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A Systemic Framework to Develop Sustainable Engineering Solutions in Rural Communities in Colombia

Case Study: Ingenieros sin Fronteras Colombia

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Abstract In several rural areas in Colombia there is a serious lack of water quality supply. Thereby the problematic situation is understood as complex one that involves stakeholders with pluralistic interests, multiple variables and requires the development of sustainable and suitable solutions. In order to address this issue, this paper proposes an integration of engineering design framework (CDIO) with a systemic approach. Particularly the approach emphasizes on systemic elements such as autonomy, systems within systems, cooperation between stakeholders and cause effect relations; it also proposes a previous observing phase for engineering design framework. Thus the proposed systemic framework aims to generate projects that improve living conditions in rural communities and promote the production of knowledge between the stakeholders to ensure sustainability in the long term. To illustrate the proposal, this work contains a case study that discusses a project carried out by a research team—*Ingenieros Sin Fronteras Colombia*—in a rural district near to Colombia's capital. The experience, which involved and benefited 16 families in the community, provided strong evidence to support the proposed framework. The paper concludes with a discussion about the replication of this proposal in other contexts.

Keywords Systemic approach · CDIO · ISF Colombia · Sustainable engineering solutions · Rural community development · Vulnerable communities

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Introduction

In order to make academic activities *relevant*, students, professors and researchers should carry out activities with real practitioners and real organizations, especially those which attempt to solve contextual needs (Chang et al. 2011). In Colombia, where 53.51% of rural population has problems associated to unsatisfied basic needs (DANE 2010), engineers and engineering have the opportunity to promote the development of rural communities. Chief among these problems is the lack of safe water in rural communities, which often leads to high impact diseases such as Malaria, Vivax and other related problems (Defensoría del Pueblo 2009). Furthermore, this situation affects a large number of people, since in rural areas in Colombia, where 24.02% of the total population lives (DANE 2010), average water supply coverage is at 53.5% and average sewerage system coverage is only at 26.1%; these numbers are significantly lower than the average coverage in urban areas, which are 89.9 and 78.5% respectively (Defensoría del Pueblo 2009).

The gap between urban and rural water supply coverage could be explained by several causes, including the impact of the internal armed conflict (CICR 2010), and also the fact that national public policy has focused on increasing water supply coverage in urban areas, but has paid less attention to rural areas (Defensoría del Pueblo 2009). Even more and unlike other Latin American countries, there is no institution or nationwide program providing adequate and sufficient technical assistance to the 12.000 communitarian organizations that offer their services in rural areas (Ramírez et al. 2011). Thus, the water access problem in rural areas is a situation that involves several actors, with pluralistic interests. What has happened when one of the actors tries to solve the problem separately? In the case of the central government, despite its efforts, the goal of increased coverage and improved water quality has been elusive (Fernández 2004), mainly because technical solutions for water shortage were designed in order to shape socio cultural factors instead of doing the opposite (Brooks 2004). Initiatives coming from departmental and municipal governments have not been successfully accomplished. Even more, efforts coming from the communities have also failed due to the lack of technological know- how (Defensoría del Pueblo 2009).

According to this, water access problems in rural areas in Colombia involve several stakeholders with pluralistic interests, multiple variables and require that whichever solution is carried out must aim for appropriation and construction of scientific and non-scientific knowledge, in order for that solutions to be sustainable and suitable (Rist et al. 2006). Because of these reasons, the problem can be defined as a *complex* situation, (Schwaninger 2000), thus, it is unlikely that any separate stakeholder will be able to get to the real root of the problem individually and come up with a lasting solution.

In this context, this paper proposes that a *systemic approach* (Flood 2010) is necessary in order to generate a suitable solution to the water access problem in rural areas. This paper develops a *systemic framework* that may be suitable to conceive, design, implement and operate engineering solutions that aim to improve access to quality water in Colombia. This framework should also deal with multiple interests and multiple variables, but furthermore, should promote the development of cooperation arrangements between stakeholders, which in turn help to quell this turbulent situation (Flood 2010), and more important, it should contribute to the creation and appropriation of knowledge that can make the solution sustainable. Based on these ideas, the paper proposes a way to integrate an engineering design and implementation framework (CDIO—explained below) with a *systemic* approach.

The paper is organized as follows: in "Theoretical Foundations for a Project Design Framework Using a Systemic Approach" section, the proposal is developed, by integrating different systemic elements with the CDIO framework. "Case Study: The Implementation of the OCDIO Systemic Framework in a Rural District by Ingenieros Sin Fronteras Colombia" section describes the case study used to illustrate the implementation of these ideas, where the research team ISF Colombia developed a project with the framework proposed. Here, the actions of engineering students, professors and a rural community were integrated in a systemic way aiming to improve water quality access in the community. "Main Results" section discusses the results obtained in the case study, both from a theoretical and a practical point of view; it also addresses the question of the validity and replication of the proposed framework. The paper finishes with some conclusions and perspectives on future research.

Theoretical Foundations for a Project Design Framework Using a Systemic Approach

In order to develop a *systemic framework* for project design in the context described above, several issues must be addressed. First, it is important to understand *why* a systemic approach is required. Second, the *goal* of this *framework* must be clearly defined. Third, it is important to state which *systemic elements* should be included into the proposed framework. Finally, it is necessary to specify *how* those elements can be integrated into a project design and implementation framework, particularly with CDIO[1].

Why a Systemic Approach Is Required

In the context described in "Introduction" section, generating engineering solutions to these problems should be carried out from a systemic perspective, mainly for two reasons: (1) Since several actors with pluralistic interest are involved in a situation with multiple variables, a *complex* problem requires an accurate observation and then an appropriate design of solutions that integrate different perspectives; (2) since it is required that technical solutions be sustainable in the long term, the solution should also promote the autonomy of those directly affected by the problem, in order for the system's operation to be carried out by them in the long run (Nuttal et al. 2010).

The literature on systemic thinking also provides evidence of why this approach is appropriate for situations related to water issues. Berlinck and Saito (2010) articulated the Action Research Spiral with General Systems Theory to develop environmental education activities as part of a participative management approach to water resources in rural Brazil. Simon (2007) showed that, when dealing with water conflicts, working with systems methods such as Soft Systems Methodology, and Information and Communication Technologies can help transform traditionally linear modes of negotiation into collaborative learning, holistic, interest-based modes of negotiations. Furthermore, Rist et al. (2006) argues that sustainable natural resource use requires that multiple actors reassess their situation in a systemic perspective, and illustrate their argument with case studies in Latin America, Africa and India. All these previous studies show strong evidence that a systemic

[1] The CDIO initiative is an innovative educational framework which provides students with an education stressing engineering fundamentals set in the context of Conceiving—Designing—Implementing—Operating real-world systems and products. http://cdio.org.

approach is required to generate engineering solutions for quality water access problem in rural Colombia.

What Is the *Goal* of this Systemic Framework?

The goal of this framework is to improve life quality in rural communities. This framework should be able to integrate several perspectives coming from the relevant stakeholders (engineers, community and government), and promote active participation throughout the entire project to foster a sense of ownership and continuous feedback to ensure sustainable proposals (Cohen et al. 1961). The framework should also help communities to acquire the knowledge and tools necessary to operate the projects, in order to make them sustainable without relying on external actors indefinitely. It is essential that the group of engineers take into account technical and sustainability aspects and actively involve those directly affected by these water issues in order to develop innovative solutions that have a positive impact. Thus, the group of engineers must *learn* and *work* together with the community to make the most of the community's knowledge and experience to design and implement solutions adjusted to the context jointly with the stakeholders.

Which *Systemic Elements* Should Be Included?

Autonomy

The framework seeks to develop local autonomy both within the community and the team of students and professors of engineering. This means that certain properties should emerge within the system designed by engineers and the community, such as auto-critical capacity and self-organization throughout the design and implementation of the projects (Beer 1985; Ashby 1964). The system must genuinely learn to learn in order to build an "intelligent" community-university organization (Senge 2006).

Systems Within Systems

It would be of little impact to implement any technical solution if the group does not take into account variables, which might have an impact (negative or positive) on the proposed technological design (Schwaninger 2000). It is fundamental that the framework helps the group to understand aspects such as: regional and national regulations, economic and productive systems and actors who might have some influence such as landowners or local politicians (Duque 2006) (see Fig. 1).

Cooperation Between Stakeholders

It is important that the framework takes into account the points of view of those directly affected and the actors who seek to contribute. This is why it is very important to involve the following actors in every decision: the community, local government entities, researchers working on appropriate technologies students and professors.

Cooperation with the communities is essential throughout the design, implementation and evaluation of the project's results in order to promote sustainable solutions and autonomous communities (Cardenas 2009). It is not enough for a group of engineers to simply implement an engineering solution to a given issue. Without actively involving the community from problem identification to design and implementation the generation of

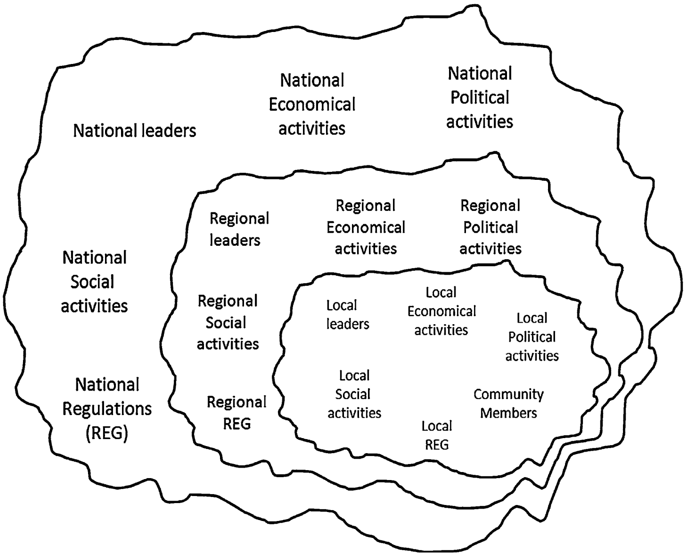


Fig. 1 Systems within systems

sustainable solution in the long term is unlikely, reducing the group's effort to little more than good intentions and paternalism (Lucena et al. 2010).

Bearing this in mind we define the meaning of cooperation within a team that works in order to accomplish a goal in an engineering project. By *cooperation* we understand the social situation in which the members of the team have objectives tightly related to each other's goals (Espejo and Reyes 2011). That is, the members of a team perceive that their objectives can be achieved if and only if other members are able to achieve their own objectives (Deutsch 1968). In other words, if a member of the team achieves his/her objective then the other members, to some extent, achieve their respective objectives (Laverie 2006) (see Fig. 2).

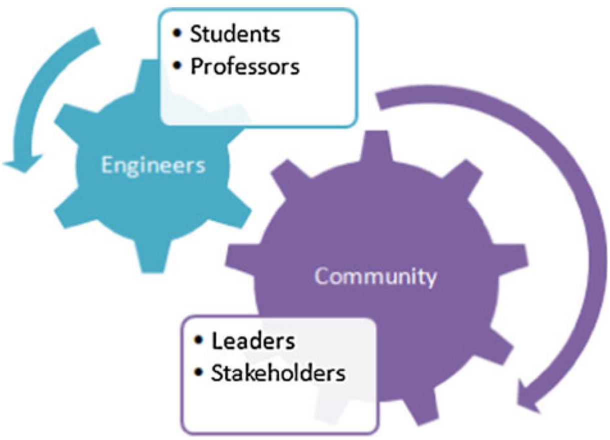


Fig. 2 Systemic relation between Stakeholders

Cause and Effect Relationships

Another aspect is the development of schemes through which the processes have the permanent capacity to provide feedback and correct the path (Herrscher 2006). Understanding these impacts is crucial in replicating the participation model in other communities and contexts and adapting the project design and implementation processes in order to facilitate organizational and technical learning. Every decision has an impact on the community, and the team and the community must have the necessary tools to effectively learn from this and generate new knowledge which might aid current and future project design and implementation.

Integrating CDIO Framework With a Systemic Approach

In a regular project design and implementation framework, the CDIO[2] framework presents a view of how product or system development moves through four metaphases: conceiving, designing, implementing and operating. Conceiving runs from market or opportunity identification through high level or conceptual design, and includes development project management. Designing includes aspects of the design process, as well as disciplinary, multidisciplinary, and multi-objective design. Implementing includes test and verification, as well as design and management of the implementation process. Operating covers a wide range of issues from designing and managing operations, through supporting product lifecycle and improvement, to end-of-life planning (Crawly 2001).

Based on previous systemic aspects, the research team uses the CDIO framework as a way to integrate engineering technical knowledge with local knowledge from the community, particularly as a way to focus said integration towards the design and implementation of solutions. Thereby to design an engineering solution to a problem such as quality water access in rural areas it is necessary to integrate a design framework like CDIO with a systemic perspective. This creates a new framework that enables the integration of technical engineering knowledge with local knowledge from the community in order to improve living conditions within the community. In this case, once the community and the group of engineers identified the problematic situation then they could *Conceive* a solution technically viable and empower-able by the directly affected.

Bearing the result of the *Conception* phase in mind, it is necessary to establish a *Design* that meets the engineering, legal and community requirements. Then, an *implementation* phase is required to test the solution in laboratories and in the field, particularly the last one to obtain feedback from the members of the community. During the *Operation* phase the project should guarantee the comprehension of the technology by the community and its correct operation. This phase is conducted by the community with the aid of the engineers.

Until this moment, the community has gone through a learning process and it is conscious of some facts: (1) its participation is fundamental for *Conception* and *Design* phases; (2) in the *Implementation*, local and community knowledge is necessary to guide the testing; (3) the steps of conception, design and implementation (CDI) allow the development of commitment within the stakeholders and the implementation of empowering engineering solutions to improve quality of life; and (4) the participation of the stakeholders and the engineers during the process promotes a better operation of the technology as a result of a better comprehension and practice.

[2] See footnote 1.

Focusing the previous CDIO framework in the academic context, this paper includes universities as a stakeholder, which makes necessary some modifications to address the specific challenges posed by work with rural communities and students, the implementation of sustainable solutions and the development of autonomous communities. This paper proposes a previous phase in order to develop abilities in new engineers and mainly (for this paper) to guarantee a systemic development of projects. However, this proposal could be applied in other engineering projects based on the CDIO framework. In consequence the authors realized that observing is a previous phase before actually *conceiving*, and it leads to the identification of the problematic situation based on an observation process. The aim of this observation process is that students, professors and the community identify variables, actors, roles and aspects that describe the complexity of the situation. In this way the collective work guarantees an identification of the problem from all the stakeholders points of view.

Likewise, the causes, impact and behavior of complex situations could be identified through this *observation* process. In order to achieve this, students must develop observation abilities that include the identification of cause-effect and feedback relationships, leaders, symptoms, conditions and relations with similar problems, as well as Strengths, Weaknesses, Opportunities and Threats regarding the project's implementation within a given region (Carvajal et al. 2012). These abilities are especially useful if the group is also expert using tools such as interviews, polls, short conversations, literature research, and relations with public, private and educational institutions, which facilitate the correct identification and definition of the problem. Thus, this paper proposes OCDIO as a more appropriate framework to use in projects that seeks to design and implement systemic solutions with vulnerable communities (see Fig. 3).

Based on previous proposal, the students and professors observe vulnerability situations and approach the problem by interviewing the people involved, exchanging ideas with

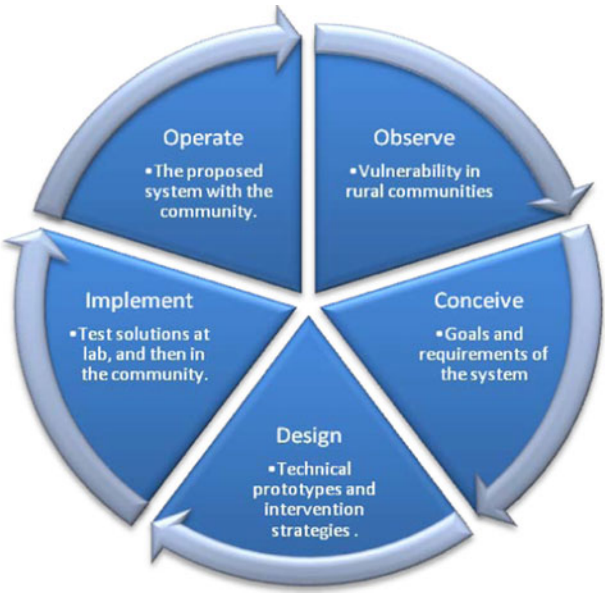


Fig. 3 Summary of OCDIO

experts and researchers and exploring knowledge on the subject at hand. Once the observation process is finished, the group conceives the formulation, contextualization and a possible solution to the observed reality together with the community. This conception requires a great deal of creativity and innovation to offer technology that meets the community's needs. After an evaluation stage, the process moves on to the preliminary design phase of the prototype and a proposal for implementing the technology in order to improve vulnerability conditions in the community**.**

Subsequently, assistance from teachers is intensified and the development of the project is deepened. This allows the design to be carried out with greater precision regarding the prototype. During the implementation phase, the efficiency of the prototype is monitored and adjusted periodically through lab test and community visits. Finally, the project is put into operation. The group and the community regularly evaluate the experience and learning generated during the project's design and evaluation, in order to improve the cooperation model and the methodology, hoping to replicate the project in other areas of the country which present drinking water problems and unsatisfied basic needs.

Case Study: The Implementation of the OCDIO Systemic Framework in a Rural District by Ingenieros Sin Fronteras Colombia

The proposed framework was applied in the design and implementation of a project of the group Ingenieros Sin Fronteras Colombia. Particularly, the aim of this project is to improve water quality in the Torres district. The first subsection describes the main characteristics of this group. Then, the main issues around the OCDIO phases are described.

Ingenieros Sin Fronteras Colombia (ISF Colombia)

Highlighting the problem context described above and having shown the complexity of the water access problem due to pluralistic interests and multiple situation variables, the Universidad de los Andes and the Corporación Universitaria Minuto de Dios created Ingenieros Sin Fronteras Colombia. The objective of the group is contribute to improve the water problems in rural areas by involving all of the stakeholders throughout the process, applying knowledge from different engineering branches (civil, environmental, chemical, industrial and mechanical) and working together with the members of the community to identify concrete water issues and design engineering solutions tailored to the community's specific needs .

The ISF Colombia team works in several projects taking advantage of the strengths of each discipline or role of each stakeholder. For example activities like identification of the community needs are leading by social workers working together with community leaders. Industrial engineers lead the planning of the project, establish the performance indicators to monitoring the activities and guide the project to achieve learning and established goals.

About technical issues, there is a collective work between chemical, environmental, mechanical and civil engineers. To make this experience richer, the members of ISF Colombia conduct research from different engineering branches and participate in several projects which often result in academic publications or theses. All of the process is developed within a participatory frame where the other stakeholders are actively involved.

Thus ISF Colombia has not only made a proposal from an engineering perspective but it has also guaranteed that the community, government, students and teachers work systemically to improve water conditions. ISF Colombia has created a cooperation scheme in which every individual helps in order to achieve both personal and collective objectives. The students, together with the teachers, develop technologies and organizational designs from the OCDIO methodology to improve water quality; the community helps with the conception, implementation and operation of the project.

The following sub-sections describe the project developed by the group in a rural district called "Torres" located in a town named 'Guayabal de Siquima', located 150 km far from Bogota, the capital of the country where both universities are located. The project began in late 2007 and it was carried out during 2008 and the first half of 2009. However, monitoring process continued until late 2010. The project involved near than 10 professors and more than 20 students during it several phases. The fact that during the project was both students and professors coming in and out implied that the organizational structure should be flexible to that. The following table (Table 1) describes the main elements and responsibilities of the organizational structure.

In order to illustrate the different phases of the proposed framework, the project is described around each one of the OCDIO phases:

Observation

The observation phase of the project was implemented in two steps: first, the ISF Colombia group observed the seriousness of the lack of access to safe water problem in many vulnerable communities in the country. A summary of the situation is provided in the introduction of this work. A second step was to observe the specific vulnerability in some rural communities, in order to choose one to develop the project. The group of engineers must identify a community with serious water issues which can be addressed through

Table 1 Elements and responsibilities of the organizational structure

Area	Members	Responsibilities
Organizational team	Industrial engineers and social workers (3 professors and 10 students)	General planning of the project Monitor and evaluate the project through performance indicators Understand economic, social and cultural conditions of the community Prepare and organize workshops and meetings with the community Manage materials, transportation and supplies procurement
Technical team	Civil, environmental and chemical engineers (6 professors and 10 students)	Technical assessment of water conditions in the community. Technical conception, selection and design of the technologies Work in the field and in the laboratory to validate the technology Lead the construction and implementation of the designed system Lead the technical evaluation and training related to the project

Source: Authors

relatively simple technologies, and is willing to recognize said issues and work together with the group of engineers in the identification of specific problems and the design of appropriate solutions. If the community is not completely committed with the work at hand it is practically impossible to ensure sustainability in the long term. After observing several communities near Bogotá, the Torres community in a town called Guayabal de Síquima was selected. A brief description of the community is provided:

Community Description

The district is called Torres and it is located to the north of the municipality of Guayabal de Síquima. There are approximately 30 families distributed amongst different areas. Our main area of concern is "High Torres", where the district's aqueduct operates and where 16 families are located. Community's main characteristics are summarized in Table 2.

Water Features in the Torres district

Torres has a small aqueduct system that consists of a water source, a storage tank and a water distribution system by gravity through pipes, which supplies most of the families located at the tank's level. It also has a secondary pumping storage system for the families located above the tank's level. Agriculture and livestock seem to be the main sources of microbiological contamination (faecal and total coliforms).

Table 2 General characteristics of Torres District

Geographic information	Guayabal de Síquima is located northwest of Bogotá. Inside the district there are two main sources of water: the source where the aqueduct's water inlet is located and a small stream from which the inhabitants obtain the water they use to feed the livestock
Economy	The main economic activity is agriculture, specifically sugar cane, corn and coffee. Most of the people own small farms. Some of the inhabitants work in larger farms which produce brown sugar and coffee
Society	A large part of the population is made up of adults since most of the younger people have left in pursuit of better opportunities. The average size of a family ranges from 4 to 6 people
Health	The life expectancy for women is between 70 and 80 years. The life expectancy for men is 70 years. The main causes of death are violence and advanced age. There are mosquitoes all year round which cause several diseases. The mayor's office runs health campaigns every four months, but most of the inhabitants of the community have never attended them
Education	There is a primary school in the district which has 20 students. There are also 3 high schools in the region. Approximately 10% of the population is illiterate and most have never finished high school
Utilities	In the town, water is provided by the district's aqueduct at prices considered to be high by the population. There are no phone lines so the inhabitants must communicate by cell phone. The aqueduct was constructed approximately 10 years ago. This tank doesn't have any filtering system which has a noticeable impact on the quality of the water obtained from it. The water distribution system suffers regularly from lack of water pressure. Furthermore, the water source is located on private property which makes access difficult and increases the risk of contamination due to the presence of livestock. During the months of July and August there are shortages of water and food due to lack of rain

S*ource*: Authors

The main features of the district's water are shown in Table 3. The source of water for the Torres district could be characterized as inadequate according to parameters such as color, according to Resolution 2115, 2007—RAS 2000; and deficient according to microbiological parameters from the same code. The water might owe its color to scarce maintenance of the storage tank and organic matter falling into it. It is important to point out that in the study; different fecal and total coliform concentrations have been found in the water arrival points in the households. This fact could be due to bad sanitary habits.

Conceiving the Engineering Solution

Once a community is selected, the next step is to conceive the engineering solution. The goal of this step is to work together in the planning of an appropriate solution which responds to the community's specific characteristics and those of the problem at hand, define objectives and propose a viable solution, which is coherent with group's systemic and participatory perspective. This last idea implies developing autonomy within the community, which means helping the members to acquire the skills necessary to operate the system and ideally, to replicate the technology (see Fig. 4).

Once the overall goal of the project was defined, the group began designing a technological process that was consistent with the project goals. The group of engineers worked closely with the members of the community to specify the problem and identify the main concerns of the stakeholders. Work was carried out in two fronts simultaneously. Workshops and meeting with the community were arranged in order to understand the problem and the community's perception, their needs and expectations and possible difficulties for the appropriation of the technology. ISF Colombia also performed tests on the water supply in order to identify the main problems and begin working on an appropriate technological alternative.

The group was especially careful to take into account cultural and social aspects such as the way in which the community's members use water, the location of water sources within homes, hygiene practices, perceptions of water related problems, the language used by them and community leaders among others. These aspects are especially important because a truly sustainable solution must be culturally suitable and must be designed so that it can be incorporated into the community's day to day life as seamlessly as possible. However, quite often, the socio-cultural aspect is overlooked or not given enough relevance. ISF Colombia has had an advantage in this aspect, its members being closer to the realities faced by these communities, which is not usually the case in joint projects between

Table 3 General water characteristics in the Torres district

Parameter	Water	Norm 215 of 2007	Units
Alkalinity	13.2	200	mg/l-CaCO3
Color	10	15	UPC
Conductivity	62.7	1000	µS/cm
Total hardness	17.7	300	mg/l-CaCO3
pH	5.90	6.5–9	pH
Iron	0.04	0.3	mg/l-Fe
Turbidity	0.644	2	NTU
Total coliforms	100–1000	0	UFC/100 cc

Source: Authors' calculations

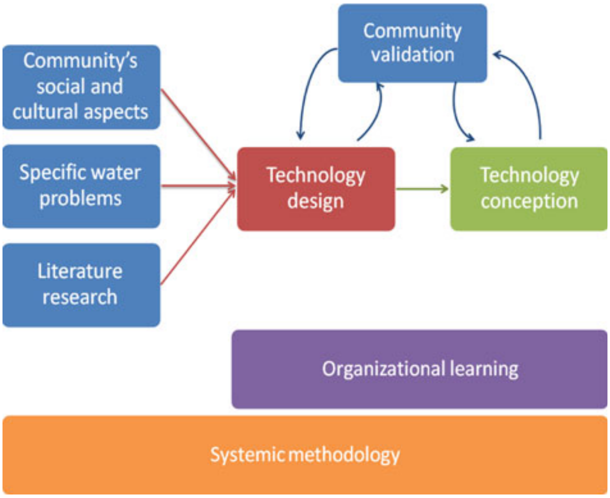


Fig. 4 Design and conception of the technology

engineering teams from developed countries and communities from developing countries. To achieve this, the following strategy was followed:

- Approach the community through local actors. In this particularly case one member of UMATA.[3] This helps establish trust.
- Identify other key actors for the development of the project: beneficiaries, partners and opponents. Based on this first characterization, students and teachers could adjust their intervention and approach strategies to better take into account the multiple stakeholders.
- The use of surveys and semi-structured interviews, to help students and teachers understand the living conditions, habits and establish communication in two directions which will help create trust relationships.

Otherwise and based on bibliographical research in water treatment, water filtration is one of the most important and basically steps where remaining solids can be separated from the rest of treated water (Ratnayaka et al. 2009). Especially the bibliographical research focus on two types of water filtration, (1) fast filtration, frequently used on high flow and subsequent to chemical treatment, and (2) slow filtration, commonly as slow sand filtration it is characterized by the effective pathogens removal on its filter layers (Bauer et al. 2011), and also it can handle regular flows where prior treatment is not necessary (Ratnayaka et al. 2009).

Thus, taking into account the previous technical and socio-cultural aspects, the most suitable technique was determined to be slow sand filtration, which besides being approved by the World Health Organization to improve water quality in rural areas, is adequate as it is easy to use and its maintenance and management is simple since it doesn't require calibration mechanisms or electronic devices.

Slow sand filtration (SSF) consists of a set of physical and biological processes that destroy pathogenic microorganisms present in water that is not apt for human consumption. SSF is a clean technology that purifies water without producing further contamination for

[3] Unidad Municipal de Asistencia Técnica Agropecuaria (In Spanish).

the environment or the consumer. It is characterized by a simple, clean and at the same time, efficient system for water treatment. Its simplicity and low cost of operation and maintenance make it an ideal system for rural areas and small communities, promoting appropriation and management by the community and facilitating future replication and expansion.

Ratnayaka et al. (2009) described the disinfection method through slow filtrations as crude water slowly circulating through a porous, sandy blanket. During the process, impurities come into contact with the particle's surface and are retained. Additionally, chemical and biological degradation processes take place. These processes reduce the matter retained to simpler forms, which leave the filter as a solution or remain as inert matter until subsequent removal or cleaning. As Bauer et al. (2011) explains the oxygen that is formed during the process is dissolved in the water, starting a chemical reaction with organic impurities and making those impurities easier to assimilate for microorganisms. On the filtering device's surface an organic matter layer is formed. The intense action of these micro-organisms traps eats and degrades organic matter contained in the water. At the same time, the compounds containing nitrogen are degraded, the nitrogen is oxygenated, some of the color is removed and a great quantity of suspended inert particles is retained by sieving.

Particularly, ISF Colombia developed this filter with easy to acquire materials and low technological complexity. These characteristics facilitate the learning process, the appropriation of the technology by the community as well as maintenance and replication.

Design

Parting from slow sand filtration technology, the group proceeded to design a system that was appropriate for the conditions presented in the project. The first step was to validate that the proposed filtration technology was suitable for the community's technical and sanitary conditions (Bauer et al. 2011). In order to carry out this step, it was necessary to compare the results of the microbiological water quality (previous Table 3) with the working ranges of the technology according to available literature.

Bearing in mind the slow filtering features, a prototype was designed in the laboratory. This design took into account the working principles that were proposed for the project, particularly that the designed technology should be appropriate for *working with* the community and easy to replicate. Thus, a simple and low cost design was chosen. The design process was developed during several discussion sessions, where students and professors from both universities were involved. Based on field observations, microbiological results and previous knowledge obtained in class; students integrated these in a variety of design proposals. Later on, with teachers supervising the process, the team established two alternatives as previous result. At the end, the team chose the design shown in Fig. 5.

Parallel to the engineering design work, the team also worked in the design of an organizational system for the implementation and development of the project. As result of the discussions between professors and students, it was decided that the validation process of the technology should be carried in parallel both in the laboratory and in the community. This last point implied developing several workshops with the community with the following purposes: a) understand the community's perception regarding water quality issues; b) raise community awareness on the necessity of implementing a system to improve water quality; c) understand their perception regarding the technological proposal and; d) obtain significant feedback about the proposed design.

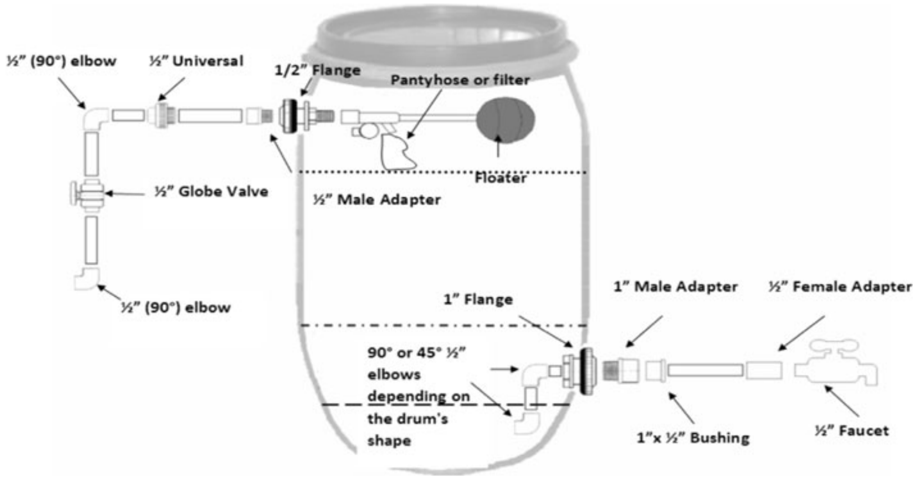


Fig. 5 Filter schematics

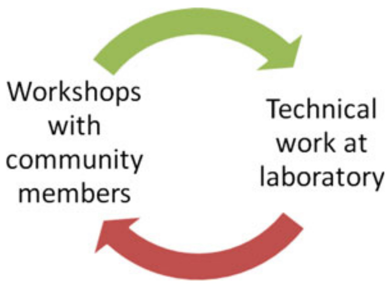
Implementation

The implementation phase had two components: one was developed with the community, and the other in the laboratory. The activities described in this section allow adjusting the technology to community context, in order to develop a socially robust technology (Gibbons et al. 2001). This concept can be seen in Fig. 6:

Work at the Laboratory

After assembling and stabilizing the filtering bed, the technology was tested in the laboratory with water from the district. The trial's results showed a continuous flow and improvement in water quality. Subsequently, a second phase was carried out which consisted of filtered water analysis following physiochemical and microbiological parameters: (turbidity, pH, conductivity, real color, total coliforms and *E-coli*). All the information related to the filter efficiency in the laboratory was recorded which includes the reviewing quality parameters related to the organoleptic properties of the treated water corresponding to tests carried out over three weeks, yielding reliable results under current environmental laws in the removal of substances in solution and particles suspended in water. As the filter bed develops over time, the filtration system increases its effectiveness producing safe

Fig. 6 Feedback process during implementation phase



water, apt for human consumption and demonstrating that the filter design through grain components and accessories is likely to be a suitable technology to provide quality water to the underprivileged (Ramírez et al. 2011).

Work with the Community

Keeping in mind that the group had decided on the type of technology based on the community's feedback and the characteristics of the water, the implementation process with the community was participatory in nature. Activities and responsibilities were jointly coordinated with the community. Sometimes, engineers provided and validated specific engineering knowledge; other times, it was necessary that the community had an active role in implementing the proposed solutions and providing feedback, even in technical aspects. The members of the community were responsible for organizing meetings between them and the group of engineers; preparing the installation sites for the filters and providing technical and cultural feedback regarding the use of the filter and its maintenance (see Fig. 7). Involving the community is a central part in the implementation of the project as it promotes ownership and helps develop the knowledge and skills necessary to operate the system autonomously. The community participated giving their opinion and suggestions about important aspects such as:

- The specific implementation of the filters in houses, including the materials and the design of the water connections.
- The installation process: in which order the filters would be installed, in order to define a pilot phase (phase 1) and replication phase (phase 2).
- Determining which members would participate in the building process and which would be in charge of maintaining the filters.

These three elements were crucial, in developing empowerment and autonomy in the community regarding the project, promoting the sustainability of the solution in the long-term. Moreover, the involvement of the community made the original design proposed by engineers to fit the conditions of the community.

Fig. 7 Work with community during implementation phase

As it has been said before, these sessions allowed discussion, the exchange of ideas, and validation of the process and feedback of the project. During the entire project, the team of engineers had to make sure that all relevant stakeholders were being taken into account and that all opinions were given the same importance. In order for this to happen it was necessary to gradually construct a common language which would allow effective communication and avoid exclusion of stakeholders and confusion. This was carried out through meetings and workshops aimed at establishing this common ground. After these workshops, ISF Colombia carried out a pilot project in four homes, one of which belonged to the community leader. Working these four homes allowed the team to obtain valuable feedback regarding filter design, the construction process and how to incorporate the community's unique social and cultural characteristics into the project's design and development.

As a side note, the team had to very careful when dealing with local government and politicians in order to avoid them taking credit for the work being carried out as they might use this to promote their political career. As such, ISF-Col was very careful not to commit to anything it might not be able to accomplish and made it very clear that the implementation of the project was a joint work between the members of the community and the engineering team.

Although in previous phases ISF Colombia attempted to work with the community, it is in the process of implementing the technology where the characteristics of a system that learns to learn are observed. At this stage, a system composed of subsystems can be observed, where these subsystems can integrate the local knowledge (community) and scientific knowledge (ISF), so that the technology that has been designed can really help to improve life quality within the community, create autonomous communities and generate technological knowledge that can be replicable in other contexts.

Operation

Filter Assembly in the Field

Having implemented the pilot project, consensus was reached with the community regarding the construction process. Mainly the decision was about the order of filter installation that would depend on the level of participation in the implementation phase workshops. As a result, 16 filters were installed in Guayabal de Siquima.

In this phase the community's help was very important (see Fig. 8). A tank was installed in an assigned place in every house. The filtering bed was poured in a way that would guarantee that its stratification had the same dimensions as the laboratory prototype. In addition, awareness campaigns were addressed to the community by the students who played a crucial role. The community provided ideas for controlling and managing the proposed system.

Monitoring System Operation

In order to ensure the sustainability over time, the engineers and the community developed two monitoring subsystems:

- The main community leader postulated himself as a sort of inspector to ensure the correct functioning of the filters. He took advantage of his previous knowledge in plumbing and his good relationships with all community members. For example he

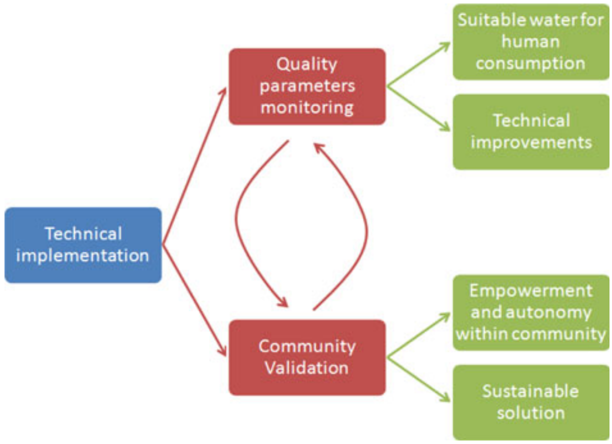


Fig. 8 Feedback process during operation phase

conducted minor repairs and informed the engineers of the improvements or final status of the filter. Thus, the main community leader became the maintenance inspector and the link between engineers and community.

- Engineers carried out periodic visits to check the filters' status and the filters' impact over the community. In the first monitoring visits, engineers did microbiological tests to determine whether the filters were functioning properly. Subsequent visits were conducted to analyze physicochemical aspects. In the third group of visits, the team provided further training to the community regarding filter operation and validated the maintenance process with the community. Finally some semi-structured visits were made to inquire about several aspects such as the identification of new replication opportunities, and discuss the project to promote knowledge transfer between the stakeholders (Ramírez et al. 2011).

Main Results

The aim of this section is to discuss the results obtained in the case study from two perspectives: first, the results obtained in the field, regarding *water quality*, from the point of view of the *community* and the *engineers*. Second, based on these results, we discuss how the systemic framework proposed on "Theoretical Foundations for a Project Design Framework Using a Systemic Approach" section impacted project development.

Field Results

Regarding *water quality*, the implemented system has been able to remove 90% of fecal and total coliforms during the maturing period of the filtering bed (see Fig. 9). This shows that the technology proposed improves the organoleptic conditions of the water to be treated; hence it substantially decreases total suspended solids present in the problematic water source and increases the quality of drinking water. This shows that the device provides safe water for human consumption, with a small amount of pathogen agents present at the filter outlet. The microbiological colonies present are not a risk for human

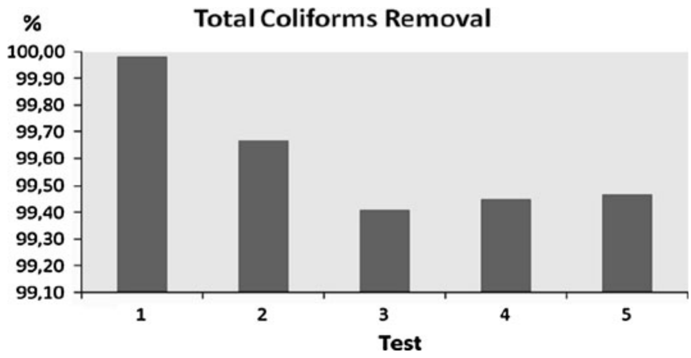


Fig. 9 Removal efficiency of micro organisms

health. The microbiological and physicochemical results presented here were approved by the Environmental Engineering Laboratory of the Universidad de los Andes. This laboratory is certified by IDEAM[4] (Spanish acronym), particularly regarding standard 17025 for the water matrix in the following parameters: DBO5, DQO, Detergents like SAAM, total suspended solids and total nitrogen. Also it is certified for pH and authorized by the Ministry of Social Protection of Colombia. It participates as part of PICCAP (Spanish acronym)—Inter-laboratories Program for control the quality of drinkable Water (Laboratorio Integrado de Ingeniería Civil y Ambiental, n.d.).

Regarding the *community,* the technology described above was implemented in 16 families and is currently being operated by at least 14 of them (Ramírez et al. 2011). Furthermore, the project improved health conditions and the community, since one of the main causes of gastrointestinal diseases was eliminated.[5]

From the social point of view, the relations within the social network inside the community were strengthened, since the interaction and cooperation between community members during the project improved their relations. Furthermore, one of the leaders acquired the role of carrying out the maintenance of the filters, generating a new network inside the community. From an individual point of view, the families acquired several new knowledge that may contribute to improve their living conditions. Many of them acquired new healthy practices: some families improved their practices related to dwelling, improved or reorganized their house, and changed some of their habits. Examples of this were the installation of a grid to avoid insects, the use of rain water through a collection point to use this water in the filter, or restricted the interaction between animals, water and food.

In addition, the community acquired several technical skills, which may promote a sustainable operation of the filters; the community learned how to build a filter, the inner characteristics that enable it's the correct functioning and the main points regarding the maintenance process. Even more, the engineers presented cases when the filter might need a change or improvement and what to do in those cases to at least one member of each family and gave special training to the community leader, so that he may act as a supporting system in maintenance process. These observations were made during the

[4] Institute of Environmental Studies (Instituto de Estudios Ambientales).

[5] However, there is no medial proof of this statement, since there was not possible to access medical statistics.

monitoring process after the project was finished, which included several interviews (Ramírez et al. 2011).

Regarding the *engineers,* they gained valuable experienced that may serve as a model for future interventions in communities with similar problems and socio-cultural conditions to make possible the group's action regarding water at a national level. Furthermore, the group learned that when working with vulnerable communities, the implementation of appropriate technology requires much more than theoretical and laboratory work. The involvement of the community is very important, so engineers learned that every time progress is made in the design table or at the laboratory, the results should be shared with all relevant stakeholders in order to facilitate feedback and cooperation through the joint construction of knowledge.

The Impact of OCDIO Systemic Framework on the Project

The previous results showed that the integration of engineering design framework—CDIO—with systemic approach results in a scheme to develop a project that integrate engineering technical knowledge with local knowledge from the community. Particularly, the project improved living conditions in rural communities and produced knowledge between the stakeholders in order to ensure sustainability in the long term.

During the project, a good amount of knowledge was jointly constructed by engineers and community members, especially based on *observation* process where cause-effect and feedback relationships are identified, as well as *subsystems* and the several *cause and effect relationships within the system*; this is crucial in knowledge's construction.

Then they conceived together the formulation, contextualization and a possible solution to the observed reality that allows the appearance of some systemic elements. For example, it allowed *cooperation between stakeholders* and *autonomy* on system operation; two characteristics that considerably improved the probability of the system being *sustainable*. In developing cooperation between several stakeholders, it was necessary to develop communication channels between engineers and community members, and particularly with community leaders; thanks to this each stakeholders could define responsibilities and their role in the project. Mainly in this process, each actor participated in the activities related to his area of expertise. For example in design and implementation phases of the project, engineers guided the process and technical issues, leaders guided the process to the community context, and finally the community participated and validated the identification of the problem.

However, the integration of knowledge coming from pluralistic actors was only possible through a partnership between Engineering and Social Work. This discipline places emphasis on the particularities of the communities with whom professionals work, recognizing and addressing that communities are composed by individuals who bring their knowledge, stories, dreams, experiences, and frustrations. All of this is vital for all of the framework phases. This dialogic process changes the perception of some engineering professionals, who believe that technical solutions are sufficient to address and mitigate certain perceived needs in society. It also opens the door to include participatory processes in project development.

Consequently, the proposed framework allow to real contribution to community development through the integration of engineering and real world problems. Mainly, this integration is established based on several perspectives coming from the relevant stakeholders and the promotion of active participation throughout the entire phases of the project: observation, conception, design, implementation and operation.

The practical and theoretical results of the study case presented above are strong evidence to argue that the framework proposed in this paper has a significant potential in developing engineering solutions for working *with* vulnerable communities and in addressing quality water supply problem in Colombia and in other countries with similar problems. To advance in this direction, it is necessary to consider the question of how to replicate this framework in other contexts.

Limitations

When addressing the question about the replication of the proposed framework, it is also important to highlight the theoretical and practical limitations of our proposal. It is important to recognize that the methodology used in the case study does not have general validity, since other projects would require that the *framework* be adapted to different social, technological and cultural contexts. Regarding the case study presented, it is important to recognize that the community was deeply involved in the implementation and operation phases of the project; however there was not the same degree of participation in the observation, conceiving and design phases. Recent experiences from ISF Colombia projects have shown that involving local high school students as key actors in these phases can generate solutions with great potential to involve all the community. These limitations are a key component in the learning process of the group, and they have become relevant aspects when the framework has been replicated in other communities. It is expected that future projects can produce theoretical and practical results that will result critical in developing further our framework.

Conclusions

In rural areas of Colombia there is often no safe water supply available to the population in those areas. Despite several efforts coming from the national and local governments, and rural communities, the problem still persists in several locations. To face this situation, a systemic framework to design engineering projects to improve the quality of life of the most vulnerable populations is proposed. This framework should integrate pluralistic perspectives coming from several stakeholders, and furthermore, should enhance cooperation and empowerment between them. The proposed framework is based in the CDIO framework: conceive, design, implement and operate. This paper proposes to add the *observation* phase as the initial step of the process. In order to illustrate the potential of this framework a group of students and professor from two universities called ISF Colombia ran a quality water improvement project in a rural district called 'Torres'. The project focused on developing a decentralized filtering system that currently benefits 16 families from the area. The technical joint work was characterized by the commitment displayed by the members of the community.

The project resulted in the improvement of the living conditions, through the creation of a reliable water supply through a filtering system supported by training in monitoring and the maintenance of the system. Furthermore, the quality of life in the community improved thanks to the implantation of good sanitary and hygiene practices in daily life; the social relationships in the community strengthened due to the positive interaction between neighbors and the professionals from ISF Colombia. Engineers involved learned several strategies to work with vulnerable communities, where they recognize that the conception, design, implementation and operation processes are useless if they are not carried out jointly with the direct beneficiaries, the community.

The results of the case study provide evidence that the proposed framework can achieve very significant results in improving quality water access in other rural areas in Colombia. The integration of systemic elements with a design framework such as CDIO, including the addition of an observation phase, can promote autonomy and cooperation between stakeholders in a complex situation such as this, ensuring long term sustainability of the solution. However, as discussed before, there are still several limitations for replicating this proposal. Current research from ISF Colombia focuses on addressing these issues.

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