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# Formation of critical thinking related to the energetic efficiency of applied physics processes of civil engineering works

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**Abstract.** Current problems associated to contamination and climate change claim for urgent solutions to make real a sustainable development of modern societies. To answer that call, the efficiency of applied physics processes must be continuously evaluated. Particularly, engineering programs are called to strengthen the training offer related to basic and applied physics sciences considering energetic transformation and transferring processes. In the civil engineering field, design, construction, functioning, and final disposition of buildings can be understood as applied physics processes. This work proposes an approach for defining and studying possible variables related to energetic processes and their mutual relationship. Such variables must be able to describe the processes of energetic changes which can occur during construction of civil works. To do so, qualitative analysis of mathematic expressions is done to promote the formation of abstract mental connections made of sensitivity and logical thinking. The methodology is based on four moments: (a) students' brainstorming related to a particular issue, (b) identification of main topics related to energy transformation, (c) variable operationalization, (d) proposal of mathematical expressions. This proposal is expected to facilitate the construction of concepts related to sustainable development and help students to trust themselves when taking well thought out risks.

## 1. Introduction

Modern life comfort has made people to forget how much effort is involved to make the parts of a building work. For example, a simple faucet is composed by a flow stopping device and a tubular structure which are made of multiple materials. A typical user is not usually aware of how it was manufactured and what to do if repairing is needed. Furthermore, it is often ignored how long the tap has been in service and how long it can last. These and other reflections show that aspects related to keeping the tap in service are often ignored. Talking in terms of applied physics, when the faucet ends its useful life, energy will have been invested in extraction of raw material, processing, transportation, installation, use and disposal. Each of these sources of energy consumption is made up of countless promoters. For example, the energy consumed by use of the tap is a function of the frequency of opening and closing, user treatment, obsolescence of the appliance, water quality, water waste, bioreceptivity, and many other factors [1]. However, to deal with the problem in a rational manner, these promoters must be grouped and treated by means of simplified expressions that appropriately describe their contribution to energy consumption. This work presents a proposal to help students taking applied physics subjects to connect abstract ideas with concrete solutions, through the analysis of promoters of energy consumption in civil works and their influence on sustainable development.

Although the "dissection" of knowledge can be helpful in simplifying teaching, ignoring the context of what is being taught can be a major obstacle. On the other hand, the need to train large numbers of



people is undeniable, so strategies must be sought to improve education policies around the world. In fact, the standardization and industrialization of teaching often impose limitations on the individual capabilities of students. It is urgent to find a balance between standardized teaching for groups and that required by the individual [2]. To achieve this balance, the science, technology, engineering, art, and math (STEAM) education philosophy proposes not to separate what is taught from the context in which what is taught occurs.

The so-called STEAM education is based on the teaching of science, technology, engineering, art, and math knowledge to promote the formation of abstract mental connections made of sensitivity and logical thinking [3,4]. This work is based on the postulates of STEAM education. Colaborative work, artistic sensitivity and emotional manifestations have been considered to complement the “hard sciences” knowledge. This communion of knowledges will facilitate the construction of concepts of efficiency, efficacy, durability, quality, and identification of building processes. Also, it will help students to trust themselves when taking well thought out risks [5].

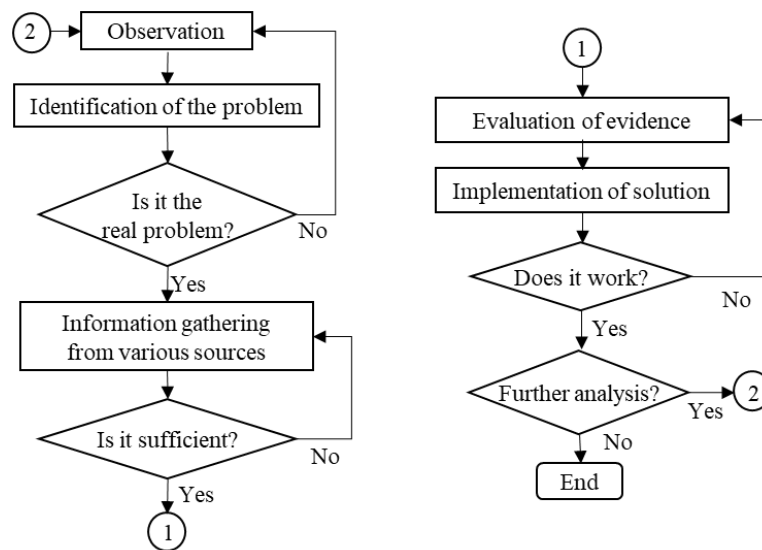
## 2. Approach to a definition of critical thinking

The concept of critical thinking is dynamic and subjective and objective at the same time, so it cannot be defined in a strict form. However, it is necessary to have a guide on how it can be developed in the students of applied physics subjects. In this sense, critical thinking can be understood as a mental process that enhances abilities to conceptualize, analyze, apply, provide feedback, reason, communicate and rectify any type of knowledge [6,7]. This process promotes the self-regulation of the thinker and can be facilitated with methodologies called learning-by-doing, in which the imagination and the artistic spirit make him fall in love with knowledge.

Critical thinking is associated with essential human values. Freedom, independence, awareness of unity, respect for the other, open mind and strength are hallmarks of a critical thinker. Critical thinking requires will, dedication, and innocence, characteristics that should not be confused with recklessness, arrogance, and naivety. For this reason, it is important to awaken attitudes and strengthen aptitudes in the student to fertilize the mental field where the human values of critical thinking will grow. Understanding what critical thinking is and its possibilities requires deep philosophical reflection and evidence based on real observations. It is not enough to use personal intuitions and popular beliefs to explain its relevance and implement proposals for its strengthening. Indeed, it is necessary to strengthen the frame of reference, and complement the limitations arisen from the numerical handling of the evidence, considering the possibility that the thinker is formed as proposed by the theory of dual inheritance (gene-culture coevolution) [8,9].

In this proposal, Bloom's taxonomy is adopted to delimit the object of attention to the so-called superior thinking skills [10]. Such skills involve analysis, synthesis, and evaluation of what is thought, and the creation of new thoughts born of the hybridization of the objective and the subjective. In practical terms, these abilities are based on what is sensory captured, and on the emotions involved in that act of capturing. However, the synergy generated in the mind of the thinker allows him/her to adapt to a changing world, an ability that empowers him/her to be ready for existing and future job requirements.

Figure 1 presents a flow chart of the critical thinking training process. Here, the definition of a problem is given in a positive sense as “question to be clarified, a thing that is difficult to deal with or to understand” [11,12]. The thinker first looks at reality and identifies a problem. Then he/she preliminarily evaluates whether the problem deserves to be studied. If the answer is yes, he/she proceeds to collect information that confirms or contradicts what he/she believes may be the genesis of the problem. Once he/she considers that there is enough information, he/she filters it to understand it and propose some solutions. Then he/she chooses the best solution and applies it to study its efficiency and effectiveness. After evaluating the results of the applied solution, the thinker can choose whether to accept it or to improve it. In fact, once the dynamics of thinking critically has been promoted, the process tends to continue indefinitely following the route marked by number 2 in the diagram. This dynamic is what strengthens the human being mentally and consequently his/her entire being.



**Figure 1.** Flow chart of activities related to the formation of critical thinking.

### 3. Methodology

This work proposes an approach for defining and studying possible variables related to energetic processes and their mutual relationship. In terms of applied physics, such variables must be able to describe the processes of energetic changes which can occur during construction of civil works. Using qualitative analysis of a mathematic expression inspired in the fundamentals of the so-called STEAM education, it is possible to harmonize science, technology, engineering, art, and math knowledge and promote the formation of abstract mental connections made of sensitivity and logical thinking [3,4].

The methodology of this approach is based on five moments; (a) brainstorming from students related to a given issue; (b) identification of main topics related to energy's transformation; (c) variable operationalization; (d) proposal of mathematical expressions; (e) interpretation of numbers given by defined expressions.

The teacher must be able to guide and connect all previously defined parts of the process. The proposal of the issue to study can come from the students or the professor, although it is preferable that one of those involved knows in depth the issue's context. Then, all the ideas arisen must be recorded to classify them with reference to the transformation of energy that they require. This classification makes possible to identify the basic promoters of energy consumption and insert them into large categories called "energy consumers". Once the promoters have been identified, an operationalization of variables which are related by means of mathematical expressions is proposed. Mathematical expressions can include coefficients and exponents to describe the weight of each variable according to its importance within the energy consumption process. Finally, all the participants discuss their interpretation of the results obtained by applying the mathematical expressions.

This work proposes to use two forms of combination for mathematical expressions based on polynomials of several variables of degree 1 and 2 as shown in Equation (1) and Equation (2).

$$y = \sum_{i=1}^n x_i * (1 + m_i + a_i), \quad (1)$$

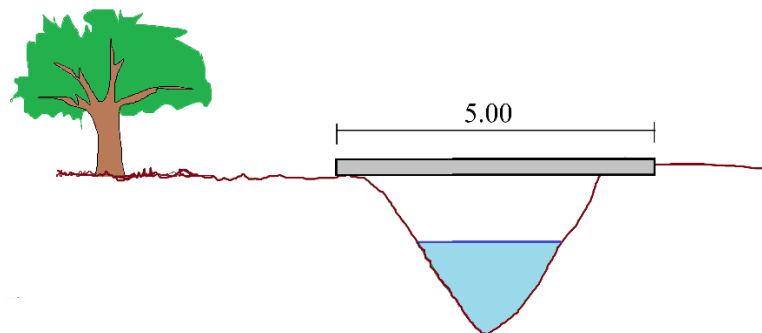
$$y = \sum_{i=1}^n x_i^2 * (1 + m_i + a_i), \quad (2)$$

where  $x_i$  is an objective variable that describes the weight of each promoter of energy consumption.  $m_i$  is a factor for considering emotions. It varies between 0 and 1;  $a_i$  is a factor for considering aesthetics and artistic harmony of the solution. It varies between 0 and 1.  $n$  is the number of promoters used in the model.

To seek objectivity in the results of Equation (1) and Equation (2), it is necessary to normalize the energy consumption per year of each promoter with respect to that of the promoter that consumes the most. It is suggested to use a normalization scale with whole numbers from 1 to 5, where 1 represents very low consumption and 5 very high consumption. On the other hand, it is considered that the current energy balance constitutes the base line of all calculations, that is, it defines the origin of coordinates for the variables of Equation (1) and Equation (2).

#### 4. Practical example

From an objective point of view, the energy consumed for the construction of civil works is spent in processes of raw material extraction, processing, transportation, installation, use and disposal of final products [13,14]. To define realistic proportions of these measurable consumptions, it is necessary to study statistics and trends given by the literature related to the processes to be evaluated. However, there are intangible values that must be considered in the evaluation of this consumption. In this work, these intangible values are categorized as “uncertainties” and are associated with emotional aspects and artistic perception.



**Figure 2.** Practical example for critical thinking training related to energy consumption.

For example, critical thinking can be formed analyzing the energy efficiency when building the river crossing shown in figure 2. To do so, the process recommended in section 3 can be applied according to the following:

- Three possible structural materials are chosen: wood, steel, or reinforced concrete.
- A brainstorming related to promoters of energy consumption is recorded and summarized in columns 2, 4, and 6 of Table 1.
- The promoters are grouped according to the categories of energy consumers shown in the first column of table 1.
- An objective value  $x_i$  is assigned to each promoter based on what is found in the literature and it is recorded in columns 3, 5, and 7 of Table 1. To assign this value, the amount of material required for conforming the beam and consumed energy before construction are considered. Consumed energy before construction is associated to the raw material production and final shaping and installation of beam [15,16]. For example, literature reports that producing a unit of steel raw material requires between 10 and 12 times more energy than that required for reinforced concrete. However, the strength of steel is much higher than that of reinforced concrete [17,18]. This fact translates into a smaller volume of steel compared to that required of reinforced concrete. Ultimately, under optimal conditions, producing a steel beam may require between 1.00 and 1.20 times the energy required for a concrete beam. This process is associated with the stage of operationalization of variables.
- The preponderance that the community can give to the “uncertainties” is discussed before assigning a numerical rating that allows them to be included in a mathematical expression.

- It is chosen whether to apply Equation (1) or Equation (2) to calculate a unified energy consumption factor for each one of the three proposed solutions.
- The results obtained are compared and interpreted and the process is fed back until there is a consensus on the best solution.

Table 1 summarizes the entire process described and the results obtained when applying Equation (1). To give an initial understanding of the process, the uncertainties have been treated as objective numerical variables type  $x_i$  while the factors  $m_i$  and  $a_i$  have been taken equal to zero. The last row shows the comparable total values of the three solutions. According to the results, the lowest energy consumption is obtained when using wood and the highest is associated with reinforced concrete. The use of wood and steel demand 82% and 92% respectively of the energy demanded by the reinforced concrete.

**Table 1.** Example of brainstorming results classified according to the promoter category.

Energy consumer	Wooden structure	$x_i$	Steel structure	$x_i$	RC structure	$x_i$
Raw material extraction and processing	Type of wood	1	Iron ore mining	5	Cement	4
	Wood sawing	1	Steel scrap	1	Stone extraction	1
	Sawing waste	1	Grinding	1	Stone crushing	1
	Preservatives	1	Sieving	1	Water supply	2
	Treatment	1	Furnaces	5	Mixing	1
	Labor	1	Lamination	2	Labor	1
	Equipment	1	Labor	1	Equipment	1
			Equipment	1		
Transportation	Transport of wooden beam	1	Transport of steel beam	1	Transport of materials for mixing	2
Installation	Structure assembly	1	Structure assembly	1	Casting	3
	Labor	1	Labor	1	Curing	1
	Tools	1	Tools	1	Labor	1
					Tools	1
Use	Wood rot	3	Corrosion	3	Deterioration	1
	Water pollution	1	Water pollution	1	Water pollution	1
	Fire	3	Fire	2	Fire	1
Final disposition	Disassembly	1	Disassembly	1	Demolition	3
	Debris disposal	1	Debris disposal	2	Debris disposal	4
	Debris Recycling	1	Debris recycling	2	Debris recycling	5
Uncertainties	It is made of a living organism	5	Decomposition time	3	Decomposition time	5
	Affected species	4				
	Reforestation	1				
Total		31		35		38

As a tree needs a seed, critical thinking needs to start from prior knowledge to develop its potential. Also, thus as other forms of hybridization will allow that tree to transform even more, critical thinking will be strengthened when the issue's context grows. In the case of the training of civil engineers, this seed can be made up of technical knowledge and the emotional structure of each student. However, the interaction with their academic peers and the study of the state of the art of the issue will foster hybridization that will unlimitedly expand the possibilities of creating and strengthening a critical thinker.

In the example developed in the previous section, verifiable knowledge of energy consumption associated to extraction of raw material, processing, transportation, installation, use and disposal of final products was used. Furthermore, the possibility of introducing intangible values in the expressions of evaluation of consumption was considered. Intangible values were called "uncertainties" and were associated with emotional aspects and artistic perception. These uncertainties can control the final

decision if larger weight is assigned to them, or if they are elevated to an exponent bigger than 1 when introducing them into the mathematical expression to potentiate more their influence (as shown in Equation (2)). The foregoing allows us to perceive the possibility of applying this proposal in decision-making of small communities, provided that the variable values assignment is done rigorously and supported by the literature or popular consultation.

If the example presented in the previous section is now applied in an area where trees are sacred, it may be advisable to use Equation (2). In this case, the variables associated with uncertainties when using wood could have an exponent equal 2. Also, if  $m_i = a_i = 1$ , the total value of columns 3, 5, and 7 of Table 1 becomes 147, 35, 38, respectively. These results indicate that the energy consumed when using wood would be of the order of four times that of using the other materials. This new result will make reverse the conclusion given in the previous section and surely better describe the perception of the community.

## 5. Conclusions

This work presents a practical proposal for the formation of critical thinking in students which take applied physics subjects. The proposal is based on the definition and study of possible variables related to energetic processes and their mutual relationship expressed as a mathematic equation.

To show how the proposal can be applied, a practical example of application of physics concepts related to the energetic efficiency of design, construction, functioning, and final disposition of civil engineering works has been developed. Real data of energy consumption related to raw material extraction, processing, transportation, use and final disposal of structural components were used to define adequate normalized numbers to be used in mathematical expressions. Also, intangible values such as emotional aspects and artistic perception were introduced as numbers into such expressions.

The methodology of this approach is developed on five moments: Brainstorming from students related to a particular issue, identification of main topics related to energy transformation, variable operationalization, proposal of mathematical expressions, and interpretation of numbers given by those expressions.

The proposed methodology leads students of applied physics courses to identify basic promoters and consumers of energy associated to the civil works processes. Those elements are represented by numbers within the mathematical expressions which, in turn, can be composed by lineal combinations or using second degree polynomials. At the end, resultant values of mathematical expressions are interpreted and discussed by all participants.

Finally, for further research, many other uses of applied physics can be identified and handled using topics representing energy consumption related to the sustainable development issue. For example, applications in medicine, economy, astronomy, computing sciences or business administration could use a protocol similar to the proposed in this work taking care of using the necessary adaptation of variables and equations.

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