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Article

Implementation of Environmental Engineering Clinics: A Proposal for an Active Learning Methodology for Undergraduate Students

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Abstract: Quality education focused on quality, inclusion, and opportunity is one of the United Nations Sustainable Development Goals to reduce inequality in the knowledge of the people who are educated. In this sense, universities have a role in rethinking the teaching model, changing their strategies, and including new experiences based on active learning. This article makes a didactic methodological proposal for undergraduate and graduate students using learning experiences for solving regional environmental problems proposed by municipalities. This method considered creating an agreement, defining topics, preparing bases and study areas, analyzing problem solutions, and delivering products. The results showed the implementation of the environmental engineering clinics (ECCs) in five subjects of the curriculum, with the participation of sixty students, who solved problems from seven municipalities. The results showed a correct implementation of the active learning methodology, allowing for knowledge to be transferred in a real-life scenario, significantly facilitating student learning. The plan–do–check–act (PDCA) cycle provides a practical framework for learning while solving real-world challenges, empowering learners to personally engage with authentic and meaningful challenges within their communities. As was previously stated, this article presents a methodology that can be introduced in universities to improve the learning process through active learning and the link with real problems of the territories where they are located, which also allows for improving the connection with the environment, contributing significantly to the sustainability of the territories.

Keywords: engineering education; empirical learning; environmental engineering; Chile

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1. Introduction

The Sustainable Development Goals (SDGs) established goal 4 to provide "quality education", considering quality and inclusion as the main focuses, and must be accompanied by different opportunities for better learning [1]. In this sense, the fulfillment of goal 4 makes it possible to reduce the gap in the knowledge of the people who are educated, and this contributes, in the long term, to the realization of the other goals [2].

Sustainability must be understood as a balance between social, economic, and environmental factors. For this, it is necessary to teach students engineering and forms of relationship and practical experiences. This has implied a rethinking of the teaching model, which, until then, was based on teacher-based teaching, transferring this new approach into an active learning model based on strategies that focus learning on the student, not turning the system around the teacher, but rather a function of the activities carried out by the student to achieve their learning objectives [3]. The implementation of an active learning program has been recommended by professional European engineering associations and the UNESCO Active Learning in Engineering Education network, among others [4,5].

The change in roles between students and teachers must be reflected in teaching planning [3]. Likewise, there is evidence that case problem analyses and resolution methodologies in groups with few students favor learning [6]. In this sense, it is a priority to rethink the traditional teaching model, migrating from teaching centered on the teacher to one centered on the student, considering that teaching practices are decisive in student learning [3,7]. This is a complex process, since it requires modifying the study plans and, in general, introducing methodological innovations in a traditional teaching model, in addition to the active and deep participation of the students in developing the activities. Focusing the learning process on the student implies a teaching effort since it requires being the conductor of the orchestra, that is, directing, but not conducting, but instead teaching how to learn by performing [8].

On the other hand, engineering students who are essential for meeting this SDG [9] go from being passive recipients of knowledge or information to active participants in the learning process, sharing, reflecting, and deciding the best strategy to address the problem guided by their teacher [8]. Active learning considers several active methodologies: analysis and problem-based learning, team learning, and flipped classrooms [6,10–12]. Problem-based studies are undoubtedly one of the most relevant strategies, given the integration of theoretical knowledge, its applicability to real situations, and its integration [10,13]. In this sense, it is necessary to consider that students improve their learning process by actively participating in the experience, creating everyday situations in real-life activities [14,15].

In this sense, Vygotsky's theory focused on social development becoming relevant, which states that social interactions are essential to people's cognitive development and learning. Figure 1 shows the main aspects of the sociocultural theory of Vygotsky [16,17] that has been oriented to the teaching role to maximize learning effectiveness.

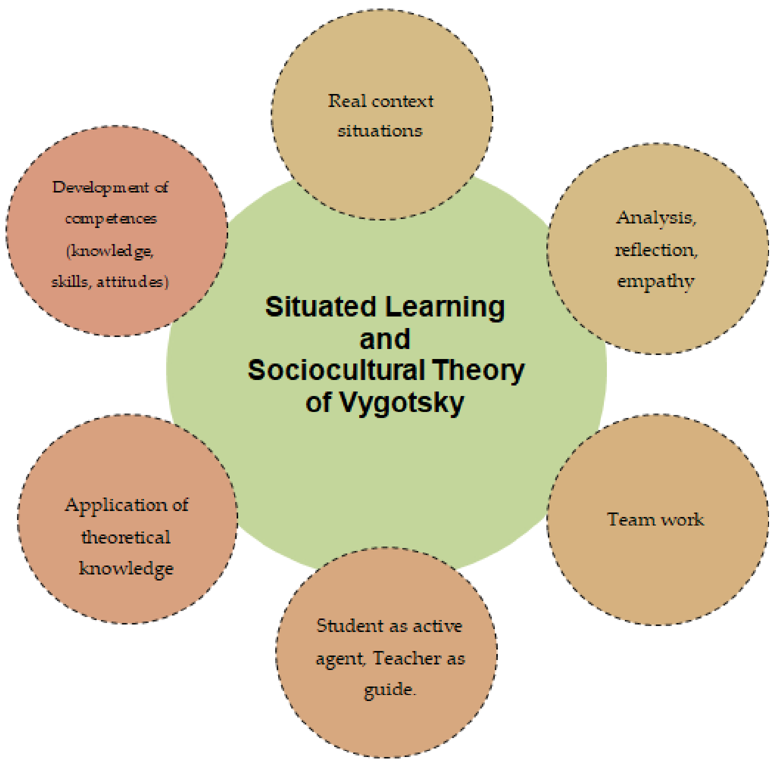

Figure 1. Conceptual or theoretical scope of the innovation experience based from Vygotsky's theory [16,17].

In Vygotsky's theory [16], the realization of activities focused on sociocultural aspects can improve the skills of the students and even their cognitive development. For the implementation of this theory, the role of the teacher is essential, since this teaching-learning methodology seeks to generate solutions, generating significant learning while searching for alternative solutions. On the other hand, the teacher has a vital role since they must stimulate the critical thinking of the group and permanently guide it [18].

In the global context, the environmental engineering clinics (ECCs) arose from the need to solve environmental problems for which there were no economic or human resources in the municipalities to be able to solve them. Considering the above, the ECC has emerged as a methodology that allows for students of the environmental civil engineering degree to be linked early with the environmental problems of the region, that is, problems that they will encounter when they enter the world of work. The main structure of the ECC is focused on the student (student centered). The continuous improvement of community problems is based on plan–do–check–act (PDCA) cycles supported by standard work concepts. Every cycle is planned and executed, and then the results are verified with the commune user, and decisions on the next cycle are taken [19,20]. Environmental civil engineers have a fundamental role in promoting sustainability based on their acquired knowledge and convictions. The ECCs contribute significantly to sustainability, as they consider the three basic elements of sustainability and were conceived to search for environmental solutions that are related to social demands in contexts where economic resources do not exist to address the environmental problems that are identified in the territories.

This article provides a didactic methodological proposal to promote the professional training of undergraduate and postgraduate students through situated learning experiences through the resolution of regional problems on environmental issues. Thus, it has been possible to deliver tools and information to the municipalities of the Araucanía region that facilitate their local environmental management through the action developed by the students through the ECCs.

This model includes a manual of procedures based on the application of situated and experiential teaching, facilitating active learning focused on meaningful experiences. In this way, students have been linked from the first to the last year with real problems, which allows for them to develop their talents, put them into practice, and install social responsibility with activities of this sort. Empathy is the crucial factor that enables this methodological approach to be successful, since it provides the necessary approach to real problems from the users to the student teams to search, study, formulate, and create solutions.

2. Methodology

2.1. Agreement Creation

First, an agreement was signed between the Universidad de La Frontera (UFRO) and the Ministerio del Medio Ambiente (MMA), which provided the formal basis for establishing a relationship of coordination and collaboration between these counterparts, designating professionals as facilitators that were responsible for the development of activities around the resolution of regional problems in environmental matters, with a particular emphasis on the municipalities of the Araucanía region, belonging to the Sistema de Certificación Ambiental Municipal (SCAM) [21]. Chile is located in South America, has 17.5 million inhabitants, and a length of 4,200 km of continental territory. The Araucanía region is located in the South of the country and has 32 municipalities [22,23].

2.2. Participants and Definition of Subjects

At the beginning of each academic semester, a call was made to the different professors of the mandatory subjects of the Faculty of Engineering and Sciences to participate in the EECs. Once the issues were confirmed, the UFRO and the MMA analyzed and discussed the learning opportunities to be addressed that were inherent to the professional profile and consistent with the environmental problems of the municipalities in the Araucanía region [21]. Consequently, all students (participants) in the subjects that were selected had to essentially participate in the ECCs. The participants were aged between 17 and 23 years old and were students of environmental civil engineering between the 1st and 11th academic semesters.

2.3. Preparation of Bases and Study Areas

Then, the bases were prepared, and the following were established:

- Subjects available for case studies.
- Student competencies categorized by level and learning outcomes.
- Essential and mandatory requirements for municipalities, e.g., attendance at meetings, provision of data for studies, etc.
- Obligations of the university, e.g., analyze the cases under a PhD-holding individual's supervision and deliver a final report with the results to the municipality.
- Selection criteria for selecting the cases: clarity of the requirements (15%), technical relevance (25%), consistency of the request with the environmental strategy of the city (30%), coherence of the request with the regional problem (10%), and contribution from the municipal counterpart (20%).
- Members of the selection committee: A representative from the UFRO and another from the MMA are appointed. The selection committee reviews the applications and their correspondence with the requirements established in the bases and based on the score obtained, the case studies are selected. Then, an adjudication document is prepared and sent to all the applicant municipalities.
- Deadline for applications: the application deadlines are established, an application form is delivered, and the e-mail to which the application should be sent is indicated.

Then, when the bases were completed, they were formally sent by the MMA to the municipalities of the Araucanía region attached to the SCAM.

2.4. Problem Solutions and Product Deliveries

Once the cases under study were awarded, a meeting (in person or online) was coordinated between the teacher and students of the subject and the municipal counterpart indicated in the application form. During this meeting, detailed information on the problem was delivered, and subsequent instances were coordinated to review the joint progress of the case under study between the parties [21].

The teaching strategies of the subjects linked to this project were based on situated and experiential teaching, facilitating active learning focused on meaningful and motivating experiences (authentic), and promoting critical thinking and awareness.

The intermediate results of this process were presented internally in instances according to the subjects involved, and the final presentation was made in some cases in the respective municipalities and at the closing ceremony of the EEC, one week before the end of the academic semester. A public presentation of the results was carried out, and a document with these results was delivered to the person in charge of the municipality. In this presentation, two members of each subject made a brief technical presentation of the results of the problem addressed in the EEC.

During this stage, the selection committee follows up by organizing at least three meetings (throughout the semester) with the academics responsible for the subjects to monitor the progress of the activities of the requirements received in the EEC, guaranteeing the product's delivery during the closing ceremony.

Figure 2 summarizes the stages of this process from the preparation of the bases to the delivery of the product.

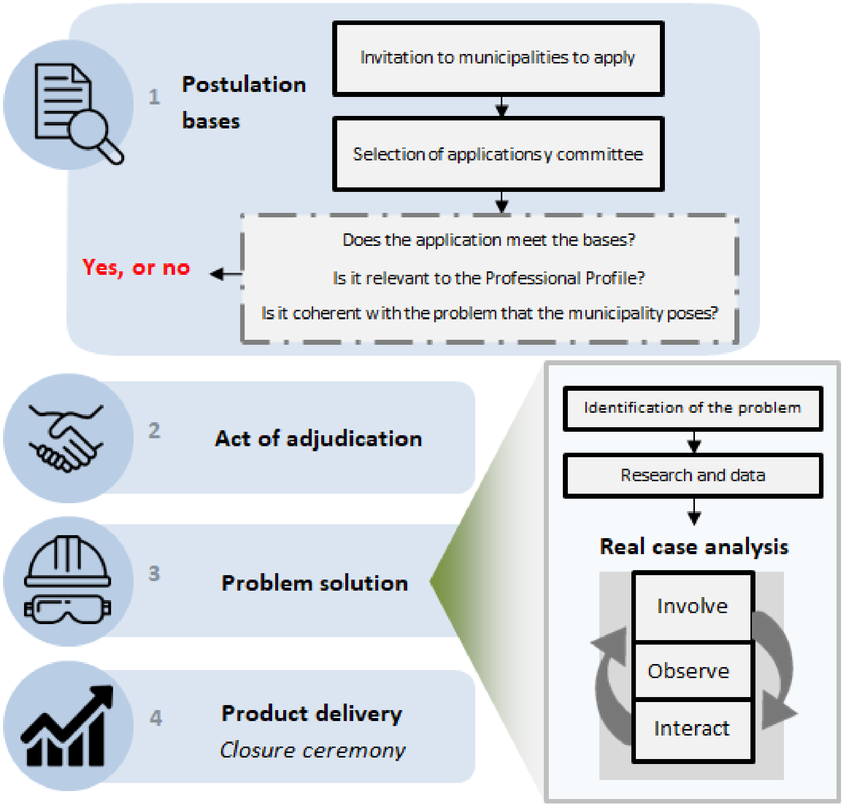

Figure 2. Stages of the process.

3. Results

3.1. Definition of Subjects

In the meeting that was called with all the teachers of the different subjects of the Faculty of Engineering and Sciences, the options for implementing the ECC in the academic semester were analyzed. This analysis considered the learning objectives of the subject, the possibility of incorporating practical experiences, and the teacher's interest in innovating through the ECC. The implementation of the ECC agreed upon jointly with the teachers is shown in Table 1.

Table 1. Subjects that were selected to implement ECCs during a semester.

N°	Subject	Semester	Number of Enrolled Students
1	Environmental analytical chemistry	7th	5
2	Wastewater engineering	8th	14
3	Industrial processes	3rd	11
4	Solid waste engineering	9th	16
5	Engineering project	11th	14

All of the above subjects belong to university studies on environmental civil engineering and are taught by professors with a PhD. The selected subjects are mandatory and are located between the 3rd and 11th semesters, and the number of students fluctuates between five and sixteen. It should be noted that environmental civil engineering has a duration of 12 academic semesters, and all students enrolled in the subjects must participate by solving the selected problem.

3.2. Applicant Municipalities

Thirty-two municipalities in the Araucanía region were invited to participate in the ECC. In the call, the requirements and selection criteria established for the selection were announced. The following table (Table 2) shows the selected municipalities and associated subjects, all being municipalities of the Araucanía region.

Table 2. Municipalities that were selected and problems or needs raised.

ID Municipality	Characteristics	Population (Inhabitants) [22]	Problem or Need Raised	Subject
A	Located in a mountainous zone	10,251	Sampling and physical–chemical characterization of the San Pedro and Jara lagoons	Environmental analytical chemistry
B	Located in the central valley	34,182	Sampling and physical–chemical characterization of the Traiguén river	
C	Located in the central valley	6905	Sampling and physical–chemical and biological characterization of the wastewater treatment plant and Perquenco estuary.	
D	Situated in a coastal zone	12,450	Sampling and physical–chemical characterization of the “May 21 estuary”	
E	Located in a central valley municipality	38,013	Diagnosis and recommendations to improve the operation of the Lautaro fish farm.	Wastewater engineering
D	Situated in a coastal area	12,450	Analysis of alternatives for wastewater treatment in rural areas.	
D	Situated in a coastal area	12,450	Training in sustainable entrepreneurship	Industrial processes
F	Situated in a coastal area	32,510	Analysis of alternatives for the treatment of city waste	Solid waste engineering
G	Located in a north zone	7733	Design of a composting plant for the city of Ercilla	Engineering project

In this first version of the ECC, three applications from municipalities were rejected, mainly because the requests were not related to the learning objectives of the subjects, the problem was not well identified, and/or the expected result was not specified. In general, there was great interest on the part of the municipalities in applying.

3.3. Products Obtained by Subject

At the global level, the students applied the plan–do–check–act (PDCA) cycle, which is a four-step model for carrying out changes. The PDCA cycle is considered a project planning tool for process improvement that focuses on continuous learning and knowledge creation and is undertaken as a cycle [24,25]. Figure 3 shows an approach with a “plan” step to meet the requirements of the municipalities to provide answers that adjust to their needs of real problems.

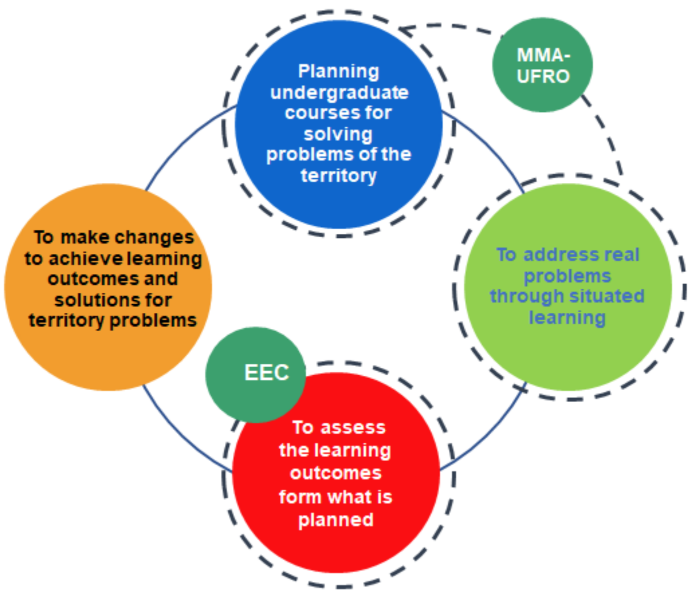

Figure 3. Continuous loop of planning, doing, checking, and acting.

The results that were obtained in each of the subjects are detailed below.

3.3.1. Environmental Analytical Chemistry

The five students, under the supervision of a teacher, took samples and characterized the water bodies of the four cities that requested them (Figure 4). The determination of water quality in lagoons, rivers, and estuaries was relevant for these municipalities; in fact, this was the topic of greatest demand. The results that were obtained are shown in Table 3. These results were compared with several parameters of the Chilean Standard (NCh) 1333, "Water quality requirements for different uses". This Chilean standard establishes that with a conductivity of less than 750 µS/cm, no harmful effects are observed for the irrigation of plants [26].

Figure 4. Sampling process in municipality 1.

Table 3. Laboratory results that were obtained.

Parameter	Unit	San Pedro Lagoon	Jara Lagoon	Traiguén River	Perquenco Estuary	May 21 Estuary
pH	-	6.4	6.9	6.3	6.67	7.0
Conductivity	µS/cm	148.1	70.4	53	78	507
Turbidity	NTU	3.2	13.0	19	6.55	28
Settleable solids	mL/Lh	<0.2	5	<0.2	0.2	<0.2
Total solids	mg/L	286	236	250	-	460
Total suspended solids	mg/L	158	160	114	3.8	198
Total phosphorus	mg/L	<0.5	1.38	<0.5	<0.5	-
Ammoniacal nitrogen	mg/L	<1	<1	<1	<1	<1
Total coliforms	NMP/100 mL	2.3×10^2	7.9×10^2	-	7.9×10^3	1.1×10^3
Fecal coliforms	NMP/100 mL	<2	70	-	2.3×10^3	1.1×10^5

In the same way, NCh 1333 showed that for recreation with direct contact, the pH must be in the range between 6.5 and 8.3, the turbidity must not exceed 50 NTU, and they must have a maximum of 1000 NMP/100 mL for fecal coliforms. The requirements of NCh 1333 also establish general conditions for waters intended for aquatic life, which indicates that the pH must be between 6.0 and 9.0, and the settleable solids must not exceed the natural value of waters designed for aquatic life. Therefore, the only parameters that exceeded the regulations were the fecal coliforms in Perquenco estuary and May 21 estuary, which indicate microbiological contamination in their waters.

3.3.2. Wastewater Engineering

In relation to the fish farm located in the central valley (municipality E), the students carried out field visits and meetings to collect information, in addition to a bibliographic review, from which they prepared a report that contains the characteristics of the production process, the main waste generated by the activity, a review of the existing information on flows, and physical–chemical and biological parameters. Based on the above points, they prepared proposals for improvements of the production process and the industrial waste treatment system.

In the case of the problem reported by municipality D, an analysis of the alternatives for the treatment of wastewater for rural areas was carried out. The above considered a report with a technical–economic proposal for the implementation of four alternatives for modular plants from various manufacturers of wastewater treatment systems.

3.3.3. Industrial Processes

Based on their interests, jobs, and activities expressed by the program members (including crafts, sewing, baking, and housework, among others), the students proposed creating three products using the most abundant solid waste in the community: plastic, glass, and used cooking oil. This initiative aimed to generate useful and/or decorative items with a high labor-added value, potentially serving as a source of income for the participants.

Residents of the coastal area were trained with recycling technique options via civil environmental engineering, such as making soap from domestic waste and reusing glass and plastics. Figure 5 shows images of the products obtained by the students.

Figure 5. Products obtained by the students and presented to the members of the social programs: (**A**) a vertical garden, (**B**) glass, (**C**) soap, and (**D**) a digital magazine.

The execution of this training activity forced the students to study the different waste management options, in addition to looking for elements that would allow them to carry out practical activities to get to know their citizens better. Furthermore, implicitly, the students had to face a real audience that questioned and discussed each of the activities that were carried out.

3.3.4. Solid Waste Engineering

The students projected the population and generation of waste, analyzed different waste management possibilities (recycling, composting and anaerobic plants, and inorganic material recovery plants), and determined the minimum technical and economic requirements. The product obtained was a technical report with waste management alternatives for the city. This product allows municipal authorities to carry out a conceptual analysis with the purpose of projecting and determining the feasibility of designing and executing a large-scale project, prioritizing the scarce resources available from the municipality for these purposes.

3.3.5. Engineering Project

A composting plant for solid organic waste was designed, and the operation method, location options, and regulatory requirements of the projects were considered. The designed composting plant makes it possible to identify the ideal method of operation, the minimum necessary equipment and machinery, the critical infrastructure, and the costs associated with investment, operation, and maintenance, thus allowing for the dimensioning of what it means to have a municipal composting plant.

At the end of the semester, a ceremony was organized to deliver the products to the municipalities, in which each of the students made a presentation regarding the work they carried out, and also received a participation certificate from the MMA.

4. Discussion

Good technical performance by students was obtained; students learned by creating meaning from real day-to-day activities. In fact, the collaboration between the university and the municipalities offers a real work scenario that allows students to visualize the scenarios of their future work, similar to what was pointed out by Zhang [27] in the relationship between universities and companies. In this sense, knowledge acquisition was obtained by transferring the classroom into practice by incorporating experiences in students, generating opportunities for actively acquiring learning in a real context. On the other hand, in studies carried out by other authors on engineering students, another advantage was pointed out, which was related to the fact that engineering students increased their environmental awareness by taking subjects with educational content [28].

Therefore, it is essential to situate learning that implies locating thoughts and actions in a specific place and time. Situating means engaging other students, the environment, and activities to create meaning, finding in a particular environment the thought and action processes used by experts to perform knowledge and skilled tasks [29] (Figure 6). In the classroom, in this experience, it was possible to situate learning by creating conditions for participants to experience the complexity and ambiguity of learning in the real world. This is how the students who participated learned from their experiences, highlighting the relationships with the other participants, along with the activities, environmental signals, and social organization the community develops. In this sense, it is essential that students are committed to their assigned task [30]. The ECC approach has been positively valued by students [27] since it allows them to relate early on to real scenarios. At the end of the activity, the students indicated that they felt better prepared to enter the world of work, since they faced real problems, had to find solutions, and satisfy clients (municipalities). In fact, when students face real problems, they have the opportunity to devise solutions collaboratively, expanding their skills of analysis, creation, and expression of their ideas and networking.

The ECC requires them to develop social skills, generic skills (teamwork and leadership), and the creativity to solve real problems through analysis, reflection, and trial and error, where errors are seen as opportunities for improvement that stimulate them to fulfill their purposes. They leave the role of the student, and it allows them to become aware of what they are training for. Motivating them to identify the root cause of different problems in order to influence people's well-being, it was extremely satisfying for them to see how the solutions generated by them influence people's quality of life and realizing this stimulated them to move forward with great motivation and commitment [31,32].

On the other hand, the municipalities have expressed their agreement with the results obtained, since it allows them to obtain information for decision making in environmental matters. From the other point of view, the ECCs allow for sustainability, since the collaboration of the university in solving socio-environmental problems is necessary, considering the degree of specialization of PhDs. In this sense, it is important to keep in mind that for the success of the ECC it is necessary to have teachers with a high degree of specialization, since students need to be constantly guided in the search for solutions to the problems posed.

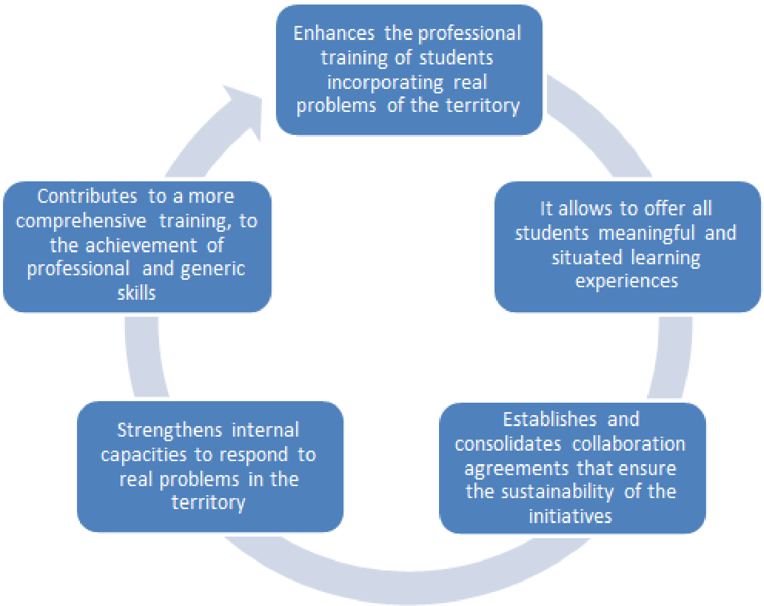

Figure 6. Situated learning essentially derives creative meaning from real problem solving.

From the point of view of managing the implementation of the ECC, it is important to consider that a person responsible for the UFRO and the MMA is permanently required for the implementation of the ECC; in addition, these professionals must have the technical capacity to analyze the various situations from a global perspective and also exercise leadership that allows symbiotically linking the university and the public institutions of the state.

At the conclusion of the first version of the ECC, there were requirements to incorporate other undergraduate courses from the Faculty of Engineering and Sciences to the ECC, which demonstrates the great interest in the execution of this practice; however, the ECCs were conceived to solve environmental problems, but this model is scalable to other types of problems. Considering that other undergraduate programs may have other learning objects, it is always possible to apply the methodology, changing the type of problems to be solved.

The ECCs have managed to position themselves among the students and municipalities of the region; this methodology gave rise to the licensing contract being signed in January 2022 between the Ministry of the Environment and the University of La Frontera. Thus, what started as an undergraduate activity has now become a protocol that protects itself; it has become a license for a technology transfer from the university to the environment, the most concrete way to transfer knowledge and technology.

It should be noted that this innovative educational experience also gave rise to the creation of the Node for Strengthening Local Environmental Governance (Spanish acronym "NOGAL") of the Ministry of the Environment of Chile. In this way, knowledge and technology will be transferred through a license. This experience has been licensed to other universities, such as the Catholic University of the North, Austral University of Chile, the

Puerto Montt branch, and six different universities, which demonstrates how innovative this methodology is and the advantages involved in implementing it with undergraduate students since it is active learning located in a real context that also collaborates in the solution of local and real problems, which do not have resources for solution management.

5. Conclusions

The results show that the correct implementation of the ECC active learning methodological proposal depends on a series of factors, such as the professional capacity of the designated counterparts from the MMA and the university, the adequacy of the teachers to employ the new method, and the ability to respond to the requirements of the municipalities.

After this first experience of implementing the ECC, new versions have been developed, all with a high percentage of subject participation, incorporating other new undergraduate studies, and a high demand for participation from municipalities, which demonstrates that this methodology has been consolidated in its application.

The subjects that presented the greatest number of requirements corresponded to environmental analytical chemistry and wastewater engineering, in the first case due to the need to know the baseline of water bodies and, in the second case, the search for solutions for the treatment of solid and liquid wastes, which generates great impacts on the environment.

The development of activities in a real context allowed for the classroom to be transferred into a different scenario, which allowed for active learning to be experienced, developing students' skills, and acquiring knowledge experientially, which will enable us to train professionals who meet the needs of our society [27].

The implementation of the ECC has been positively valued by students since it allows them to face a real scenario, identifying early on how they will perform at work in the future. From the point of view of active learning located in real contexts, this methodology allows students to face real problems, where there are clients that they must satisfy, and to do so, they must be able to diagnose, plan, learn, and evaluate. This is consistent with the growing interest on the part of international agencies in higher education institutions in developing technical skills but also soft skills in real-life scenarios [33].

The PDCA cycle methodology allowed us to guide the students' work to satisfy municipal requirements, such as rainwater harvesting systems, composting plant projects, biodiesel plant projects from domestic waste oil, and environmental education strategies.

The methodological framework that has been introduced in this study seeks to serve as a guide for the universities of the world, which aims to develop active learning in its students, considering real contexts and a real connection with society in the search for solutions to the environmental problems present in the territories.

The main limitation of the implementation of the ECC methodology is that it requires a permanent administrative structure at the university and in the MMA, to grant autonomy, in addition to financial resources to carry out a number of field and end-of-semester activities. In this sense, the possibility of incorporating the implementation of the ECC into the academic careers of teachers, in addition to the incorporation of other degrees into the ECC, arises as an opportunity for improvement with the aim of solving problems from a more general perspective. Both improvement proposals provide autonomy, scope, and a comprehensive approach in the search for solutions to environmental problems.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Application form.

<table>
<tr><th colspan="4">Application Form
Environmental Engineering Clinics</th></tr>
<tr><td colspan="4">1. General data</td></tr>
<tr><td colspan="2">Municipality</td><td colspan="2">SCAM level:</td></tr>
<tr><td colspan="2" rowspan="4">Designated counterparty</td><td colspan="2">Name</td></tr>
<tr><td colspan="2">Position:</td></tr>
<tr><td colspan="2">Telephone:</td></tr>
<tr><td colspan="2">Email:</td></tr>
<tr><td colspan="4">Date</td></tr>
<tr><td colspan="4">2. Requirement data (mark only 1 subject per requirement)</td></tr>
<tr><td rowspan="8"></td><td rowspan="4">Select the subjects</td><td>x</td><td>Subject 1</td></tr>
<tr><td></td><td>Subject 2</td></tr>
<tr><td></td><td>. . .. . ..</td></tr>
<tr><td></td><td>Subject N</td></tr>
<tr><td>Description of the problem</td><td colspan="2">Explain the problem in a maximum of 100 words.</td></tr>
<tr><td>Result expected by the municipality</td><td colspan="2">Explain in a maximum of 30 words the result that the municipality expects.</td></tr>
<tr><td>Contribution of the municipality</td><td colspan="2">Example: only incorporate pecuniary contributions.
By en.: the municipality will provide transportation for students from the UFRO to the water sampling point.</td></tr>
<tr><td>Does it agree with any line of the environmental strategy?</td><td>Yes
No</td><td>Which?</td></tr>
</table>

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