training and learning connect and respond to societal demands and those from the productive sector [8]. The flexibility and accessibility of the model generates in students the ability to continuously recognize, manage and build their own competencies. Consequently, an essential role falls to the teachers and instructors in the model from the transmission of teaching to the evaluations and assessments. The adoption of this type of educational model has created a new generation of academics who have discovered the need to prepare new learning environments and test emerging teaching techniques in order to help students develop skills [12].

The notion of "competence" has several definitions, and this is in constant review due to research developed around the concept and the practical implications at different levels and contexts of education. The European Commission defines CBE "as a combination of knowledge, skills and attitudes appropriate to the context." [9] This definition could be succinct in "the proficiency level of a person with respect to a context," [13] taking into account that competencies support the development of an integrated approach at the higher education level and involve all dimensions of human beings, i.e., the knowing about, the knowing to do, the knowing to be, and the being [14]. Some of the most popular teaching methods for developing competencies are flipped classroom, game-based learning, blended learning, active learning, authentic learning, research-based learning, online learning, flexible learning, hybrid learning, just-in-time learning, experiential learning and challenged based learning, among others [15].

The teaching methods and tools selected for application in this research are experiential learning and challenge-based learning. The main reason behind the selection of these two techniques resides in offering industrial engineering students a field experimentation based on learning practices and experiences [16]. This study is also about creating a contribution in terms of the challenges faced by educators in the lean manufacturing discipline to offer appropriate experiences in which students develop competencies and collaborate to design, build and deploy real systems to solve problems based on engineering solutions [1], carry out research, and intervene in real situations and challenges.

Thus, EL is referred to as the process of extracting meaning from direct experience, i.e., "learning from experience." [17] The experiential education is a "philosophy that informs many methodologies in which educators purposefully engage with learners in direct experience and focused reflection in order to increase knowledge, develop skills, clarify values, and develop people's capacity to contribute to their communities." [18] The University of Chester refers to this type of EL as work-based learning, emphasizing the practical development of knowledge acquired in the institution and the exploration of personal sensitivity to solve problems with the intention of forming capable citizens to learn from their own experience in any environment [19]. Some universities refer to projects in class, research work, student clubs, thesis write-up and any practical academic work at different stages in their development (through one or several disciplinary paths) as examples of experiential learning for students. Some examples can be found in the engineering programs of Purdue University [20], Oregon State University [21], University of Chester [19], University of Colorado at Denver [22] and at The University of Texas at Austin [23]; that is, from humanities to sciences in university institutions.

Additionally, it is important to mention the study of Kolb (1984) regarding the four critical steps associated with experiential learning:

- *Action or concrete experience* involves the student's sensory and emotional commitment.
- *Reflection or reflective observation* involves seeing, hearing and discussing the experience.
- *Abstraction or abstract conceptualization* phase of deep reflection, which integrates theories and concepts in the learning process.
- *Application or active experimentation* phase of doing, where the experience is tested in a specific context [17, 24].

According to this study of four phases, EL has been distinguished as a holistic, integrative approach that combines experience, cognition and behaviour [25]. Therefore, the ChBL has had as a principle and foundation EL, being immersed to grant a pedagogical approach where students apply what they learn in real situations where they face problems, discover for themselves, try solutions and interact with other students within a certain context [24]. Moreover, ChBL is an educational experience, where learning is carried out through the identification, analysis and design of a solution as a socio-technical problem. The learning experience is typically multidisciplinary and aims to find a collaborative solution that is environmentally, socially and economically sustainable [1].

ChBL is also referred to as an active learning environment that encourages students to determine their own goal and structural model of learning content based on collaborative Problem-Based Learning (PBL) [26]. ChBL has some elements in common with PBL and also with what is called Project Based Learning (POL); however, important differences are highlighted in Table 1.

The literature review covered the study of learning spaces, simulators, and games, among others; however, none of them showed significant evidence of educational possibilities where developed interactive methods and experiential learning spaces to design products and manufacturing processes. This review can also refer to focus on other aspects of education [27–36].

3 A proposed learning–teaching model

The main proposition of this research work is explained in this section in detail in relation to presenting a CBE, which, within an experiential learning space, introduces a learning challenge in order to provide a unique learning experience for student competency development in a context of an interactive product and process design.

This learning model (Fig. 1) might be recognized as a Learning Experience (LE) aligned to a socio-technical challenge (defined in a general way), which can be accepted and taken on over a pre-defined time period with specific objectives, learning sub-challenges, activities, educational resources and the collaborative design interaction of participants. This conceptualization, within a contextual environment, incubates an effective learning experience (EL) [18] that helps students make significant progress in the

Table 1 Comparison of challenge-based learning, problem-based learning and project-based learning

Issue	Challenge-based learning	Problem-based learning	Project-based learning
Problem	Relevant issue in the social, economic or environmental context. It is open, and it may even be undefined	Relevant according to a subject, usually fictitious	Relevant, already defined and delimited by the project manager
Solution	Demands an urgent real solution, applicable and verifiable. Requires a product and/or service implemented with concrete actions and effectiveness, defined by the objectives set	No real urgent solution is required. A solution or product proposal that demonstrates the learning process is enough	A real solution is expected (which may already be pre-directed), but not necessarily urgent. It can be a product, presentation or implementation
Actors	Stakeholders and experts according to context: coaches, mentors, professors, researchers, etc., as support for the student	Professor(s)	Professor and/or project manager

development of their intended competencies. The model sets a background for understanding how to abstract and design learning experiences in an experiential and challenge-based learning space (EChBLS).

Each of these integrated elements of the model aims to reach "pertinence or relevance in education," to stimulate students to generate new points of view, attitudes and emotions (as mentioned in [37–39]), in order to create individual motivation to participate and contribute within a wider context to solve social, economic, political or environmental challenges effectively.

Figure 1 can be studied bottom-up or vice versa, providing a logical framework of concepts to understand the mutual relationships among LE, learning space and learning resources, ChBL, EL and CBE, going from the conceptualization of learning objectives and purposes down to the practical execution of learning experiences.

Accordingly, in order to achieve relevance in education, educational objectives and learning purposes must be defined and translated into learning activities. For this reason, a general working method is presented next that incorporates educational intentions, competencies, experiential learning and learning challenges into a learning space to facilitate the recreation of an effective learning experience (LE).

The steps of the working method are (1) define the learning objectives; (2) select the competencies and sub-competencies to develop; (3) continue with the design of experiential learning by giving a detailed description of the challenge and sub-challenges to solve a real problem situation; (4) proceed with the design of the learning space and the selection of the adequate learning resources to build a significant learning experience; and, finally, (5) design the competencies' evaluation instruments and carry out the evaluation.

The model and the working method are the result of the literature review to accommodate and give structure to ideas for designing and developing learning experiences [25, 40–43]. In the following sections a more detailed description of the proposed model is explained.

3.1 Experiential Learning in the Lean-Thinking-Learning Space

The educational objectives and learning proposition behind implementing experiential learning inside the LTLS is based on the concepts and tools of Continuous Improvement of Processes by Maasaki Imai [44] and the subsequent evolution towards the Lean Manufacturing production model of the Toyota company described in the book, *The Machine that Changed the World*, written by Womack et al. [45].

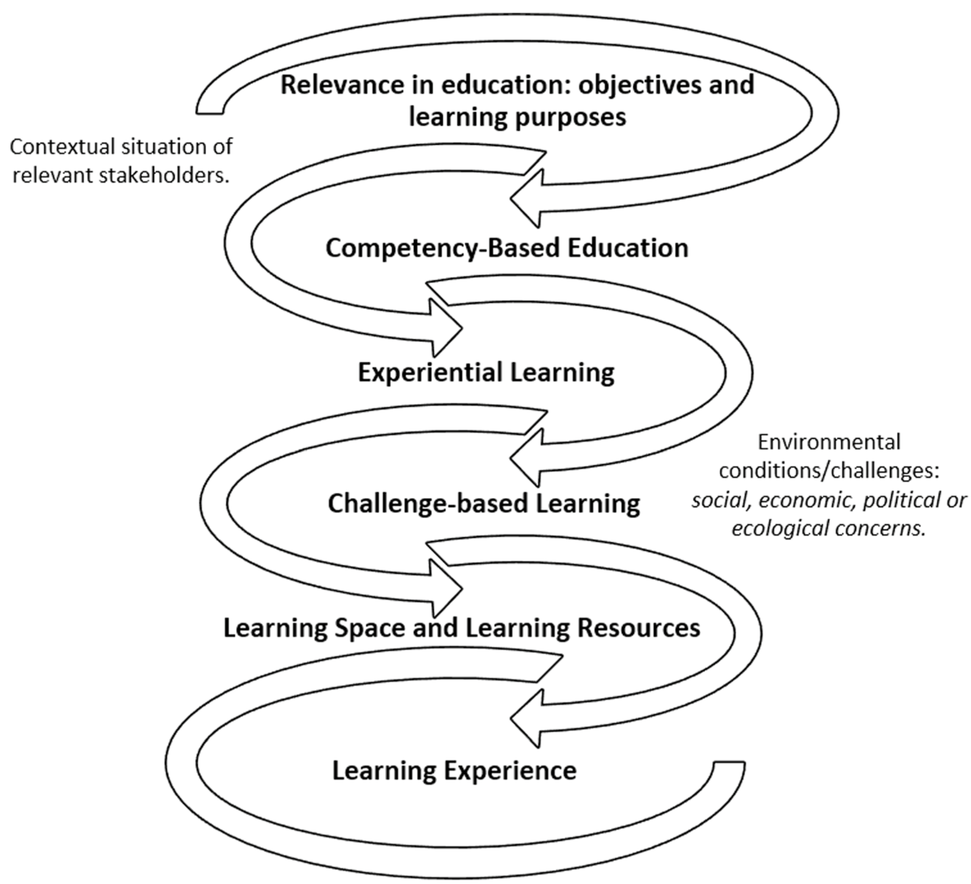

Fig. 1 Proposed model for Experiential Challenge-Based Learning Spaces (EChBLS)

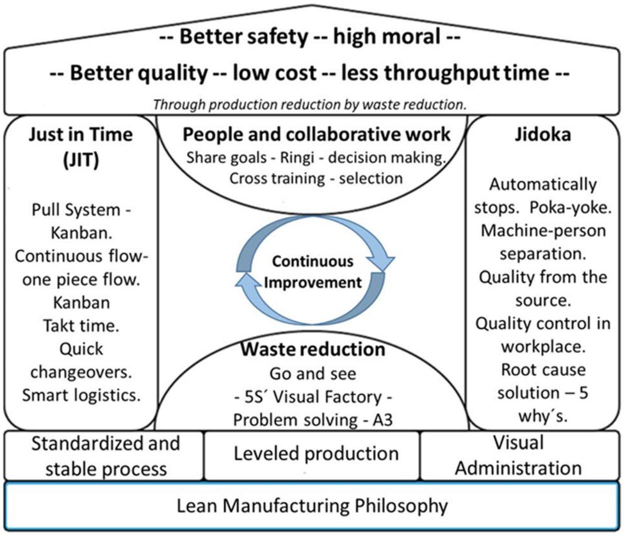

Fig. 2 Implemented tools and methodologies within the LTLS. Based on [45, 50, 51]

This production model seeks the progressive improvement of operational efficiency in processes by building up process capacities in terms of waste elimination, operational stability, quality in the workplace, continuous flow, Just-in-Time methodologies, collaboration and teamwork (see Fig. 2).

This model has been defined with the purpose of impacting the flexibility and responsiveness of processes, as clearly defined by Taiichi Ono in his book, *Toyota Production System* (1978) and by Jeffrey K. Liker in his book, *The Toyota Way* (2004).

Based on the ideas presented above, our project was executed to identify possible answers to the research question, "How to create an experiential learning space that foments relevant, personal and disciplinary competencies that will improve and optimize processes in professional practice?"

Based on those premises, the proposal for this research work and the research methodology within the LTLS are presented. The proposal aims to enable students to experiment within the learning space, to test concepts in real applications and to learn through the experiences of challenges; all of this building and reaffirming the knowledge they acquire throughout the practice. Therefore, the LTLS is a flexible and innovative physical space purposely designed for the development of disciplinary and personal competencies through experiential learning and challenge-based-learning. This innovative, educational project proposes to create an environment of continuous production with all the factors of a real productive process in play, where the students are immersed in the experience and make decisions that lead to an efficient transformation from a process with waste to one with zero waste.

This LE must allow students to develop solutions to problems inherent in a manufacturing process under changing demand for products and, therefore, the solutions must be flexible and adaptable to changing process transformation needs to maintain adequate levels of performance; for example, by modifying product specifications, delivery times and product availability according to the shifting paces of demand. During the operation of the LTLS, the objectives of the learning challenge, defined by the demand, must be progressively achieved as the students consolidate the understanding and knowledge that they acquire; i.e., the learning is incremental.

As explained in the literature review, the purpose of ChBL is that students face socio-technical problems which they identify in order to generate and test solutions that are focused on environmental, social and economically sustainable environments. They need to do this while collaborating with other students within a certain context. For these reasons, LTLS complies with the main ChBL characteristics as well as the development of LE through a set of designed activities that involve activities of reflection, critical analysis and synthesis. These must include diverse activities where students take initiative, decide and hold themselves responsible for the results. A more detailed description of these activities and the methodological design are explained in the following section.

3.2 Challenge-based learning: a learning experience model in the LTLS

A learning challenge presented, developed and executed within the LTLS has been defined as, "Students should design a product and the necessary processes for its manufacture by means of the transformation of a production system from a 'push system' into a 'pull system,' applying the methods and tools of continuous improvement and lean manufacturing for the purpose of impacting key performance indicators. The challenge must exist under the operating constraints defined in the experiential work space (for example, machinery, labour, raw material, etc.) and be based on premises of process sustainability."

It is worth mentioning that the manufactured product has to be designed and produced considering the utility and use of the product by a customer or its satisfaction of some social need. The challenge includes that all the production meets the defined quality standards to be delivered to the client in the predefined time over the duration of the challenge. The learning challenge is then to create a controlled production process with deliveries on time and meeting the quality requirements of a defined market and specified service levels.

In this way, the application of knowledge to solve the challenge, focused on the production and improvement of

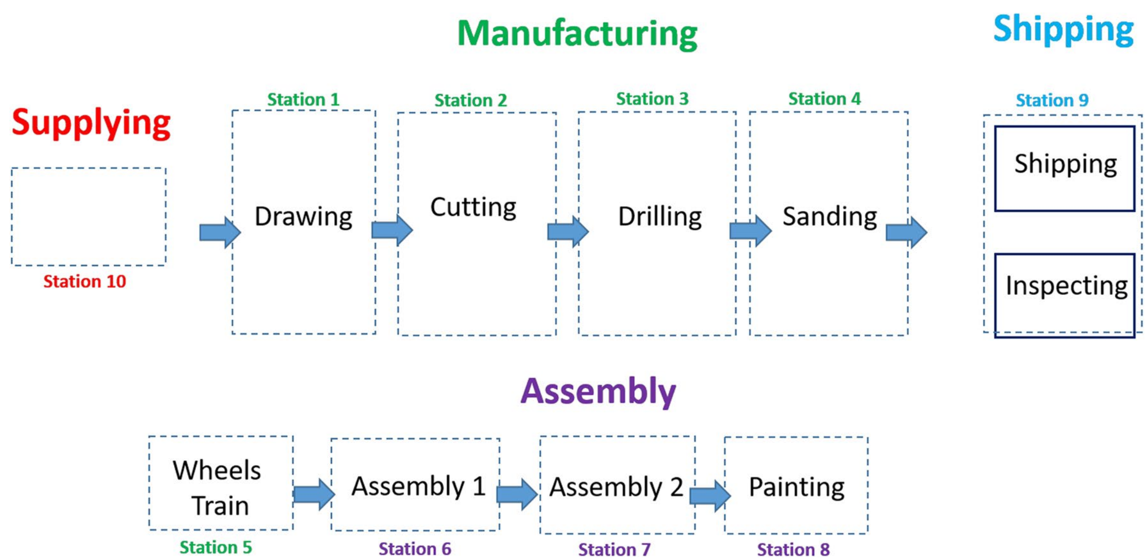

Fig. 3 Lean Thinking Learning Space layout, stage 0

processes, establishes a clear methodological understanding of production processes of goods or services, attributes of added value and waste, outcome variables (e.g. cost, time, quality and safety), working methods (i.e., A3 format), and evaluation of the process performance (i.e., operational efficiency).

Some of the main lean manufacturing tools applied throughout the challenge were the A3 Problem Solving Method, the Standard Work, the 5S's, Visual Management, Total Productive Maintenance (TPM), Single Minute Exchange of Die (SMED), Jidoka, Andon, Poka-yoke, Kanban and Overall Equipment Efficiency (OEE), among others. The improvements brought about by using the above tools can be seen reflected in the challenge results at the end of the immersion period, as students move from a non-standardized and inefficient production system to an optimal production system under lean principles, which is achieved with the aforementioned tools and documented in a portfolio with the evidences of the implemented engineering methods and the resulting skills, abilities and competencies developed.

Other realistic conditions that the students must face during the learning challenge include maintaining adequate safety and hygiene conditions during the production runs in the LTLS. In addition, a consensual-decision-making process is required within the work team, who operate under a vision of sustainability and a code of ethics.

3.3 Learning space and learning resources: Teaching Model at LTLS

The LTLS resembles a wood job shop. It consists of an area with nine work stations outfitted with machinery, tools and devices, where a production process takes place. The operations carried out in each work station are: Station 1: product design; Station 2: cutting with a circular saw; Station 3: Cutting with a jigsaw; Station 4: Drilling; Station 5: Sanding; Station 6: Assembly 1–2; Station 7: Painting; Station 8: Assembly 3; and Station 9: Inspection and packaging. The raw materials available are MDF boards of 3 mm and 12 mm thickness and coffee stirrers and recycled tops. Figure 3 shows the layout and initial arrangement of stations, as well as some of the different products that have been made during the academic periods. This layout could change during the course period in order to optimize and increase efficiency in the production processes.

The instruction within the LTLS is developed through four production scenarios, where each is executed based on the Kolb Model [46] for experience-based learning. The four production scenarios to be executed are:

1. Preparation;
2. Stability of the process/push production;
3. Principle of continuous flow/one-piece flow;
4. Principle of pull/pull production.

The objective of the scenarios is to apply knowledge and reaffirm concepts through the sub-challenges that arise in each stage, always taking into consideration the initial main challenge for the development of incremental competencies in each scenario.

Figure 4 shows a summary of the scenarios, the knowledge and lean manufacturing tools applied, and some performance indicators measured over time to identify improvements in productivity, efficiency and waste elimination; all based on a philosophy of continuous improvement.

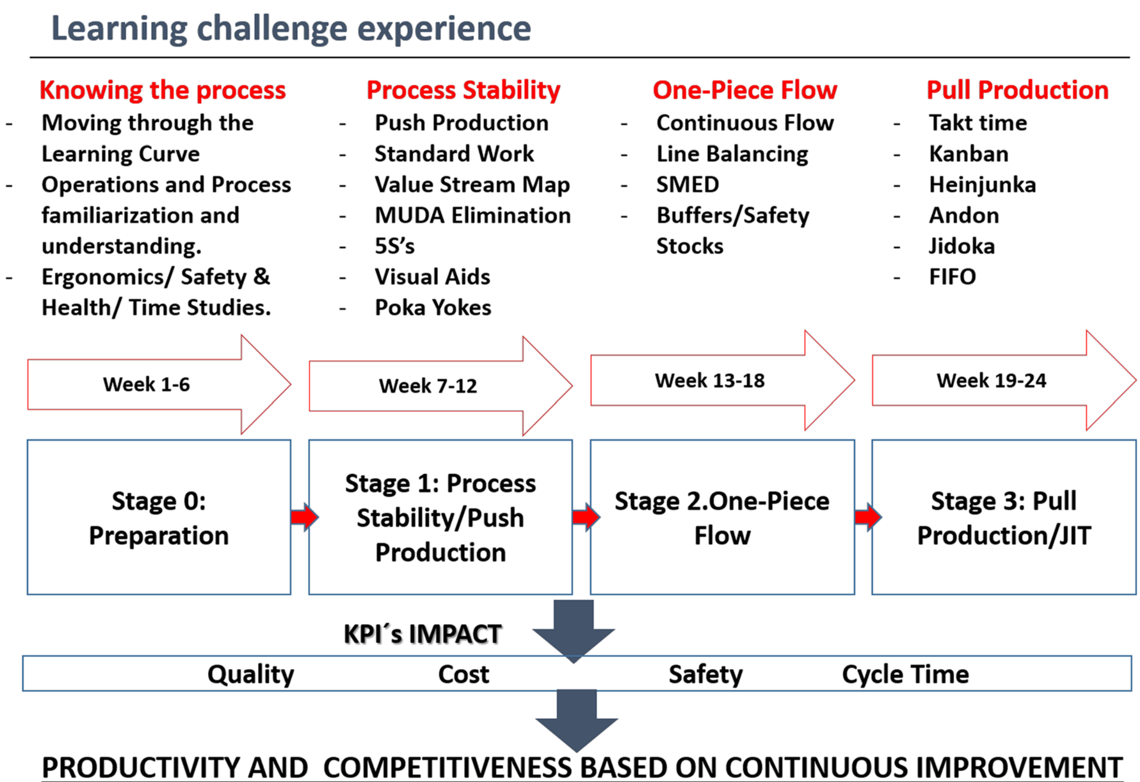

Fig. 4 Lean Thinking Learning Space stages and the implementation of the Lean Manufacturing techniques

Students play roles in the product manufacturing operation and in the implementation of lean manufacturing tools. The roles for the manufacturing operation are: (a) Operators at each of the workstations. (b) Supervisor or process leader focused on the development of culture, motivation, operational efficiency and production flow; but, also, in charge of the cross-training of operators, noting achievements and measurement of KPIs. (c) Industrial engineering manager, aware of standardized work, ergonomics, safety and health, and time and movements. (d) Logistics and supply chain engineer in charge of inventory, design of the layout and optimal management of materials, contact with the clients and relationships with suppliers.

The roles for the implementation of lean manufacturing production are: (a) Lean Six-Sigma leader in charge of SQC/Six Sigma/Kaizen/A3/Yamazumi/Takt time/line balancing/VSM; (b) Leader for Pull System implementation and in charge of the Heijunka and process stability; (c) Leader for 5S and Visual Factory implementation; (d) Poka-yokes designer throughout the system; (e) TPM and SMED supervisor; and (f) Implementation officer for Jidoka/Andon OEE.

These roles are not defined as formal and strict positions. The objective is that students get involved where they consider necessary, supporting and contributing to the whole system through cross-trained functions, but always first fulfilling the roles assigned to them. This means that they reflect, make conscious decisions and generate actions from what they consider to be their position within the challenge.

Moreover, although students assume very specific roles, this is not a limitation in the development of competencies of all the participating students, because the experience is in a group, and the roles are changed through cross-training. In addition, the groups share reflections at the beginning or end of each session about what is experienced. In Appendix 2, some images of project roles are shown.

Due to the multidisciplinary work generated through the different roles that each student must take, the relationships of the students as individuals, in groups with other students and with students in the world grow and mature throughout the whole experience. Whenever students encounter a sub-challenge, typical of the phase or the implementation of tools, they must take the initiative, decide and be responsible for the results. Therefore, students are creative throughout the experience, and they participate actively in the posing of the questions and the solution of the problems that arise.

In each of the phases described, students develop activities and make decisions about production problems in line with their roles in the manufacturing process. In each session of experiential learning, students must generate a log of the problems faced, the results obtained during the implementation of improvement tools and process optimization, as well as the disciplinary learning that the experiences have

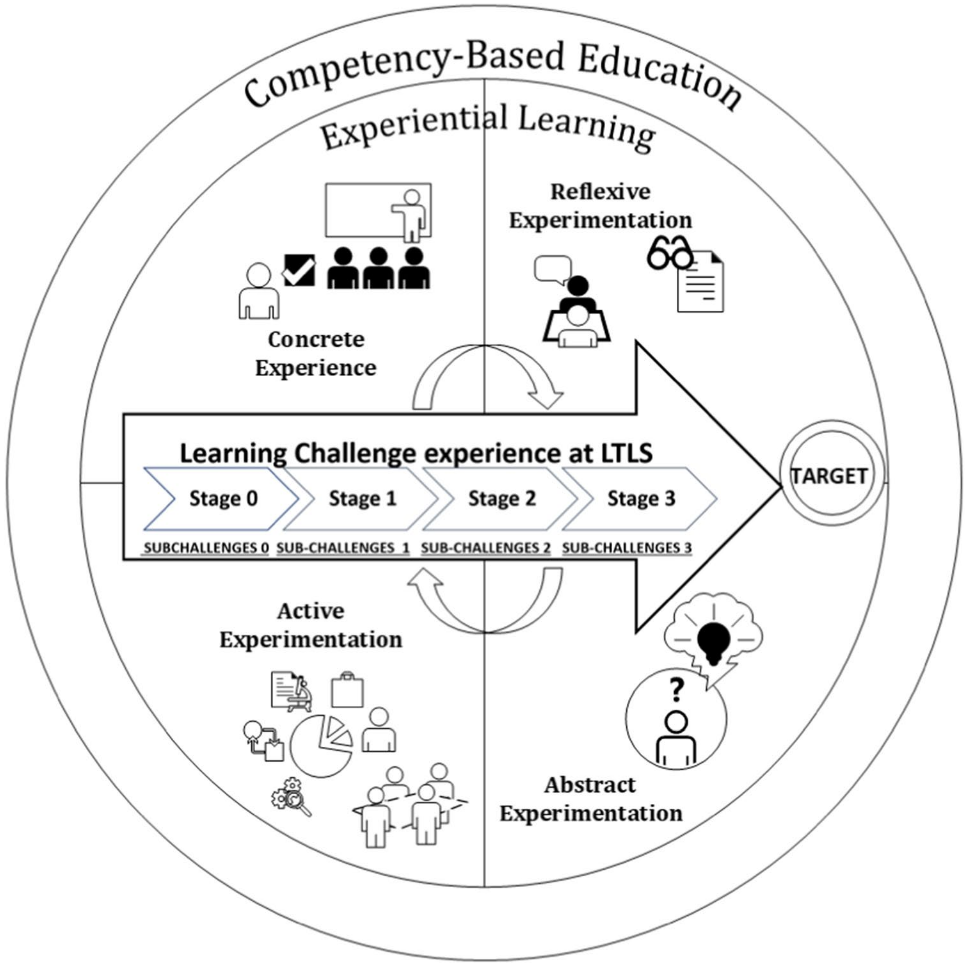

Fig. 5 Teaching model of the Lean-Thinking-Learning Space (LTLS)

generated. At the end of each phase, students must submit an individual portfolio of evidence that includes the consolidation of the logbook information with the description of the challenges faced; the solutions achieved by the implementation of disciplinary tools; a critical reflection-analysis and synthesis of all that has been experienced; and a conclusion about future aspects to be implemented and developed. Through these deliverables, it is remarkable how much the student gets involved intellectually, creatively, emotionally, socially and physically.

During the time spent in this learning model, both the instructor and the students experience success, failure, uncertainty and risk taking, because the results of the experience are not predictable. The role of the professor is fundamental in the LTLS, specifically, playing the roles of: (a) designer of the challenge, according to the requirements demanded by the body with which he has been linked; (b) challenge coordinator, who defines the metrics under which students will be working (product characteristics, restriction of manufacturing times and machines, etc.); (c) mentor, who is the knowledge facilitator in the implementation of process improvement tools; and, (d) evaluator of the competencies, who also creates assessment instruments, such as rubrics and observation lists, which are used by the academic faculty who support the competency evaluation.

Without leaving aside those moments that occur naturally in an experiential learning space, the instructor has to recognize and promote spontaneous learning opportunities that may impact favourably on the development of other competencies that were not declared. This situation could impact the professional training of students in terms of resilience, intellectual curiosity, critical thinking, problem solving and leadership, among others.

A systemic view of this instructional model is observed in Fig. 5, which illustrates the four phases of Kolb's experiential learning (1984) [46]; namely, concrete, reflexive, abstract and active. This model synergistically integrates a four-stage progressive scenario of learning experiences within the LTLS, involving an incremental problem-solving resolution of a main learning challenge and secondary sub-challenges, all focused on the development of competencies. The learning challenge goes from Stage 0 (Preparation), Stage 1 (Stability), Stage 2 (Continuous Flow) and Stage 3 (Pull-JIT) within the framework of the four quadrants of

Experiential Learning, immersed in a Competency-Based Education.

The learning model presented in this paper has as its ultimate goal to develop the competency declared by ABET, “The ability to design a system, component or process to meet the desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability and sustainability.” [47] As described previously in the literature review section, other spaces generate isolated practices. In this case, the methodology within the LTLS is cumulative, incremental and directed to the development of competencies. Students obtain feedback through the assessment instruments and peer-evaluation reports.

4 A modern and interactive approach to learning engineering

The challenges mention on the introduction section showed an urgent vision to teach in higher education interactive methods to design products and manufacturing production processes. The main focus aspects are to create disruptive learning spaces where the students could experiment and interact with people, tools, machines, to promote new innovations referring to Industry 4.0 devices, enablers and features.

The creation of form for the behavior of products, services, environments, and systems only could be realized through different approach to deliver a knowledge. Only presenting to the undergraduates’ engineers, challenges based on the brand-new and ongoing technologies to fusion of product design, computer science, and communication design could be emerged in them such abilities, and competences to solve specific problems under a specific set of contextual circumstances.

The learning space proposed in this research work has an interactive approach to learning engineering and to teach new interactive methodologies to reduce the limitations of communication through and with technology during a continuous run production process.

The LTLS connect the entire team through specialized software programs to deliver Jidoka, Andon and Kanban systems to obtain a pull-system manufacturing and gives purpose to the Interaction Design of a product and a process through meaningful experiences, providing interactivity through a focus on the capabilities and constraints of human cognitive processing.

In the next section the results for the research methodology and results are described.

Table 2 Descriptive Statistics for the students’ competence level experiment

Type of learning space	Traditional classroom	Lean Thinking Learning Space
N	20	20
Mean	2.65	3.413
Standard deviation	0.792	0.558
Minimum	1.5	2.5
Q1	2.063	3
Median	2.5	3.25
Q3	3.5	4
Maximum	3.75	4
Range	2.25	1.5
Mode	2.25, 3.5	3, 4

5 Methodology and experimentation

The validation of this conceptual model was carried out through the sampling of 40 students. Experimentation was implemented comparing two groups of students from the Industrial Engineering Design Lab and the Operational Optimization course. One group of twenty students, the control group, took the course in a classroom following a traditional learning method (the lab practices were isolated from the topics covered). The second group of twenty students, referred to as the experimental group, took the course using the LTLS model of this research.

The objective of the study was to verify a possible significant difference in learning outcomes between those taking the course with traditional teaching methodologies and those within the LTLS by observing and evaluating the attitudes, skills and values developed under the LTLS-defined competencies. The competency evaluation was developed by the academic faculty, who performed the assessment using a rubric and an observation checklist. The response variable of the experiment was measured through a four- level scale, where 4 was established as the highest achieving value.

The evaluation was carried out by the academic instructors through the Platform System for the Administration of Programs Evaluations (SAEP in Spanish) [48]. This system has been working since 2010 to evaluate competencies in selected courses of the academic programs.

The initial study of the sample data was carried out by conducting an analysis of descriptive statistics using the specialized software. As shown in Table 2, significant characteristics can be observed in the development of competency in the group within the LTLS. Principally, this is shown in terms of a mean much closer to the highest level of the competency, a standard deviation and a smaller range, as well as a mode or repetition of the evaluations level much closer to

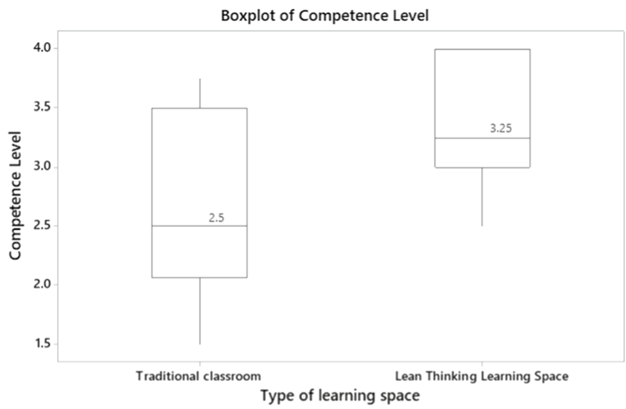

Fig. 6 Boxplot for two different learning spaces

the ideal state of the observation of the competency. Other relevant data were the values of the median, shown in the boxplot of Fig. 6.

Subsequently, a Design of Experiments (DOE) [49] was carried out to validate a significant effect upon the level of development of competency in a traditional space by means of a 2^2 Factorial Design in relation to the level of attainment in the development of competency as a variable of response. It is worth mentioning that those two groups of students had two different instructors. Therefore, an experimental matrix of factors is defined with their corresponding levels:

As mentioned, Table 3 shows the factors of the experimental matrix, where it can be identified that the experiment considered two instructors involved (Instructor 1, Instructor 2) in two types of learning spaces (traditional classroom and LTLS), leading to the planning of the starting hypotheses that are presented below.

Table 4 shows the hypotheses to test as follows: "The instructors, the spaces and/or the combination of both may, or may not, generate a significant effect on the development of competency." The response variable is the evaluation carried out with the measurement instruments of competencies used during the observations and assessments performed during the course. The validated information was collected via the SAEP System.

6 Results and discussion

Figure 7 shows the Design of Experiments (DOE) results, with a level of significance of 0.05 related to fail to reject the null hypothesis for the instructor variable as well as for the interaction between the instructor and the learning space. This means that neither the instructor nor the interaction between the instructor and the learning space had a significant effect on the level of the competency achieved by students. On the other hand, it can be observed the analysis rejected the null hypothesis for the factor "type of learning space," which means that there is significant statistical evidence that the type of space in which the students take the course, either in a traditional classroom or in the LTLS, has a significant effect on the competence assessment level.

It is worth mentioning that the Normal Plot of the Standardized Effects (Fig. 7) shows the B factor (type of learning space) on the positive side of the X axis, which means that the effect that this factor has on the competency level achieved by students is positive; that is, as we move from a traditional classroom to an LTLS, this significantly increases the level of achievement in the student's competency assessment results.

In Fig. 8, we can see the Interval plot for the assessment level of competencies. We can graphically observe the sample means, and the confidence intervals for the population means of both learning spaces. Therefore, with a confidence level of 95%, it can be affirmed that the average population level of competency evaluated in a traditional classroom falls between 2.28 and 3.02, and within the LTLS it falls between 3.15 and 3.67.

This inferential statistical analysis validates the assumption described in question number 2, declared at the beginning of this research work: *Could the teaching of improvement and process optimization centered around a learning challenge within a flexible and experiential space contribute to the development in future engineering graduates the abilities that are highly demanded in industry, as defined by student outcomes "c" declared by ABET?*

Table 3 Design of experimental factors

Experimental factors	Control group	Experimental group
A: instructor	Instructor 1	Instructor 2
B: type of learning space	Traditional classroom	Lean Thinking Learning Space

Table 4 Design of experiments hypothesis

Variable	Null hypothesis	Alternative hypothesis
Factor A: instructor	H0: Effect A = 0 VS	H1: Effect A ≠ 0
Factor B: learning spaces	H0: Effect B = 0 VS	H1: Effect B ≠ 0
Double interaction factor AB	H0: Effect AB = 0 VS	H1:Effect AB ≠ 0

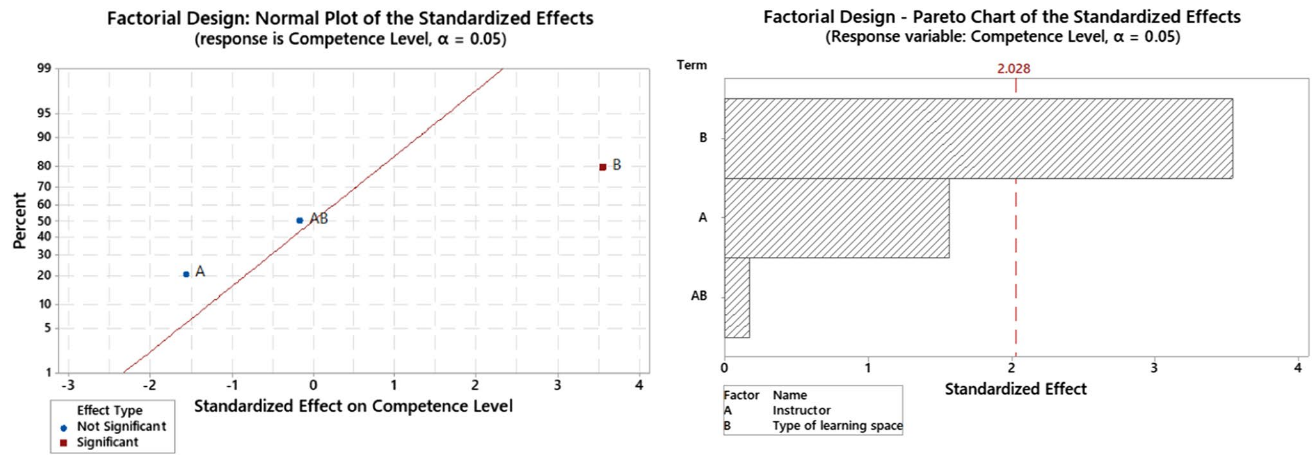

Fig. 7 Normal plot and pareto chart of the standardized effects in a factorial design

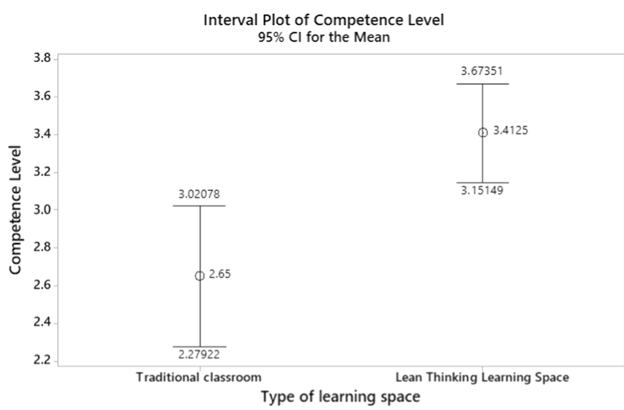

Fig. 8 Mean interval plot for competencies

7 Conclusions and future work

The conclusions on this project are favourable, and the results open the door to future research that continues with the design and experimentation with LTLS as educational innovation.

This work proposes a learning space notion beyond the traditional conceptualization of a physical lab or workshop. This is about a learning space incorporating experiential learning and challenge-based education for the development of disciplinary and personal competencies relevant for real-world problem solving and producing a social impact.

The LTLS provides a learning space for higher education with an interactive approach in teaching engineering in terms of teaching disciplinary content and developing disciplinary and personal competencies, like those declared by ABET. The LTLS also creates dynamic interactions among students and learning experiences relevant to professional practice and their future professional careers. One impact is that students recognize relevance in their studies and their universities. The LTLS also carries academics beyond textbooks and theories to seek new applications that have new impacts on society from the teachings learned and the competencies that students achieve in their disciplines.

The LTLS is the result of a collaboration through which students and academics progressively evolve and improve the learning space, either by identifying new possibilities for learning activities or by incorporating new teaching strategies and methods, resources and problem solving. The LTLS has evolved to incorporate new operations, production roles, manufactured products, activities and competencies, among others. Moreover, the collaboration among academic faculty over time has allowed replications that can extend operations from one to five campuses. However, just one campus is part of the LTLS research agenda, so far.

Difficulties can be found in terms of operating the LTLS, because it involves a live and dynamic learning experience in which multiple behaviours come into play under the demands of a learning challenge. Therefore, the LTLS involves not only the academic operation of the learning activities within a learning challenge according to educational objectives but also the dynamic interaction of students and teachers inside and outside the LTLS. The latter frequently requires aligning behaviours and making students maintain the safe and smooth operation of the learning space. This is not considered as part of the model nor the presented method; however, instructors should be aware of the conflicts and possible emotions people have when a learning challenge is executed.

With regards to the quantification of the impact results of the LTLS, favourable findings are summarized with respect to descriptive and inferential statistical analysis; as well as DOE through the 2^k factorial analysis, because significant evidence of effect between the learning space factor and the developed competencies was validated. Another relevant aspect is having found significant differences between the traditional classroom and the LTLS, insofar as the increasing of the level of competencies observed within the LTLS was 29%.

It is important to mention that during the experimentation of this LTLS teaching model, competency evaluations and constant feedback were carried out, in addition to the fact that the challenge undertaken by the students was of a higher demand compared to traditional learning; that is, the students were more creative, more involved and motivated in their own learning, developing experiences through the search for solutions and their implementation in the day-to-day production.

This study has been an important research work to verify the relevance of experiential learning spaces with challenged-based learning to build the appropriate setting for competencies development (CBE) and positively impacting how the student becomes involved intellectually, creatively, emotionally, socially and physically. In the same way, the results of the experimentation reveal areas for continuous improvement for future experimentation, such as maintaining standardization in the teaching model and enhancing the observation and feedback tools with which to assess competencies.

It is suggested that there be future study of other variables, such as the perception of the instructor or facilitator, as well as the relevance in the education of the students, with the aim of investigating beyond metacognition; i.e., the consciousness of the "being" [39].

Further work to increase the value and possibilities of the LTLS have been already considered. One of them is to continue measuring and evaluating competencies in the existing terms, as mentioned before, but identifying and refining the evaluation methods and their deployment over new learning-challenge situations within the LTLS. This is about working on the measurement instruments and the statistical analysis methods to improve the evaluations and continue validating the impact and usefulness of the LTLS. Another possibility is about incorporating new operations, processes and technologies into the LTLS to meet current industrial requirements in production processes to incorporate Industry 4.0 and the digital transformation of business models and operations. Despite that LTLS invokes a radical change in teaching/learning, this might be a next step to keep up with advancements in the discipline and the professional requirements for engineering graduates. Moreover, further work is required to extend and replicate the LTLS model to other campuses and institutions, not only to contribute to competency development in students but also to make an impact on the quality of higher education and on society and communities with this research work.

Therefore, a research agenda must be implemented and shared with other academic disciplines and institutions to implement this learning space in different contexts and circumstances. The goal would be to discover the types of learning challenges and competencies to develop not only in different industries but also in society in general where there would be wider impacts with different products and services. Another possibility involves extending the requirements of the lab to incorporate current notions of sustainability and to consider new possibilities for ecological impact, human well-being, innovation and value creation, among others.

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Appendices

Appendix 1: competence assessment instrument

Observation instrument	
ABET disciplinary competence to observe [47]	The ability to design a system, component or process to meet the desired needs within realistic limitations such as economic, environmental, social, ethical, health and safety, manufacturing and sustainability
Course name	IN3038 Design Lab and Operational Optimization
Observer Professor name	
Questions and characteristics to observe;	
1. Does the student distinguish susceptible situations to improve in a product, service, process or system design?	
2. Does the student identify the critical variables of one or more problems?	
3. Does the student propose and evaluate different solution options through lean manufacturing tools? Does the student implement solutions and apply tools for the improvement and optimization of processes?	
4. Does the student analyse, integrate and reorganize the technical results?	
5. Does the student reflect on the results of sustainable impact obtained?	

Competence assessment rubric

Guidelines Assess each of the students in the four criteria, identifying their competence level, based on each level description. Level number four is the highest competency evaluation.

Criteria	A. Analysis of the situation
Level	Description
1.	Does not identify the nature of the situation that is presented and does not follow a root cause analysis methodology
2.	Incorrectly identifies the situation. Does not follow correctly any methodology to try to begin to address the problem
3.	Correctly identifies the nature of the situation with some of its variables and restrictions: economic, environmental, social, political and ethical; and follows a methodology to begin to address the problem
4.	Correctly identifies the nature of the situation with each one of its variables and restrictions: economic, environmental, social, political and ethical. Correctly follows the right methodology for the root cause analysis and perfectly delimits the actions to begin to address the problem and the effects it has on the system that it is part of

Criteria	B. Problem identification
Level	Description
1.	Cannot identify the problem within the presented situation
2.	Needs help to correctly identify the problem, although tries to follow a methodology to address the problem
3.	Correctly identifies the problem, presents a methodology to address it, but needs help to identify the impact of the solution on the system
4.	Correctly identifies the problem, follows the right methodology to arrive at the solution of the problem and perfectly identifies the impact that this solution will have

Criteria	C. Solution and analysis of results
Level	Description
1.	Does not reach any solution for the presented problem
2.	Reaches a solution but needs help to interpret results
3.	Reaches a solution and performs an analysis of the results. Integrates some of their knowledge and experience on issues of manufacturing, safety and hygiene and sustainability
4.	Evaluates different solutions, and options and arrives at one or more optimal solutions; performs a detailed analysis of results, integrating knowledge and experience on topics of manufacturing, safety and hygiene and sustainability

Criteria	D. Use of engineering techniques and tools to solve problems
Level	Description
1.	Knows a few techniques and tools. Does not consider their impact, nor documents in the right way how to address, analyse and solve the problem
2.	Knows some techniques and tools but needs help to select and apply the appropriate one
3.	Knows and correctly applies some techniques and/or tools for analysis and problem solving
4.	Knows, masters and applies the techniques and tools correctly to analyse and solve a problem. Also makes a comparative analysis of each technique and/or tool

Appendix 2: Images of the stations and the role playing development in the Lean Thinking Learning Space

Lean-Thinking-Learning-Space Shop Floor.


Station 1: Product design.


Station 2: Cutting with circular saw.

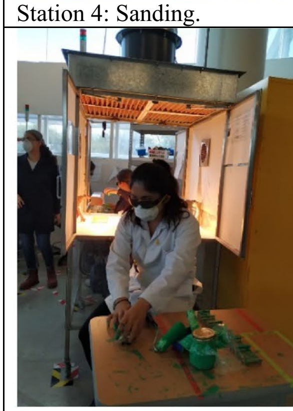

Station 2: Cutting with jigsaw.


Station 2: Band saw.

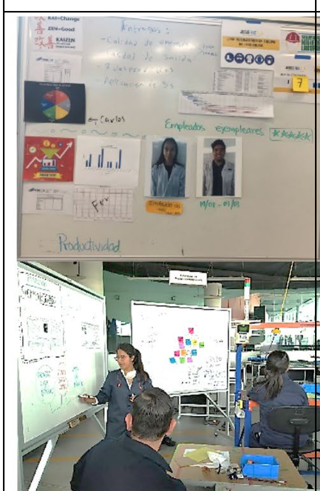

Station 3: Drilling.


Station 4: Sanding.


Station 6 & 7: Assembly.


Station 8: Painting.


Station 9: Inspection and packaging.


Continues improvement boards.


Raw materials warehouse.

Appendix 3: Web site, Facebook Group and YouTube videos

Web site page: http://dev.pue.itesm.mx/leanthinking/.

Facebook Group: https://www.facebook.com/groups/LabLean/.

Lean Thinking Learning Space YouTube videos:

1. https://youtu.be/3fDT5Bab0FI.
2. https://www.youtube.com/watch?v=M9n838H_tyw.

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