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Case studies

Design and implementation process of a pico-hydro power generation system for teaching and training

Proceso de diseño e implementación de un sistema de generación de energía pico-hidráulica para enseñanza y entrenamiento

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Abstract. - *In Mexico the development of remote laboratories is incipient, in 2020 the National Council of Humanities, Sciences, and Technologies (CONAHCYT) created a network of virtual laboratories with nine of its public research centers in order to create a virtual space that enables the development of experimental and research activities in a distance modality. However, access to virtual laboratories is limited only to its members, and the platforms are still under development. With this motivation, this article presents a multi-institutional project for the design, development, and implementation of a pico-hydraulic system for small-scale power generation for teaching and training purposes with the aim of responding to the current need for distance or virtual teaching of practical knowledge due to the coronavirus disease (COVID-19) caused by the SARS-CoV-2 virus. For the development of the system, technological innovation tools (QFD, TRIZ) were used, with which the design requirements were obtained considering the users (students and teachers) and the renewable energy-related competence of the curricula. Finally, the satisfaction of the users (students and teachers) with the use of the designed system shows the advantage of including it as part of the practical activities of the subjects to improve the development of power generation, transformation, and transmission system projects.*

Keywords: Applications of industry 4.0; Learning and training; Mechanical design; Pico-hydro systems.

Resumen. - *En México el desarrollo de laboratorios remotos es incipiente, en 2020 el Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCYT) creó una red de laboratorios virtuales con nueve de sus centros públicos de investigación con el fin de crear un espacio virtual que permita el desarrollo de actividades experimentales y de investigación en la modalidad a distancia. Sin embargo, el acceso a los laboratorios virtuales está limitado sólo a sus miembros y las plataformas aún están en desarrollo. Con esta motivación este artículo presenta un proyecto multi-institucional para el diseño, desarrollo e implementación de un sistema pico-hidráulico para la generación de energía a pequeña escala con fines de enseñanza y capacitación con el objetivo de responder a la necesidad actual de enseñanza a distancia o virtual de conocimientos prácticos debido a la enfermedad coronavirus (COVID-19) causada por el virus SARS-CoV-2. Para el desarrollo del sistema se utilizaron herramientas de innovación tecnológica (QFD, TRIZ), con las que se obtuvieron los requisitos de diseño teniendo en cuenta los usuarios (alumnos y profesores) y las competencias relacionadas con las energías renovables de los planes de estudio. Finalmente, la satisfacción de los usuarios (alumnos y profesores) sobre el uso del sistema diseñado muestra la ventaja de incluirlo como parte de las actividades prácticas de las asignaturas para mejorar el desarrollo de proyectos de sistemas de generación, transformación y transmisión de energía.*

Palabras clave: Aplicaciones de la industria 4.0; Aprendizaje y formación; Diseño mecánico; Sistemas pico-hidráulicos.

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1. Introduction

The sustainability education relationship has generated innovative approaches in education with respect to social responsibility, the reduction of environmental impact, the application of modern technology, and the use of renewable energies where the experiential study of real or modeled situations must be privileged in engineering education [1-5].

Energy production currently represents a social, economic, and environmental challenge. Although energy can be obtained from conventional or renewable energy sources, energy inequality in society will require in the short term that each household produce its own energy for consumption. To meet this challenge, it is necessary to have well trained professionals with good management of theoretical and practical concepts of renewable energy, especially those related to fluids [6,7].

Currently, the most common self-sufficiency measures are through biomass, solar energy, photovoltaic energy, wind energy, small scale hydropower, and all their possible hybridizations [8]. Hydraulic energy has been the most widely used and exploited renewable energy in the world for the production of electrical power, making up more than 16% of the world energy matrix [9]. This power source can be converted into electricity through a hydro turbine and electric generator using large scale hydro resources to maximize the efficiency of high head hydro turbines [10].

The world trend of sustainable hydraulic energy for electrical power generation is focused on the use of very low head water resources due to (i) the low negative impact they have on the environment, (ii) the low cost to generate renewable energy and (iii) the fact that it contributes to the supply of electrical energy to local or national consumers [11].

Small hydro plants typically have a generating capacity of 10MW or less; mini hydro plant capacity is less than 1MW; micro hydro is less than 100KW; and that of pico-hydro is less than 5kW. A pico, micro, or mini hydroelectric plant has a minimum water deposit, and its implantation can be carried out in rivers, irrigation canals, wastewater, or household water discharges [12]. Currently, new types of turbines are being developed that can be used in waters with the presence of solids [13], such as drainage or sewage water [14].

Micro hydro currently plays a very important role in the use of renewable energy, and while a large infrastructure and technology for power generation has been developed, the current challenge is storing the energy produced. Pumped hydropower is an efficient way of temporarily storing energy and requires temporarily storing a large volume of water in an upper reservoir and releasing it through turbines to the lower reservoir to produce electricity during periods of high-power demand [15]. Pumped hydro storage (PHS) accounts for more than 94% of the world's installed energy storage capacity. Despite the projection shown, small scale water resources have been unattractive to exploit, since low height turbines are unable to maximize the energy absorbed to convert it into electricity, along with the scarcity of professionals trained in these technologies [8].

Neither education nor renewable energies have been exempted from the technological development caused by the fourth industrial revolution or Industry 4.0 [17,21]. Monitoring energy production has been very important for renewable sources, in addition to measurement, transmission and data processing technologies that can feed information to virtual power plants [11,23]. This has been achieved thanks to Internet of Things or IOT systems. In this context, the integration of digital technologies or IoT in higher education has become an opportunity for future engineers to be trained

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with appropriate technological tools. Through IoT systems, an engineer may be able to gather vast amounts of data from sensors and processes, which can be used for optimization of manufacturing processes and real time monitoring and control applications [24,25]. The inclusion of IoT projects focused on renewable energy helps students to be prepared for intelligent applications and to introduce a multidisciplinary work environment for the development of projects of all kinds.

IoT tools and the COVID 19 pandemic have greatly triggered what is currently known as Education 4.0 in order to cover the need for distance learning [19,20]. Within these efforts for distance learning is the development of augmented reality laboratories, virtual laboratories, or remote laboratories in order to provide future engineers with practical, technical knowledge or training as an opportunity for experience [16,18]. In Mexico, the development of virtual laboratories is incipient, which represents a challenge for the attention of distance students. In this context, this paper presents the design and development of a pico-hydraulic system for small scale power generation for teaching and training purposes. Innovative technology such as quality tools (QFD), TRIZ tools and functionality analysis were used to develop the system. For the monitoring of the system, IoT tools were used. Finally, the results show the degree of student involvement and learning and identified areas of opportunity to improve the curricula.

2. Materials and methods

2.1 Quality function deployment (QFD)

QFD is a systematic deduction and analysis methodology that prioritizes interpreting and satisfying customer or market requirements during the design and manufacturing process. QFD promotes the interaction of design stakeholders such as: engineers, technicians, users, vendors, etc. The QFD approach is based on the deployment of user expectations (the "What") in terms of design and production related parameters (the "How") for the new product. This process is represented by a succession of double entry "What/How" tables that enable identifying and prioritizing the correlations between the inputs [26]. A crucial step during QFD is the translation of customer needs into engineering characteristics such as design, production, or technological requirements [26,27].

The first matrix is called the "House of Quality" (HoQ) and consists of the rows that contain the relevant information for the client, and the columns, which contain the corresponding technical translation of their needs. In addition to the "What/What" correlations, this matrix facilitates integrating elements related to the analysis of competencies and the identification of contradictions among different product features [28]. The main activities within the construction of the HoQ are the documentation of the environment in which the product is used, the classification of the needs in a logical order and the evaluation of the relative importance of those needs. The understanding of client needs is summarized in the product planning and the identification of the technical requirements that directly influence the satisfaction of said needs. Typically, design teams have to base their estimates on their own experience, intuition, and determination [29].

2.2 Theory of inventive problem solving (TRIZ)

The Theory of Inventive Problem Solving (TRIZ) is the result of extensive research carried out by Russian scientists headed by G. Altshuller [30,31]. Thousands of patents from the former Soviet Union from different areas of technology were analyzed, which allowed to understand the creation of a systematic process for the invention of new systems and the improvement of existing

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ones [31]. TRIZ integrates a set of simple tools to understand the problems and detailed techniques for systems analysis [32].

The theoretical basis of the classic TRIZ is the Patterns of Technological Evolution. Altshuller, based on this discovery, developed a set of Patterns that describe the evolution of technology, as presented within the collection of world patent literature [8]. TRIZ aims to highlight both positive (helpful functions) and negative (harmful functions) relationships between components of a system and, more importantly, uses function analysis as a means to identify contradictions and ineffective, excessive and harmful relationships in and around a system. Among the main tools of TRIZ are the following: i) 40 inventive principles, ii) nine windows, iii) eight evolution trends of technical systems, iv) Function analysis and substance field analysis, v) 39 parameters of engineering, vi) matrix of contradictions, and vii) ARIZ, the Algorithm for Solving Inventive Problems, among others [30-32].

2.3 Nine windows creativity technique

The nine windows or system thinking operator is a technique for exploring systems and their possible impacts by examining the past, present, and future. Altshuller's idea was to combine the technical evolution of a system from the past through the present to the future or thinking about time and scale to contextualize a problem and find solutions [32]. This technique consists of setting up a table with nine entries forming a 3x3 matrix, separated into three categories: supersystem, system and subsystem in the three time periods. The first step is to fill in the cells with the descriptions corresponding to the present for the three categories of systems, in order to contextualize the problem addressed in external and internal environments [33]. Second is to fill in the rest of the cells analyzing its historical trajectory and the desired future progression. With the above, the temporal evolution of the system environment is considered, and the work group is required to define and reconcile the system’s future perspectives.

2.4 Functional analysis

The functional analysis aims to analyze the interactions between all the components of a system or the functions it must perform to meet the established requirements or needs, keeping the system from having components or mechanisms with no function or that do not respond to a system or user need [33]. Function analysis helps bring to light hard to recognize issues in problems. To formulate the problem with the TRIZ approach, it is convenient to make a functional description of the system under development to define innovation directions based on areas of opportunity identified for improvement. The functional analysis technique involves defining the primary useful function of the product, that is, what the product is going to do. The main function is then broken down into subfunctions of the product and they are represented in a diagram known as the functional tree. The functional tree is a top-down decomposition analysis of the primary useful function.

2.5 Matrix of contradictions

Contradictions are a key point in TRIZ theory when trying to increase the main function of a system. They are considered the main agents of a system’s technological evolution. These contradictions can be arranged in a table called a contradiction matrix used to resolve technical contradictions through the 40 principles of invention. This matrix is formed by relating the 39 engineering parameters located horizontally and vertically [34]. The cells of the matrix provide the principles that relate two parameters so that when one of them improves, it does not affect the other. With the above, the numbers referring to the principles of invention that can be

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used to eliminate a given contradiction can be found within the matrix. The use of the contradiction matrix is intuitive and efficient for solving a contradiction [35]. Tables 1 and 2 below show the 39 engineering parameters and 40 Altshuller inventive principles used in the contradiction matrix.

Table 1. 39 engineering parameters

1.Weight of moving object	2.Weight of nonmoving object	3.Length of moving object	4.Length of nonmoving object	5.Area of moving object
6.Area of nonmoving object	7.Volume of moving object	8.Volume of nonmoving object	9.Speed	10.Force
11.Tension, pressure	12.Shape	13.Stability of object	14.Strength	15.Durability of moving object
16.Durability of nonmoving object	17.Temperature	18.Brightness	19.Energy spent by moving object	20.Energy spent by nonmoving object
21.Power	22.Waste of energy	23.Waste of substance	24.Loss of information	25.Waste of time
26.Amount of substance	27.Reliability	28.Accuracy of measurement	29.Accuracy of manufacturing	30.Harmful factors acting on object
31.Harmful side effects	32.Manufacturability	33.Convenience of use	34.Repairability	35.Adaptability
36.Complexity of device	37.Complexity of control	38.Level of automation	39.Productivity	

Table 2. 40 inventive principles

1. Segmentation	2. Extraction	3. Local Quality	4. Asymmetry	5. Consolidation
6. Universality	7. Nesting (Matrioshka)	8. Counterweight	9.Prior Counteraction	10. Prior Action
11. Cushion in Advance	12. Equipotentiality	13. Do It in Reverse	14. Spheroidality	15.Dynamicity
16.Partial or Excessive Action	17. Transition into a New Dimension	18.Mechanical Vibration	19. Periodic Action	20.Continuity of Useful Action
21.Rushing Through	22. Convert Harm into Benefit	23. Feedback	24. Mediator	25. Self-service
26.Copying	27.Dispose	28.Replacement of Mechanical System	29. Pneumatic or Hydraulic Constructions	30.Flexible Membranes or Thin Films
31.Porous Material	32.Changing the Color	33.Homogeneity	34.Rejecting and Regenerating Parts	35.Transformation of Properties
36. Phase Transition	37. Thermal Expansion	38. Accelerated Oxidation	39. Inert Environment	40. Composite Materials

2.6 QFD and TRIZ integration research

QDF and TRIZ integration for problem solving has been widely reported in new product design areas, among others [36-38]. The main advantage of integrating both techniques is to meet client needs efficiently and with the perspectives of technological evolution of a system, allowing the proposal of totally new solutions based on knowledge of the system. QFD and TRIZ interaction is very interesting because while QFD identifies present needs, TRIZ identifies future needs through patterns of technological evolution [33]. Mainly, this integration occurs at the design specification and decision-making stages. One of the main contributions of the interaction between QFD and TRIZ occurs at the top of the quality house where negative correlations between quality parameters desired for the design can be identified [37]. With the above, the contradiction matrix can be used to resolve these design conflicts through the 40 principles of invention. Additionally, in this work, to increase interaction, the technical requirements or quality characteristics were selected using 39 engineering parameters proposed by Altshuller as a reference. The following figure shows the QDF and TRIZ integration proposal used in this work.

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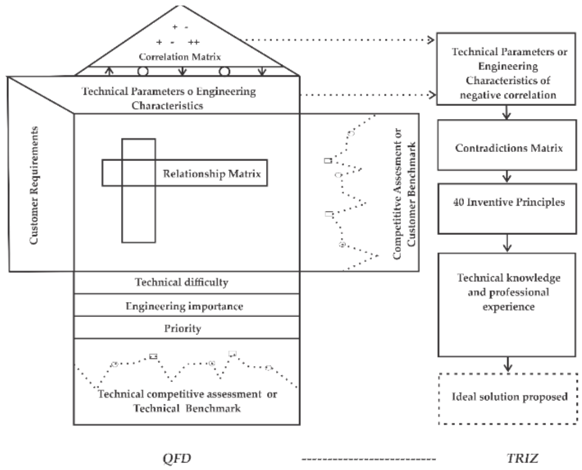

Figure 1. QDF and TRIZ integration proposal used.

In the QFD and TRIZ integration proposal, user or client demands and technical or engineering requirements are placed in the QFD quality house. The roof of the quality house will present positive and negative interactions with respect to the requested requirements that can be solved by combining the QFD and the TRIZ. Other important fac-tors to find a suitable solution are the knowledge and experience of the work team. Once the interaction of QFD and TRIZ was defined, the methodological process to be followed for the design and development of the pico-hydraulic power generation system was elaborated. The following figure shows the proposal of the activities to be developed using the QFD and TRIZ tools that go from the definition of the problem to obtaining the final prototype.

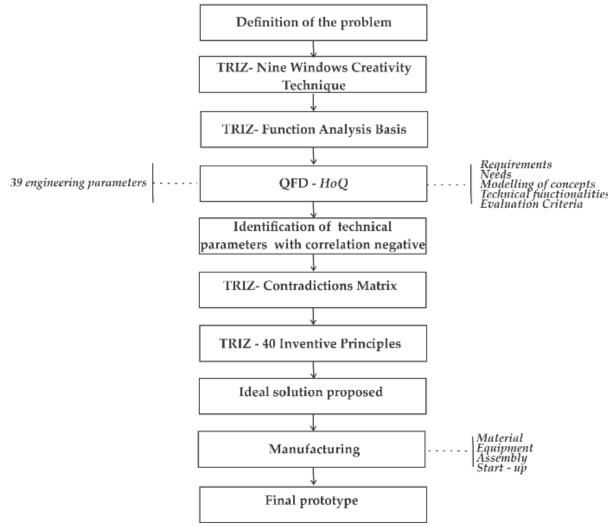

Figure 2. QFD -TRIZ methodological proposal

Work team

For the development of this work and in order to collect the necessary information from university institutions, the criteria of 28 participants were counted among teachers and students, laboratory technicians and vendors who are related to the subject. In addition to the above, an exhaustive search for patents and scientific articles was carried out, which was complemented with a benchmarking.

The universities and academic programs related to this multi-institutional work are: mechanical engineering (UASLP UAMRA - CARHS), chemical engineering (UASLP UAMRA), electronic engineering (ITSCHI), electronic industrial engineering (ITSCHI), renewable energy engineering (UASLP UAMRA) and mechatronic engineering (ITSON, UASLP UAMRA). Each academic program mentioned above has its own objectives, courses and policies, but all programs have a common professional competency in energy or renewable energy in their curricula. This professional competence was generalized by the work team as: *ability to manage, analyze and develop projects in energy generation, transformation, and transmission systems*.

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Table 3 shows the institutions that participated in the development of this project.

Table 3. Institutions participating in the work team

City	Institution	Number of lectures and students
Chicontepec, Ver. Mexico	Instituto Tecnológico Superior De Chicontepec (ITSCHI)	5
Obregón, Son. Mexico	Instituto Tecnológico de Sonora (ITSON)	5
Matehuala, SLP. Mexico.	Universidad Autónoma de San Luis Potosí – Coordinación Académica Región Altiplano (UASLP -UAMRA)	13
Tamazunchale, SLP. Mexico.	Universidad Autónoma de San Luis Potosí – Coordinación Académica Región Huasteca Sur (UASLP -CARHS)	5

3. Results

All information required to implement the nine windows technique was gathered with input from each institution and work team to contextualize the study addressed in external and internal environments in teaching hydraulic systems for power generation at the engineering level. For the development of this technique, the main system was defined as a hydraulic system for power generation, while the subsystem was all the components or elements that allow the main system function to be carried out, and the supersystem was the environment or context where the functions of the system are developed, in this case teaching and training activities. The nine TRIZ windows are shown in Table 4.

Table 4. Nine windows - hydraulic system for power generation

• Manual labor • Small work groups • Incidence of local knowledge • Limited training topics	• Small work groups • Human-machine interface • Incidence of local knowledge • High demand for use • Difficult access for student use • Specialized training to operate	• Incidence of global knowledge • Flexible usage platforms at the human-machine interface • Large number of work groups or unlimited students • Focus on sustainability • Virtual education environment • Better learning experience • E-Learning approach • Augmented reality environment • Virtual labs
• Simple systems • Analog measurement • Large size and robust • Reconfigurable • Large-scale energy production	• In-person instruction Complex and robust systems • Access to data locally through a display • Not reconfigurable • Digital parameter measurement • Expensive equipment • Specialized maintenance • Large-scale energy production	• Flexible, reconfigurable systems • Control of operating parameters via internet • Remote data access via the cloud • Real-time access with audio and video • Small-scale energy production • Low cost • Use of smart devices
• High-pressure hydraulic pumps • Series piping circuit • Manual valves • Manual control • Industrial electrical connection • Turbine • Electric generator • Analog sensors	• Turbine generator brake system • Robust digital sensors • Hydro pumps • Series piping circuit • Central control • Central display • Adjustable frequency drive (AFD) • Industrial electrical connection • Desktop • Software	• Smart sensors • Microcomputers • Micro or Pico hydraulic generator • Free software • Domestic electrical connection • Reconfigurable piping circuit • Video-Audio • Internet access • Cloud database
Past	**Present**	**Hypothetical Future**

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The main results obtained from the nine windows will help the work team to identify the requirements that can be included when proposing a solution or offer several ideas or reflections on the possible solution. These results are found in the last column where the hypothetical future for the hydraulic system for power generation is located. Analysis of this column shows (i) under subsystem, elements such as microcomputers, free software, smart sensors, internet access, among others., (ii) under system, elements such as the use of Smart devices, flexible reconfigurable systems, remote access through the cloud, among others., and (iii) under supersystem there are features such as a focus on sustainability, incidence of global knowledge, unlimited number of work groups, among others. Without a doubt, technology and development have caught up with us, and many of the elements considered in the hypothetical future of the system are currently being developed and implemented, but not yet in a generalized way, which offers an opportunity to consider them for this work.

Now, we analyze the main functions required when using hydraulic system for power generation to draw up a hierarchical diagram of functional requirements. With the above, the work team will be able to propose a complete design solution that includes the functional requirements of the system. These functions are everything that a user needs to be included in the design to build functionality. For the purpose of functional analysis, the users were defined as teachers and students, and the essential activity was energy production and teaching. The functional analysis is shown in the figure below.

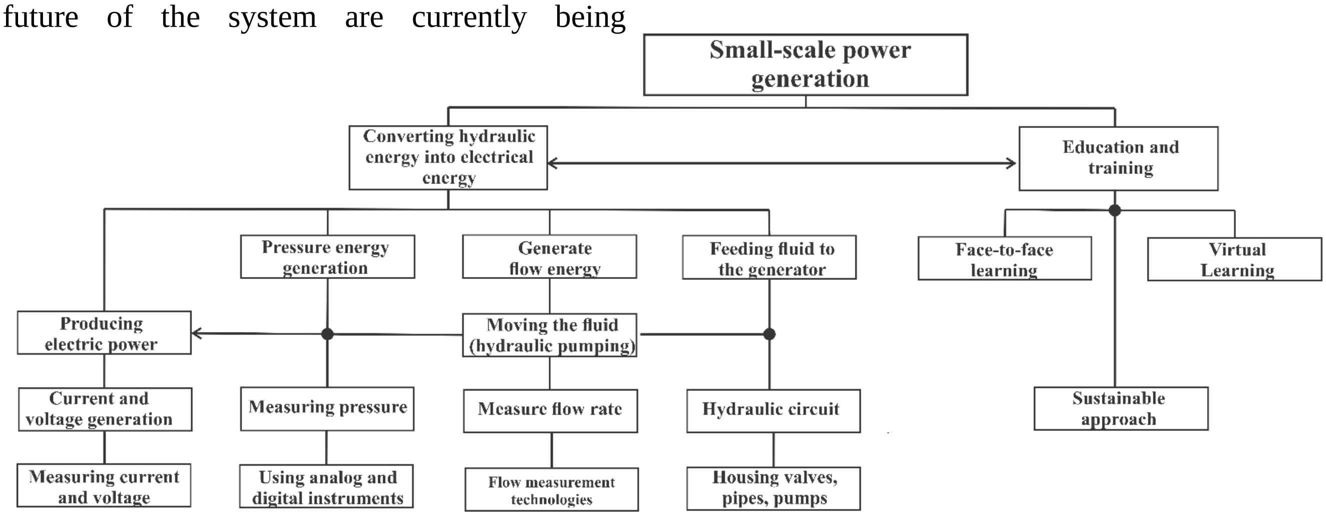

Figure 3. Functional analysis of the system

Like the nine windows of TRIZ, by identifying the main functions of the system, it will be possible to include everything that a user or system needs to be included in the requirements to increase the ideality and functionality of the design proposal by the work team.

3.1 QFD and HOQ

With the information collected from the 9 windows technique and the functional analysis, it was possible to determine the needs and requirements of the clients (students and teachers). The procedure to establish the requirements is a dynamic analysis and a team activity, for which the entire work team (5 universities, 28 people between students and

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teachers) participated. By consensus of the work team, the quantified weight was assigned to each of the requirements considered in order to rate them and define which ones will be a priority in the design stage. To qualify the weight of the requirements, importance values of 5, 3 and 1 were proposed as established by the QFD methodology, 5 being the most important and 1 the least important [39].

A satisfaction survey will be used to verify or validate the requirements established by the work team, since the information gathered is firsthand or professional experience in the area. The requirements are shown in table 5.

Table 5. Client requirements

Client requirements	Importance
Small-scale energy production	5
Reproduce processes	1
Adjustable-reconfigurable	5
Modular design	3
Students able to carry out training	5
Machine-user interface	1
Wide range of pressures and flows	5
Easy understanding of principles of flow, pressure, and power	3
Combination of different instruments to measure pressure, flow, and electrical power generated	5
Access to data in real time	3
Environment for smart devices	5
Visualize data locally (display)	1
Visualization and processing	5
Analog and digital data acquisition	3
Open software	3
Domestic type electrical connection	5
Accessible maintenance and operation	3
Low cost	5

3.2 Technical requirements

For technical or engineering requirements, the work team translates the client's needs into an engineering language. This is done so that, at the design stage, designers have clearly defined parameters and properties that must be included in the innovative design proposal. To increase the interaction between the QDF and TRIZ, an attempt was made to relate the 39 engineering parameters to the customer's requirements to include them as technical requirements. These parameters are undoubtedly very general, but some can be considered for this study. For example, the small-scale power production requirement can be related to the Power engineering parameter. Table 6 shows the requirements related to the 39 engineering parameters that were selected.

Table 6. Relationship of customer requirements with TRIZ engineering parameters

Small-Scale Energy Production - **Power**
Reproduce processes- **Adaptability**
Flexible-reconfigurable - **Shape**
Modular Design - **Manufacturability**
That allows the student to carry out training - **Convenience of use**
Machine-**user interface,** Convenience of use- **Complexity**
Wide range of pressures and flow rates - **Pressure, amount of substance, measurement accuracy**
Easy understanding of flow, pressure and power principles- **Complexity, Level of automation**
Combination of different instruments to measure pressure and flow- **Level of automation**
Analog and digital data acquisition - **Level of automation**

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With the above information, the work team was able to declare the technical requirements translated into engineering language. These technical requirements are shown in Table 7.

Table 7. Technical or engineering requirements

Power	Adaptability	Shape	Automation level
Manufacturability	Convenience of use	Complexity	Access to data in real time
Pressure	Measurement accuracy	Amount of substance	Environment for smart devices (cell phone, tablet, laptop)
Domestic type electrical connection 110 V	Open software	LCD display	Visualization and processing of data in the cloud

After the customer requirements and technical requirements have been identified, the design team proposed the following correlations for the "What" / "How", between each customer need and each engineering feature, being a 5 strong correlation, 3 moderate correlation, 1 weak correlation. Once the values of importance and the values of the correlations have been defined, the value of absolute importance (B) is calculated as the sum of the product of the evaluation of the clients multiplied by the weight corresponding to the degree of dependency. The result is given at the end of the quality house column and shows the importance of the requirement, that is, the priority quality characteristics for a customer.

3.3 Technical and competitive comparison evaluation

The House of Quality QFD tool allows direct comparison of how a design or product stacks up against competition in meeting customer requirements. The design team, with input from all members, identified several existing products to be compared, typically the proposed product and two or three other relevant competitors [26,40]. One of the purposes of this phase is to find out how the products of the competitors compare with the requirements of the client, in comparison with the product proposed by the design team.

To carry out the competitive evaluation, three commercial hydraulic systems for the generation of commercial energy were taken as close to the proposal of this work or to the equipment that the participating universities have. The following systems were considered competitors: Gunt HM 430C, Erides METP 10 and Edibon TPC. Once the competitors have been identified, a table is generated with the satisfaction of the customer's requirements by each of the competitors and the design team's proposal using a five-level scale where 1=very low satisfaction and 5=very high satisfaction.

The design quality house for the pico-hydro power generation system proposed by the design team is shown in the following figure.

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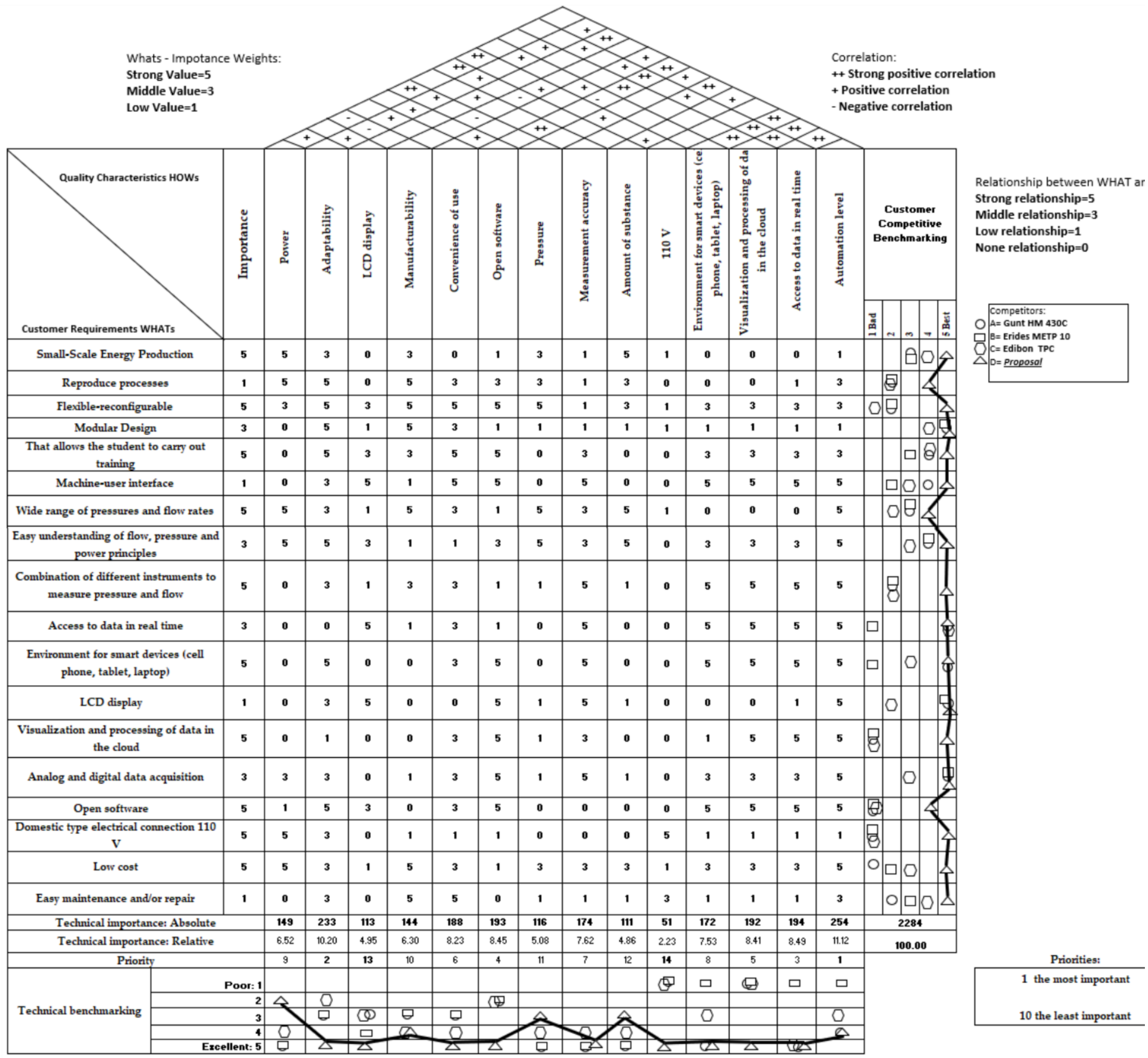

Figure 4. Design quality house for pico-hydro power generation system.

In the last section of QFD analysis, the importance of all client requirements and the contribution that each technical requirement must meeting the client's requirement is analyzed. This final analysis is crucial for the design since here the information obtained in the evaluations of the other matrices is compiled and the result of each technical requirement will be assessed and finally, they are reordered to give way to the design.

From the quality house results, especially the results of absolute technical importance (B) and priority, some requirements are more important than others. This is quite similar to the methodology, but despite its score, all requirements are met and included in the design generated by the work group. From the results of technical importance, the following can be recovered:

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1) The automation level technical requirement ranked the highest with an importance index 254 and a priority order of 1. This requirement refers to the combination of different analog and digital instruments to measure pressure, flow, and power. This means that in the proposed design these elements must be considered for the operation of the system, and, in addition, this requirement also impacts other requirements such as the environment for intelligent devices or data access in real time.

2) The technical power requirement obtained a high importance index of 233 and a priority order of 2. This requirement refers to small scale energy production. Most of the decision making regarding the design parameters of the system depends on this requirement.

3) The technical requirement of data access in real time obtained a high importance index of 194 and a priority order of 3. This technical requirement mainly impacts how the user will interact with the variables that have to be measured during teaching or training of the system.

Finally, the remaining features were lower priority, but will also be considered for the system design proposal. As can be seen within the house of quality in the competitive and technical evaluation section, the design team's proposal always remained superior to the competitions in most aspects.

The interactions between the technical requirements or quality features were set out on the 'roof' of the house of quality where both positive and negative correlations between quality characteristics are established. These interactions allow us to identify the contradictions they may present. From the analysis of the quality house, 15 strong positive interactions, 21 moderate positive interactions and 5 negative correlations were found. Without a doubt, for the design process, all of them must be taken into account; however, the main ones that must be addressed are the negative correlations. Negative correlations are not necessarily all contradictory. For example, four of these refer to Manufacturability with respect to power, adaptability, pressure, and amount of substance, and one with respect to the level of adaptability and automation (software, intelligent environments). In this sense, establishing unjustified requirements of pressure, power, amount of substance or adaptability will make the manufacturability properties more complex, it will be more expensive or the maintenance and repair more complicated. Negative interactions raise the need to act on conflicting technical requirements. The following table shows the negative correlations, the technical requirements in conflict, and the inventive principles provided by the matrix of contradictions.

Table 8. Negative correlations and inventive principles

Parameter	Correlation	Parameter	Inventive Principles
Power	Negative	Manufacturability	26 Copying,10 Prior Action,34 Rejecting and Regenerating Parts
Adaptability			1 Segmentation,13 Do It in Reverse, 31 Porous Material
Pressure			35 Transformation of Properties, 19 Periodic Action,1 Segmentation, 37 Thermal Expansion
Amount of substance			29 Pneumatic or Hydraulic Constructions, 1 Segmentation, 35 Transformation of Properties, 27 Dispose
Free software	Negative	Smart Device Environments	27 Dispose, 34 Rejecting and Regenerating Parts, 35 Transformation of Properties

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Of the inventive principles shown in the previous table, those that did not contribute to the work team's proposal were discarded and some creative ideas were generated for the conceptual design of the system considering the fulfillment of the functions and requirements of the system. The principles used and the ideas generated are shown in Table 9.

Table 9. Principles used in brainstorming

Inventive principles	Ideas generated	Frequency
1 Segmentation,	• It can be considered a hydraulic circuit that can be disassembled with quick couplings, divided into two sections that can be integrated as a series or parallel circuit. • Instead of having a single high-power and expensive hydraulic pump, two lower-cost pumps can be placed, and a greater range of pressure and flow would be obtained.	3
10 Prior Action,	Use adjustable resistors for various load cases, adjust series or parallel circuits to produce flow and pressure, select whether measured data will be displayed locally or via the internet	1
13 Do It in Reverse,	Use adjustable resistors for various load cases, adjust the system to work as a hydraulic circuit only or as a power generation system	1
26 Copying,	Use inexpensive sensors or measuring instruments that are easily removable and interchangeable, circuitry and inexpensive hydraulic connection accessories.	1
27 Dispose	Use inexpensive, short-lived materials, accessories, and sensors	2
34 Rejecting and Regenerating Parts,	• The system can be modified during its operation, either to work as a hydraulic system or a power generation system through valves • The system can be modified during its operation, whether it works in series or in parallel to obtain a wide range of pressures and flows.	2
35 Transformation of Properties,	• Flexibility, operating parameters such as pressure, flow or load can be changed. • The measured parameters can be visualized locally or via the internet	3

The system design proposal will be generated through the global analysis of the results obtained from the 9 TRIZ windows, the functional analysis, the QFD and the ideas generated with the inventive principles.

3.4 Preliminary design

Figure 5 shows the hydraulic circuit and the basic components proposed for the pico-hydraulic power generation system. Considering the ideas generated above, a hydraulic circuit made up of two sections that can function as a series or parallel circuit was contemplated to have a broader threshold of flows and pressures for the electric generator. In addition, two lower cost pumps were placed in the same way to have a greater pressure and flow range. To modify the system during its operation, either to work as a hydraulic system or a power generation system, valves and a bypass were used. Regarding the sensors or measuring instruments, pressure and flow sensors of different technologies were placed.

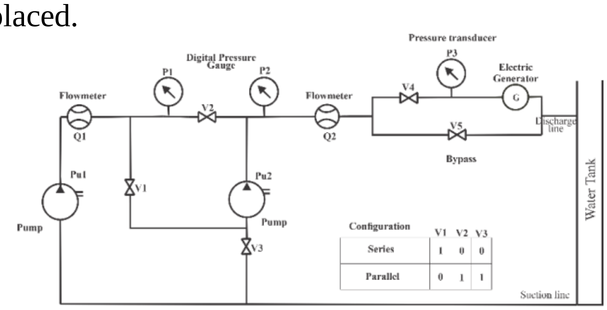

Figure 5. Hydraulic circuit and the basic components of the system.

Once the hydraulic circuit was defined, the preliminary design of the pico-hydraulic energy generation system was carried out. Figure 6 shows the design.

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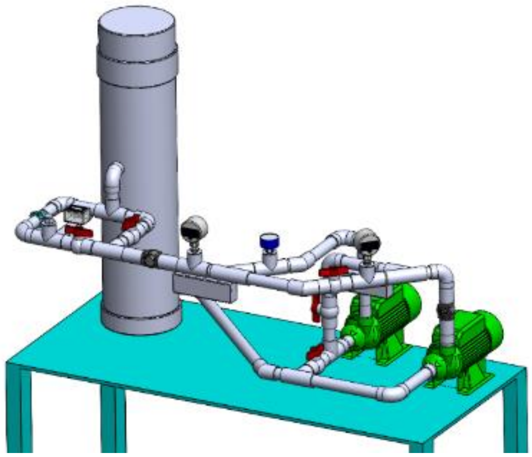

Figure 6. Preliminary design of the pico-hydraulic power generation system.

Easily removable and interchangeable low-cost sensors or measuring instruments, inexpensive hydraulic connection hardware and circuitry were used.

To carry out the construction of the system, accessories and economic commercial instruments were considered. The following table describes the components used.

Table 10. Characteristics of the components used

Component	Description
G1/4 Pressure Transducer Sensor / Pressure Transmitter	Accuracy:1%FS, Pressure Range 0-1.2Mpa, Input 5V Output 0.5-4.5V
F50-12V 10W DC Micro Hydro Generator.	Max. output voltage: 5V (1.2mpa) Max. output current: 220mA (12V)
DIGITEN G1-1/2" G1.5" Water Flow Sensor	Flow range: 5-150L/min, Sensor: Hall effect, Max. current:10 mA (DC 5V)
Digital Pressure Gauge. Bourdon tube pressure gauge with digital indicator	-100~0 kPa, 0.2%FS 0.4%FS
Dual scale pressure gauge. Bourdon tube pressure gauge Peripheral Water Pump (1 hp)	0-10BAR/PSI Flow Rate 45 LPM, 6 Bar
PVC piping, PVC ball valve, and accessories Panel Digital Dual Display Voltmeter Ammeter Current Meter	Diameter 1 in 0-100V & 0-10A
Arduino and accessories TDS-100H-M1/M2+S1/2 Handheld Ultrasonic Flow Meter Flowmeter Clamp on Sensor	UNO R3 Flow Range: 0~±32m/s non-contact ultrasonic measurement.

Requirements such as low cost, maintenance, modular design, type of electrical power, among others, were considered in the pico-hydraulic power generation system construction process. The system consists of an electrical generator coupled to a hydraulic circuit that can be reconfigured to work in series or parallel powered by two 1 hp hydraulic pumps. The piping system, valves and accessories are made of PVC, and a bypass was added in the electric generator section to have the ability to configure the system as a simple hydraulic circuit or as a power generation system. Various measuring instruments were placed throughout the system to meet the automation requirements, such as pressure gauges of various technologies, flow meters, current and voltage meters. In addition, an ultrasonic flow meter was integrated into the module as an external accessory. The built prototype is shown in the figure below:

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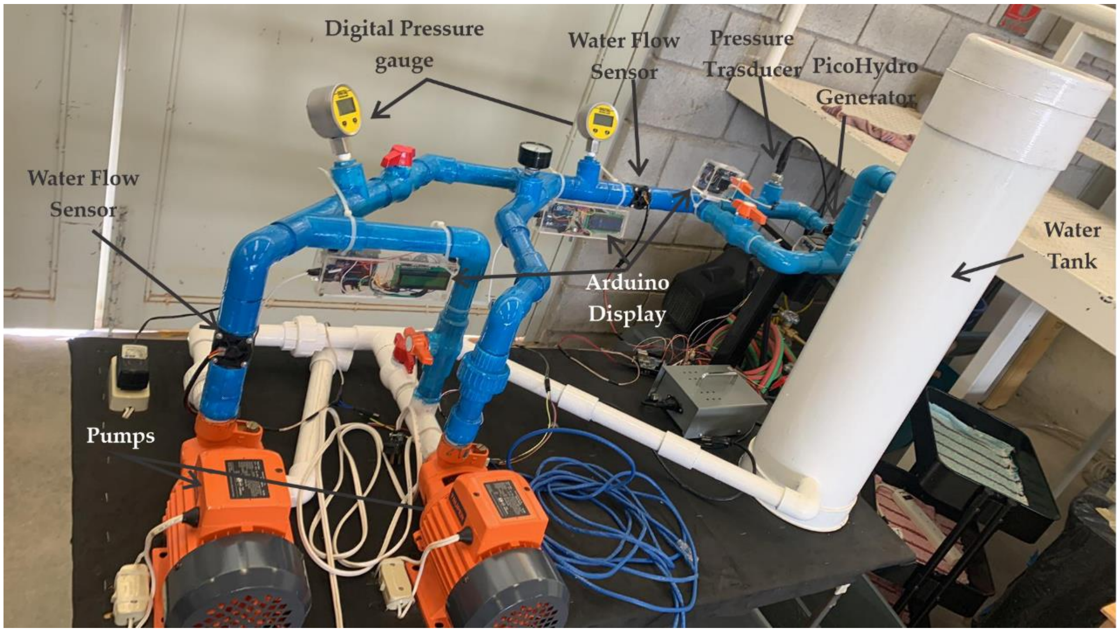

Figure 7. Pico-hydraulic power generation system final assembly.

To satisfy the requirement of displaying data measured locally, Arduino boards and display screens were used in each of the sensors. In addition, to measure the power of the electric generator, a digital current and voltage panel was used. Regarding the automation level requirements that contemplate access to measurement data in real time, visualization, and processing, free software and environment for intelligent devices, a platform was developed using the Internet of Things (IoT).

With the results, it was possible to carry out the connectivity tests of the system with other users remotely. The following figures show the physical space where the system is located within the thermofluids laboratory of the UASLP - UAMRA campus in Matehuala SLP.

Figure 8. Physical space - Thermofluids laboratory of the UASLP -UAMRA campus in Matehuala SLP.

The details of the system were able to be shared online with students and teachers from the different participating institutions using the MS Teams virtual platform. The following figure shows the link that was made:

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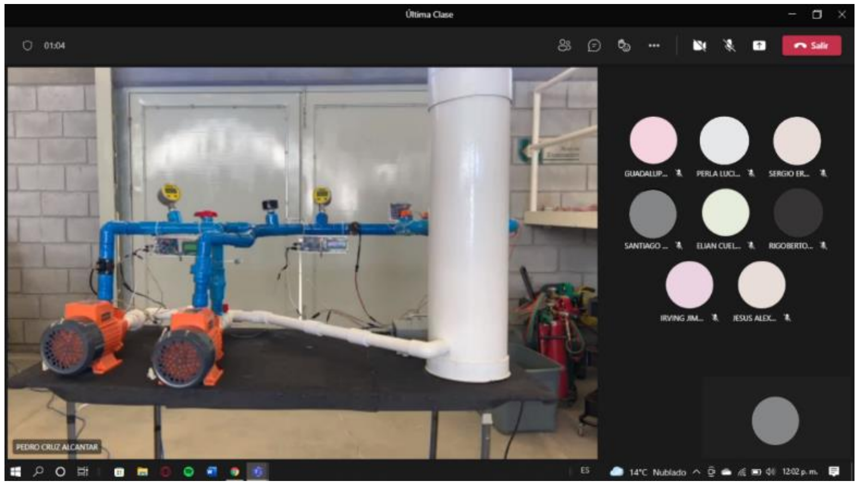

Figure 9. Virtual broadcast in MS Teams.

4. Discussion

It was possible to design, build and implement a pico-hydraulic power generation system which has the requirements requested by users (students and teachers) verifying the effectiveness of the proposed methodology process. In addition, IoT accessories were used to measure the variables of interest in the system, which are versatile and inexpensive, such as Arduino systems, with which can be used to visualize the data measured in real time.

Undoubtedly power generation systems are not new, Durrani. A.M [14] et al. used wastewater to drive a micro-hydroelectric power plant where a low head screw turbine was used to generate power and Uchiyama.T [13] et at. developed micro hydro turbine with excellent performance in passing foreign matter included in the water flow. Some studies on pico- hydro power have been conducted such as Williamson, S. J [49] et al. where they study pico- hydro power at low head deriving six key experimental parameters for a Turgo turbine and demonstrating that these systems can be used efficiently at low head in a variety of site conditions, Bozorgi, A [46] et al. numerically studied invertible low drop potential pico-hydro systems concluding that an axial pump can function properly as a turbine in low head pico-hydro power plants and Gaiser. K [42] et al. studied the optimal parameters for the empirical design of a low-cost pico-hydro power plant for distributed power generation applications. The most developed area currently is design where Yahya, A. K [44] et al. developed a pico-hydro generation system which is the effective way to help remote communities by generating electricity using water as the main source to be used for small capacity equipment such as motors and light bulbs, Cobb, B.R. [47] et al. built a laboratory scale test device to test the operational performance characteristics of impulse turbines. The results highlight the importance of proper system design and installation and increase the knowledge base on Turgo turbine performance that can lead to better practical implementation in pico-hydro systems, Zainuddin, H [48] et al. describe the design and development of a pico-hydro generation system using distributed household drinking water by developing a small-scale hydroelectric generation system using distributed household drinking water as an alternative source of electrical power for residential use and Gallego. E [44] et al. designed a low-cost Turgo turbine for a low head hydro system and experimentally evaluated the operating parameters.

Most of the works that report pico-hydraulic systems, these works are totally field,

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experimental, or totally theoretical implementations that in general seek the design of new turbines, optimization of design or operating parameters. In the case of this study, it is the design of a pico-hydraulic power generation system that responds to the new current context of distance education by COVID 19 and the use of renewable energies that are required in academic programs in Mexico. The methodology used can be reproduced by other people who need to have a system like the one presented for educational activities. Within the capabilities of the pico-hydraulic power generation system designed, there are endless teaching and training topics in the areas of mechanics, energy, and instrumentation, where the system can play an important role in learning. The satisfaction of the users of the pico-hydraulic power generation system with respect to the practice was measured through the questionnaire shown in table 11. All the participants involved in the project answered the questionnaire obtaining as a result that most of the participants totally agree or agree with the capabilities offered by the system to support the practical distance or face to face training, and that the requirements established as design parameters are met.

Table 11. User satisfaction

Question	Totally Agree	Agree	Neutral	Disagree	Totally Disagree
The system was easy to use, and the virtual connection was adequate for the practice	9	14	5	0	0
Remote use of the system allows you to expand your knowledge in different areas of the program curriculum	20	4	2	1	1
The picohydraulic generation system used in practice allows the practical learning by doing in the current COVID-19 pandemic condition.	25	2	1	0	0
The picohydraulic generation system used in practice allows a more complete understanding of hydraulic generation issues, internet of things and instrumentation through data analysis in the cloud.	11	10	3	4	0
The practice was more accessible for data visualization and processing.	26	1	0	1	0
The picohydraulic generation system used in practice allows to reproduce processes through its reconfigurable condition in the range of pressures and flow rates.	12	10	3	2	1
The practice carried out at a distance as training was significant	22	3	1	1	1

4.1. Principal contributions

The authors consider that the designed system contributes to the expansion of infrastructure and improvement of technology to provide clean and more efficient energy to help the environment through the training of professionals who are trained in the generation of energy at small scale and related parameters such as pressure, flow, energy demand, monitoring, visualization. In addition, the same micro-hydraulic systems are used to store energy from renewable energies. We believe that well trained professionals in the above topics will have a great impact on the inclusion of sustainability in society and its execution in the development and implementation of projects.

4.2. Research scope and limitations

A pico hydroelectric power generation system was obtained for teaching and training purposes that operates manually and with access to parameter measurement through LCD displays.

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For the implementation of the system was economical by using common materials, sensors, and instruments. The designed system can be easily restructured to simulate different cases or conditions of pressure, flow or load demand. In addition, it was found that a major limitation is the manual operation of the hydraulic circuit control valves, and there is still no data storage and monitoring system through cloud platforms.

4.3. Applicability for teaching and training

With the support of the MS Teams platform, a virtual session was held to show the operating parameters of the pico-hydraulic energy generation system, such as pressure, flow, and voltage obtained in the electric generator, to students and professors from the five participating universities. The designed pico-hydraulic power generation system is functional, low cost and can be easily reproduced to be used for teaching purposes.

The above limitations may be considered in future work or improvements to the proposed system.

4.4. Main findings

1) The result shows that the proposed approach can achieve greater client satisfaction (students and teachers), and that technical contradictions in the development of the system can be overcome by optimizing resources, costs, and the degree of functionality.
2) The implemented IoT has an architecture that can be adapted to different case studies through simple modifications of the Arduino code and hardware.
3) The implementation of the pico-hydraulic power generation system can be done with commercial, open source and relatively low-cost cards, allowing students to redesign the architecture of the platform to create different configurations or load cases of complex systems.
4) The satisfaction of the users (students and teachers) on the use of the designed system shows the advantage of including it as part of the practical activities of the subjects to improve the 'ability to manage, analyze and develop projects in energy generation, transformation, and transmission systems'

5. Conclusions

With the integration of QDF and TRIZ tools it was possible to design and build a pico-hydraulic power generation system for teaching and training purposes considering the requirements of both the client and the engineering requirements through a work team made up of students and professors from four universities.

6. Authorship acknowledgment

Josefa Morales Morales and Pedro Cruz Alcantar: Conceptualization, Project administration, Review and Editing. *Horacio Bautista Santos, Rafael Figueroa Díaz, César Manuel Valencia Castillo, Mauricio Leonel Paz Gonzalez:* Methodology, Review and Editing, Supervision. *Isaac Compeán Martinez*: Review and Editing, Supervision, Project Administration.

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