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Leveraging Mathematical Modeling to Expand Measurement-Process Opportunities for Engineering Students

Luis E Montero-Moguel, The University of Texas at San Antonio

Luis Montero-Moguel is a Ph.D. Candidate in Interdisciplinary Learning and Teaching specializing in STEM education at The University of Texas at San Antonio (UTSA). Luis holds an MSc in Mathematics Education from the University of Guadalajara and a BSc in Mechanical Engineering. Luis is an NSF-CADRE fellow. As part of his doctoral program, Luis has earned a Graduate Certificate in iSTEM Education and a Graduate Certificate in Engineering Education. With experience as an engineer and a mathematics teacher, he promotes the expansion of equitable and high-quality learning opportunities for both engineering and K–12 students through mathematical modeling. His research focuses on exploring the process of refining mathematical ideas and engineering concepts that engineering students develop while engaging in model development sequences built in real engineering contexts.

Dr. Joel Alejandro Mejia, The University of Texas at San Antonio

Dr. Joel Alejandro (Alex) Mejia is an associate professor with joint appointment in the Department of Bicultural-Bilingual Studies and the Department of Biomedical and Chemical Engineering at The University of Texas at San Antonio. Dr. Mejiaâ€™s work exam

Dr. Guadalupe Carmona, The University of Texas at San Antonio

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Abstract

The development of measurement skills is crucial for facing the challenges of the 21st century, particularly in the field of engineering, where the measurement process is fundamental for mathematical modeling in engineering design. However, ABET student learning outcomes do not explicitly include standards for measurement processes. Therefore, it is imperative to explore how mathematics education in engineering can better inform the professional development of students with modeling skills that include opportunities measurement opportunities. This qualitative case study, grounded in the Models and Modeling Perspective, aims to describe the measurement process that two groups of first-year engineering students developed when participating in a Model-Eliciting Activity (MEA) involving the modeling of a ram water pump's efficiency. Results show that the Ram Pump MEA offers ample learning opportunities for students to grasp measurement processes in engineering design. Through this process, the students attained a thorough understanding of measurement processes, with both teams successfully identifying the five key characteristics of measurement. This study contributes to the growing knowledge on how students might engage in these processes as part of mathematical modeling, and how this approach can be useful for providing future recommendations for curricula and learning outcomes alignment in engineering education.

Introduction

The challenges of the 21st century require students to engage in activities that enable them to "learn the importance of such decisions as what to measure, what to keep constant, and how to select or construct data collection instruments" [1, p. 58]. This activities are especially critical for engineering students because engineers are required to develop measurement processes during the mathematical modeling of designs [2]. Despite the significance of developing measurement processes in engineering education, ABET student learning outcomes do not explicitly include standards for measurement processes within data collection. Moreover, "measurement is often conceived as a mundane activity, and in school it typically arrives pre-formed" [3, p. 723], reducing opportunities for students to confront real situations involving measurement processes. Particularly, first-year engineering students face limited opportunities to encounter real-world situations because they are often perceived to have limited experience with the nature of engineering work [4]. The way in which STEM fields are taught is relevant and they must go "beyond traditional lecture and laboratory instruction, by incorporating rich integrated STEM learning opportunities" [5, p. 10]. Therefore, it is imperative to explore how mathematics education in engineering can better inform the professional development of students with modeling skills that include measurement learning opportunities.

Measurement sense and the development of coordination between measure and phenomenon to be modeled are crucial aspects when the modeling process involves measuring [3]. According to Hagena [6], the development of a strong measurement sense (MS) can be observed through five key indicators:

MS 1. Being able to identify and distinguish different quantities of measurement.
MS 2. Being able to measure, to estimate and to round.
MS 3. Being able to decide whether to estimate, to measure and to round.
MS 4. Having knowledge about units of measurement which includes calculating and converting units.
MS 5. Having a set of meaningful benchmarks for these units and being able to use these benchmarks [6, p. 186].

Prior research has been conducted to study learning opportunities bridging measurement processes and mathematics abilities. For instance, Hjalmarson et al. [7], as well as Glancy et al. [8], drawing from the Models and Modeling Perspective (MMP) [9], have conducted studies that lead to the conclusion that the use of Model Eliciting Activities (MEAs) contributes to elementary students developing a deep understanding of statistics when they participate in measurement processes. However, there is still limited research involving learning opportunities that can be expanded for first-year engineering students through the use of MEAs that involve data collection and the measurement process.

Therefore, due to the significance that measurement processes hold in engineering design and the limited attention they receive in the learning outcomes for first-year student training, this study, based on MMP [9], aims to shed light on the importance of incorporating measurement processes within mathematics education for engineering students during their initial years of training. The research question that guided this qualitative case study research was: *What opportunities to learn measurement processes does a modeling activity involving the use of a ram pump provide to first-year engineering students?* We use the implementation of a ram pump, which is easy to use and build at a small scale, as the mediating tool that allows students to measure, calculate, and build potential models based on the data collected. The following section provide a description of the context of the study and how the students went about creating their mathematical models of the ram pump as a potential engineering application.

Theoretical Framework

The MMP advocates for the use of MEAs both as research tools to investigate the nature of interpretation systems that participants develop to make sense of situations involving mathematical thinking and to foster student learning [10]. According to MMP, "MEAs are realistic, complex problem-solving tasks that elicit documentation of students' thinking and procedures through having students create models and solutions in response to the MEA" [11, p. 281]. MEAs are constructed based on six principles: (1) Model construction, (2) Reality, (3) Self-assessment, (4) Model-documentation, (5) Construct share-ability and re-usability, and (6) Effective prototype [12]. The MEAs principles are intentionally designed for students to construct mathematical systems that will be applied to address the needs of a client; this process is similar to what future engineers must learn to interpret constraints and affordances in engineering design [4]. Under the MMP approach, models can be defined as

> conceptual systems (consisting of elements, relations, operations, and rules governing interactions) that are expressed using external notation systems, and that are used to construct, describe, or explain the behaviors of other system(s)—perhaps so that the other system can be manipulated or predicted intelligently. A mathematical model focuses on structural characteristics (rather than, for example, physical or musical characteristics) of the relevant systems [9, p. 10].

The refinement of models and mathematical ideas are dynamic during the process of solving MEAs [13]. During this process, students go through different iteration processes or modeling cycles that evolve as they interact with their peers [9], [14]. In the modeling process, students cross disciplinary boundaries and engage in interpersonal communication [15].
In contrast to traditional teaching, which tends to focus on algorithmic and mechanistic processes, MMP highlights mathematical abilities such as (i) mathematizing, (ii) interpreting results, and (iii) analyzing the assumptions that alternative tools presuppose [16]. In the context of mathematization, the measurement process and the creation of representations play a crucial role in shaping conjectures that arise during the modeling process [17].

Methodology

With the aim of deepening our understanding of the measurement processes generated by students participating in a MEA, we chose to conduct a case study [18]. According to Yin, a case study is "a social science research method, generally used to investigate a contemporary phenomenon in depth and in its real-world context" [18, p. 349]. The following sections describe the context of the study, data collection, data analysis and procedures followed to interpret the data collected.

Participants and Context

This study, which is part of a larger study analyzing the development of critical consciousness through engineering design [19] involved a smaller subset of the data focusing on measurement processes and sense-making. In this paper, we describe the results obtained from two groups of first-year engineering students selected for the case study. These students were enrolled in a course titled *The Impact of modern technologies on society*, which also fulfills the social and behavioral sciences core curriculum requirement at the institution. The course was conducted at a Hispanic-Serving Institution with a large proportion of first-generation, low-income students, and spanned one semester. The students solved the activity in two teams, which were grouped as follows: Team 1, consisting of four students [four males] and Team 2, comprised of five students [two females and three males].

Context of the MEA

In order to elicit students' sense-making processes and gather information on the measurement procedures involved in modeling for this study, a MEA titled "Ram pump: a resource for providing running water to *las Colonias* community" was designed. The MEA was crafted considering the six design principles of MEAs [12] and comprised three sections. The first section included the context where students read and discussed the challenges faced by "las colonias" [the colonies] – an impoverished community near the U.S.-Mexico Border. This context was important to define for the students since the course was intended to expose students to complex problems that required a critical understanding of the social, economic, environmental, and political factors that impact problem solving. The adapted context of a real situation describes how the communities of las colonias are located on the Mexico-United States border, and often the houses in the settlements lack running water [20]. As a result, families transport water with buckets from communal tanks to their homes.

The second section was the problem situation in which students were tasked with analyzing the efficiency of the potential solution (i.e., the ram pump), and communicate their approach to solving the problem of water distribution to the residents of las colonias (i.e., the client). Their analysis was intended to provide the residents with instructions to use the ram pump efficiently, allowing las colonias' inhabitants to pump water from communal tanks to their homes. To do the analysis, the engineering students were required to develop the measurement process to obtain physical field data. Students were given a ram pump that was designed and built by the research teach for their data collection.

The ram pump was selected because it involved a simple system that pumped water without the use of electrical energy. The flow of water was generated by the flow of water itself, an air chamber, and two check valves (see figure 1). Through the water hammer effect in the first check valve, water was pumped to a final point. A distinctive feature of ram pumps is that the water hammer effect causes a certain amount of water wastage (water loss), while the remaining amount is pumped. Furthermore, since there is a relationship between the amount of water in the communal tank and the pump's efficiency, students were required to predict when it was advisable for the community to fill the tank.

Finally, the third section of the MEA consisted of presentations of engineering teams' final solutions. The implementation of this activity lasted three sessions, each lasting 90 minutes approximately, and was carried out during the second half of the course. To solve the MEA, engineering students were provided with a measurement toolkit. This toolkit consisted of a 3-meter measuring tape, a set of graduated measuring cups (1 liter, 1/2 liter, and 1/4 liter). Each of these cups had milliliter measurements marked every 50 ml, ounce measurements marked every 4 ounces, and cup measurements marked every half cup. The toolkit also included a 10 qt bucket with liter measurements marked every half liter, ounce measurements marked every 16 ounces, and gallon measurements marked every half gallon.

Data Collection

Data was gathered throughout the entire process of students' solving the MEA. For this study, we focused on students' data specifically involving their measurement processes. Data included audio recordings of each team during their measurement processes as they interacted with each other in order to determine the ways in which measurement data was collected by each team. In addition, students' presentations were audio recorded to analyze their sense-making during their measurement processes. These audio recordings were subsequently transcribed for further thematic analysis through the MEA framework described earlier. Additionally, we also collected models created and presented in class by teams. Finally, researcher's field notes were also used in the data analysis.

Procedures and Data Analysis

For the analysis, all audio recordings were transcribed, and data from each team's models were organized and analyzed using NVIVO 12 qualitative data analysis software. Subsequently, in order to understand the learning opportunities related to the measurement processes that arise when teams take measurements to build models describing the efficiency of the ram pump, a *protocol coding* focused on analyzing the measurement sense was developed. According to Saldaña [21], protocol coding involves encoding qualitative data based on pre-established or recommended coding systems, ensuring harmony with the objectives. Therefore, for this study, the protocol coding was developed based on the five indicators of measurement sense suggested by Hagena [6].

> MS 1. Being able to identify and distinguish different quantities of measurement.
> MS 2. Being able to measure, to estimate and to round.
> MS 3. Being able to decide whether to estimate, to measure and to round.
> MS 4. Having knowledge about units of measurement which includes calculating and converting units.
> MS 5. Having a set of meaningful benchmarks for these units and being able to use these benchmarks [6, p. 186].

Validity Criteria

To address the validity criterion in this study, we implemented a triangulation method suggested by Yin's [18]. This triangulation involved using multiple sources of evidence, including the integration and comparison of data from audio recordings of the measurement process and team presentations, the models constructed by students, and the researcher's field notes during the analysis. The triangulation process allowed for a deeper understanding of the measurement processes developed by the students, thereby expanding the validity of the findings. The triangulation process not only allowed for a deeper understanding of the measurement processes developed by the students but also enhanced the validity of the study by comparing findings across the analysis of different sources of information. This was because the analysis facilitated the integration of different sources of information, aligning with Yin [18]'s recommendations for case studies.

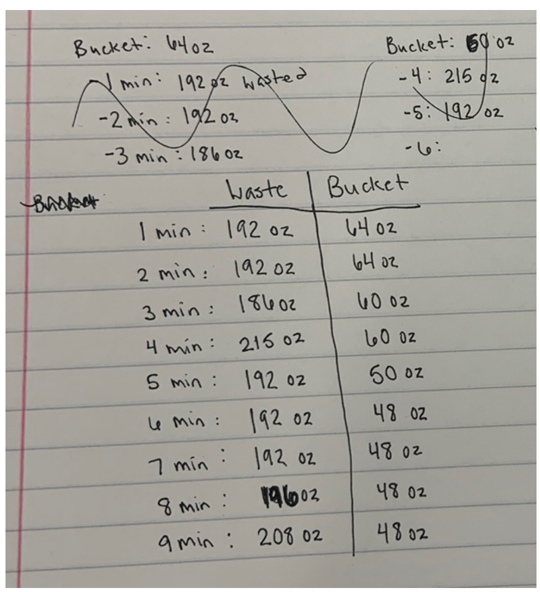
Results

Due to the MEA requirement for engineering students to describe the efficiency of the ram pump, different teams made decisions regarding the measurement process they should develop to obtain data that would enable them to model the efficiency of the ram pump. To gather this information, all teams were given individual time to operate the pump setting their own parameters. The operation of the pump involved at least three key steps: activating the suction valve, collecting pumped water (gain water), and collecting wasted water (loss water). In each case, engineering students determined which measurement tools to use from the provided tool kit (e.g., the set of graduated measuring cups, and the 10 qt bucket with measuring).

Each of the two teams organized themselves to assign roles for the measurement process. For instance, Team 1 (Fig. 1) assigned one student for manipulating the suction valve, another for recording the data and timing, a third student for measuring the pumped water quantity, and another for measuring the wasted water quantity. Two of these students transferred water from the loss water container to the measuring bucket. Each team made independent decisions regarding the data collection process, as explained below.

Fig. 1. Manipulation of the Pump by Team 1 During Their Measurement Process.

Measurement Process for Team 1. Team 1 chose to collect measurements at 1-minute time intervals; that is, they opened the suction valve, let 60 seconds elapse, closed the suction valve, and recorded the collected data. The students chose to measure both the amount of loss water and the quantity of pumped water. For pumped water and loss water the students decided to use a 10-quart bucket. During the measurement process, the team member assigned to record the data failed to note the pumped water quantity, as evident at the top of Figure 2. Consequently, the team decided to restart the measurement process.



Bucket: 64oz
-1 min: 192 oz wasted
-2 min: 192 oz
-3 min: 186 oz

Bucket: 50 oz
-4: 215 oz
-5: 192 oz
-6:

	Waste	Bucket
1 min :	192 oz	64 oz
2 min :	192 oz	64 oz
3 min :	186 oz	60 oz
4 min :	215 oz	60 oz
5 min :	192 oz	50 oz
6 min :	192 oz	48 oz
7 min :	192 oz	48 oz
8 min :	196 oz	48 oz
9 min :	208 oz	48 oz

Fig. 2. Notes Extract of Team 1’s Data Collection.

In their presentation, Team 1 described the data collection process.

> [Team 1]: All right, so these are the steps of how we took our data. So first we started by putting the hose in the bucket, and we let it run for a minute, and then we measured the

intake and the output of the water from the pump. Then we wrote the measurements using one-minute intervals, which we then listed the amount of water usable and unusable in the chart.
[Team 1]: The amount of water wasted and the amount of water that was usable from the buckets were measured separately. Using one of the buckets had measurements. The wastewater didn't. So, what we did, we measured the usable water. We dumped that out and then we poured the wasted water, poured that into the measured bucket. And then we measured how much was wasted. Then we just kept doing that until the tank was empty.

The students used the markings of the labeled bucket with measurements in ounces (maximum capacity of 256 ounces with markings every 16 ounces), estimated the approximate value of the measurement, and rounded intermediate water quantities (e.g., 60 and 50 ounces). In total, this team took nine measurements. It was noticeable that the student in charge of measuring the pumped water initially did not place the cup horizontally, but one of the team members suggested placing the cup on the table to check the measurement accurately. As the team took measurements, they engaged in reflective discussions about the pumping phenomenon as seen in their data sheet (Fig. 3).

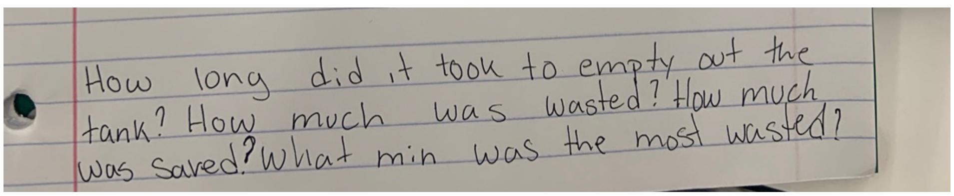


Fig. 3. Notes Extract from Team 1's Data Collection.

Team 1 also developed their interpretation of the efficiency concept based on their measurement process, pump manipulation, and interpretation of using the pump to supply water to las colonias community.

[Professor]: how would you define efficiency?
[Team 1]: We can see that during the in between like three minutes and five minutes, there's a big spike in like the amount of wasted water. Basically efficiency, trying to refill the tank before it gets to there because technically this is also going down, but it's at a standstill between the three and four minutes. But we're losing more water in that process. So maybe refilling the tank before it gets there would probably be best efficient way.

The students associated the concept of efficiency with wasting the least amount of water, hence suggesting that the tank should be kept as full as possible.

Measurement Process for Team 2. Unlike Team 1, which used time intervals (1 minute), Team 2 decided to use a 32 oz cup at full capacity as a reference point for intervals. In other words, each time the pump successfully pumped 32 oz, the team stopped the pump to take measurements of the amount of water pumped, water loss, and the duration of time. The team initially encountered challenges in coordinating the observation of the pump reaching 32 oz and closing the feed valve to take measurements. This measurement process and difficulty were described for the team in their presentation.

> [Team 2]: Okay. So, the problem, for the first initial contact, so we were doing our trials. We timed it from where we first started pulling the lever to where it dropped from the cup. And it was it like for the first time it was around 3.5 seconds, but it just kept going up and up and up and up. I just took a long time for it to actually start, start flowing and then for regulation. All of our 13 trials, we had three where it just stopped. So, if this was used for a person that was trying to use it and just trying to do something that they wouldn't be able to go and do something because it's still had to regulate it and see if it just stopped randomly. And then the weight, one of the big problems was like carrying the bucket and all of our solutions has a bucket involved. So, the problem was that it was too hard on our backs and the kids can carry it. Then our two solutions, which included the extra bucket underneath for the excess water, so that they could just pour it back into the tank but it had tubes included inside the bucket, so straight back into the tank.

Team 2 chose to use a 32-ounce cup for pumped water, utilizing the marked scale in ounces. To measure water loss, the team used the 10 Qt Bucket with a measurement scale of 16 ounces, employing the gallon and quart scale, which they later converted to ounces for uniformity in measurement units. As evident in the table constructed by the students (Fig. 4), the measurement process entailed intermediate values between the cup and bucket's scale. Consequently, Team 2 had to rely on the meaningful benchmarks of the bucket to estimate and round their actual water measurements.

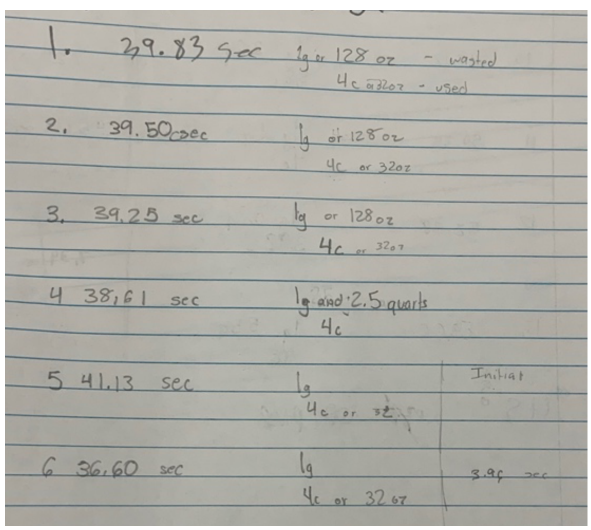

1. 29.83 Sec 1g or 128 oz - wasted
4c or 32oz - used
2. 39.50 sec 1g or 128 oz
4c or 32oz
3. 39.25 sec 1g or 128 oz
4c or 32oz
4 38,61 sec 1g and 2.5 quarts
4c
5 41.13 sec 1g
4c or 32
Initial
6 36.60 sec 1g
4c or 32 oz
3.95 sec

Fig. 4. Notes Extract from Team 2's Data Collection.

In total, Team 2 included 10 useful measurements in their efficiency analysis (Fig. 5). They mentioned that they eliminated their first three measurements due to differences in measurement process, with each iteration of the process influenced by the refinement of their techniques. For instance, initially, there was a coordination difference between the person in charge of ensuring that it reached 32 oz and the person responsible for manipulating the opening valve, but they later synchronized better.

Time (seconds)	Water Loss (oz)	Water Obtained (oz)	Time from pump to Tube (seconds)
39.83	128	32	~
39.5	128	32	~
39.25	128	32	~
38.61	208	32	~
41.13	128	32	~
36.6	128	32	3.96
42.31	128	32	5.51
47.13	208	32	8.18
44.27	208	32	6.68
47.12	211.2	30.4	7.25
50.35	288	32	5.69
52.38	294.4	31.36	7.34
53.66	304	32	6.1

Fig. 5. Data Table of Team 2's Model.

Regarding efficiency, the students included in their conclusions that "In terms of efficiency, the water loss vs. water gain was calculated to be at a 6:1 ratio". Additionally, they mentioned the following in their presentation:

> [Team 2]: Water losses is about 6.1 ratio a ram pump [6:1 refers to the ratio between wasted water and useful water]. So, in terms of efficiency, it was not efficient at all, for "las colonias" to put it in the tank, it's more the full to fill up the tank fully.

The team 2 constructed their definition of efficiency associated with the relationship they identified between wasted water and gained water. Additionally, they observed that the efficiency of the pump decreased as the tank emptied. Consequently, their descriptions of efficiency were also linked to the colonias' needs to maintain the tank as full as possible. Two teams constructed tables to describe their efficiency data collection and gathered data on water discharge and pump water loss. Team 1 presented a total of nine measurements, and Team 2 took a total of ten measurements.

Discussion and Conclusions

In this study, we conducted a qualitative case study to identify opportunities for freshmen engineering students to learning measurement processes when they engaged in a model-eliciting activity that involves the use of a ram pump. Our data analysis allowed us to identify different opportunities for learning measurement that the Ram Pump MEA created for each of the participating teams.

Throughout the measurement process, the two teams traversed the five indicators of measurement sense suggested by Hagena [6]. The interaction and manipulation of the pump, as well as the selection of containers and scales for measurement from the toolkit, demonstrate that the two teams identified and distinguished different quantities of measurement (MS1). Due to the need to obtain data to model pump efficiency, teams decided what data to collect, measure, estimate, and even round (MS3). It was observed that Team 1 chose 1-minute intervals and Team 2 decided to use the filling of the 32 oz cup as their reference marker.

Estimation and rounding (MS2) are also relevant activities at different stages of the design process [2], which are rarely encountered in traditional mathematics problems. It is noteworthy that this process was iterative and refined as students took their measurements. For example, Team 1 refined the measurement of pumped water during their nine measurements, waiting for the water to transition from turbulent to static for a more accurate measurement. On the other hand, Team 2 improved the synchronization among team members. As mentioned by Lesh and Doerr [8], models are constantly refined during the modeling process. In the specific case of the Ram Pump MEA, the processes also involved the refinement of measurement procedures and teamwork.

Due to the discrete scales on the measurement containers, students used the marked measurements as meaningful benchmarks to identify and estimate their measurements (MS5). Additionally, as students handled different types of units, they had to make multiple unit conversions (MS4). For instance, Team 2 performed conversions involving quarts, gallons, and cups. The handling of units of measurement is a fundamental skill in STEM disciplines [1]. The results indicate that each team independently decided which units of measurement to use and how to convert these units for interpreting pump efficiency. In other words, they determined the mathematics required to solve the MEA. This finding aligns with Hamilton [13]on engineers deciding and creating the necessary mathematics to address problems. Furthermore, as evident in the team dialogues, the measurement process was relevant to constructing the concept of efficiency. Teams associated the concept of efficiency with the relationship between water loss and pumped water, depending on the quantity of water in the storage tank. Students also applied the concept of efficiency to the contextual situation of providing running water to las colonias community. This finding identifies that the MEA expanded opportunities rarely available to students to "grapple with the foundational conceptual problem of generating and validating coordination between a measure and the phenomenon being measured" [3, p. 723].

In sum, when first-year engineering students solved the Ram Pump MEA, they created their own definitions of pump efficiency *in relation to their interpretation of* the specific needs of the people living in las colonias. Although the two teams concluded with the recommendation for las colonias to keep the tank as full as possible to achieve the highest pump efficiency, they focused on different aspects of the model to define efficiency. We conclude that the Ram Pump MEA opened many opportunities for first-year engineering students to learn and elicit measurement processes through the engineering design process cycle. As they collected data on water pumped and water loss, students refined their models in different ways. For instance, based on Hagena's framework and our coding scheme [6], we can conclude that students' learning of measurement processes was comprehensive, as the two teams elicited the five characteristics of measurement.

Implications

This study can contribute to engineering education by informing about teaching processes that expand learning opportunities for first-year engineering students when engaging in measurement activities. Moreover, this exploratory study could prompt a reconsideration of the importance of explicitly including measurement practices in the ABET criteria.

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