The Role of Mathematical Modeling in Integrating Disciplinary and Societal Knowledge: An Epistemic Network Analysis Study

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Introduction

Mathematical modeling is a critical component of the engineering design process [1]. Since the design process distinguishes engineering from other disciplines, mathematical modeling plays a fundamental role in engineering practice, allowing engineers to describe, analyze, and predict their designs [2]. These mathematical models contribute in addressing questions that arise during the engineering design process [3]. Mathematical modeling is essential for mitigating unforeseen consequences, which can often have significant, sometimes tragic, outcomes [4].

The importance of mathematical modeling in engineering design makes it crucial for engineering students to engage in modeling activities throughout their education, starting from foundational courses [5]. Through mathematical modeling learning activities, particularly Model Eliciting Activities (MEAs), engineering students can engage in complex, open-ended problems designed to meet real-world client needs [1], [6], [7]. However, while engineering mathematics courses include concepts relevant to the engineering field, they often lack emphasis on the development of modeling processes due to traditional instructional approaches [5]. Traditional teaching methods typically focus on algorithmic mathematical steps leading to a single correct solution. This approach contrasts with the ABET outcomes, which emphasize applying mathematical principles to solve complex engineering problems [8]. Consequently, preparing engineering students necessitates incorporating mathematical modeling problems similar to the engineering challenges faced by practicing engineers [9].

Real-life engineering challenges are sociotechnical in nature, requiring the integration of technical and societal knowledge [10]. ABET criteria further emphasize the importance of enabling students to make informed judgments within societal contexts [8]. However, engineering education frequently addresses technical issues without adequately reinforcing their broader societal implications [11, 12]. Therefore, engineering education needs to transition toward more complex problem approaches that integrate both disciplinary and societal knowledge [13]. This transition will require research in engineering education to inform teaching methods that promote the engineering students' integration of disciplinary and societal knowledge.

This paper is part of a larger study. The research presented in this manuscript aims to contribute to the field of mathematics engineering education by exploring the processes through which engineering students integrate disciplinary knowledge and critical reflections while participating in modeling activities, specifically MEAs. In this evidence-based research paper we present an exploratory case study involving five first-year engineering students. The study addresses the following research question: *How does a team of first-year engineering students incorporate disciplinary and societal aspects in their solution to the Ram Pump MEA?*

Conceptual Framework

Models and Modeling Perspective

The Models and Modeling Perspective (MMP) highlight that students possess relevant ideas enabling them to address problematic situations [14]. To elicit and promote the evolution of these ideas, the MMP emphasizes incorporating learning environments in engineering education where students engage in MEAs [15]. MEAs are defined as "open-ended, realistic, client-driven problems that require the creation or adaptation of a mathematical model for a given situation" [7, p. 17]. Under the MMP approach, models are

> "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" [14, p. 10]

The evolution of these models is not linear but occurs through iterative development cycles [16, 17, 18]**.** These iterative processes emerge as students solve MEAs and interact with peers, including classmates and instructors [14]. MEAs are designed to facilitate such interactions and ensure that the models students express through various representational media (e.g., diagrams, graphical representations, or verbal explanations) make their thought processes visible during problem solving [19]. Students' conceptual systems also evolve over time, underscoring the importance of integrating modeling activities from the early stages of engineering education rather than delaying these experiences until advanced design projects [20].

Frequently, problems in traditional mathematics education focus on students providing a single answer to scenarios defined by specific data, leading to sequences of facts and constraints predetermined by the problem designer. In contrast, with MEAs, "the heart of the problem is for students themselves to develop an explicit mathematical interpretation of situations" [21, p. 595]. This fundamental aspect, in which students themselves develop the process of interpretation, is similar to the problems engineers face in practice.
When solving MEAs, students encounter complex scenarios that require them to engage in the process of mathematization, which often involves "quantifying, dimensionalizing, coordinating, or (in general) mathematizing objects, relations, operations, patterns, and regularities which do not occur in pre-mathematized forms" [22, p. 348]. Both mathematization and measurement processes are fundamental for engineers to address challenges in the field of engineering.

The construction of MEAs parallels the development of students' models; both require iterative processes involving development, modification, and adaptation [17]. To guide the design of MEAs, the MMP outlines six principles: *model construction, reality, self-assessment, model documentation, model shareability and reusability, and effective prototype (simplicity)* [7]. In the context of engineering education, it is crucial for MEAs to be constructed within authentic and relevant engineering contexts [7, 23]. Therefore, in order to address an authentic and relevant context for this study, we base our framework on the concept of Appropriate Technology [24] which guides our selection of the MEA context.

Appropriate Technology

Appropriate Technology has been a fundamental framework supporting engineering education over the years [25]. This framework advocates for the design of *appropriate technologies* –we differentiate appropriate technologies in lowercase to refer to the specific technologies and Appropriate Technologies in uppercase to refer to the theoretical framework– that are "compatible with local, cultural, and economic conditions (i.e., the human, material, and cultural resources of the economy) and utilize locally available materials and energy resources, with tools and processes maintained and operationally controlled by the local population" [26, p. 4]. Appropriate Technology advocates for a vision in which individuals and communities build their independence through technologies they can create, use, and maintain with their own resources [27]. Therefore, the design and selection of appropriate technologies should prioritize those that are "cheap enough to be accessible to virtually everyone, suitable for small-scale applications, and compatible with humanity's need for creativity" [24, p. 20].

The education of engineering students must be reoriented to prepare them to identify a broader range of solutions that include, and even prioritize, design approaches that are organic, gentle, and non-violent toward the environment, people, and communities [23]. However, engineering programs often prioritize training students to address challenges in developed communities, reducing opportunities to tackle the problems of marginalized communities, which often face resource constraints [28]. For this reason, based on the Appropriate Technology framework, Montero et al. [6] emphasize the need to prepare engineering students with a sociotechnical perspective that departs from technocratic approaches.

Appropriate Technology encourages engineers to consider, analyze, and describe the context in which their designs will be implemented [29]. Developing engineering solutions without prioritizing the context can lead to technologies that cause disruption and foster dependency in communities, particularly those that are marginalized [24]. Through the lens of Appropriate Technology, designs should consider the social and economic characteristics of communities to promote their independence and growth [30, 31]. Thus, the Appropriate Technology framework emphasizes the critical role of education in advancing science and engineering to address fundamental needs, such as ensuring access to clean water for all communities, especially those that are marginalized [32].

Methods

To address the research question, we designed an exploratory single case study [33].

Participants

For this study, we selected a team of first-year engineering students. The team consisted of five students, three men and two women. The students were enrolled in the course *The Impact of Modern Technology on Society* at a Hispanic Serving Institution in the Southwestern United States in a U.S. state that shares a border with Mexico.

Ram Pump Model Eliciting Activity

For this study, we designed the "Ram Pump: A Resource for Providing Running Water to Las Colonias Community" MEA (Ram Pump MEA) following the six design principles of MEAs for engineering education [6]. This MEA is framed within the context of providing running water to communities located in *las colonias* [the settlements]. Las colonias are low-income communities situated along the U.S.-Mexico border [34].

The Ram Pump MEA is structured in three sections. In the first part, students explore the context and rank four pumping systems based on the order in which they consider a pump is more or less suitable for installation in the *colonias*. After completing this first section, students are asked to prepare *Presentation 1*, which includes both a verbal and written presentation of their ranking, along with supporting arguments. In the second section, students interact with a ram pump—a water pump that does not require electricity—to collect data that enables students to model its efficiency. The third section requires students to model the ram pump's efficiency and develop a pumping manual to address the needs of the client, the inhabitants of the *colonias*. Subsequent to completing the third section, students are asked to prepare *Presentation 2*, which includes both a verbal and written presentation of their final models and justification.

Data Collection and Data Analysis

The data for analysis were obtained from audio recordings of the students' discussions during their two presentations, as well as from the worksheets and models the students constructed to solve the MEA. All audio recordings were transcribed. The data were then reviewed and organized according to the activities.

To identify the integration processes of disciplinary knowledge and critical reflection, we employed Epistemic Network Analysis (ENA) [35]. ENA is a method that uses matrices created from consistent and meaningful segmentation of data, which are then qualitatively coded [36]. These matrices enable ENA to "provide a quantitative model—in the form of a network—for how people connect codes in their discourse" [35, p. 337] . By employing ENA models, it becomes possible "to examine connections, leveraging visualization and statistical techniques to identify patterns. It quantifies the co-occurrence of concepts within a conversation" [37, p. 350]. Specifically for this study, a codebook (Figure 1) was developed through a qualitative deductive-inductive process. This codebook is divided into three sections: *critical reflections, knowledge related to engineering, and knowledge related to mathematical modeling*.

Code	Description
	Critical Reflections
Critical Reflections	Process of analyzing, questioning, and reconsidering technology choices on a spectrum—from critiquing technologies that support mass production systems, which "poison the environment or degrade the social structure and man himself" (Schumacher, 1999, p. 20), to selecting appropriate technologies that "are accessible to virtually everyone; suitable for small-scale applications; and compatible with man's need for creativity" (Schumacher, 1999, p. 20).
	Knowledge Related to Engineering
Efficiency	The students include descriptions related to the concept of efficiency in engineering.
Fluid Proprieties	The students include descriptions of fluid properties (e.g., pression, flow, flow rate)
Design and technical considerations	The students include descriptions of pump system designs and/or technical considerations, such as comparisons based on dimensions and weights.
	Knowledge Related to Mathematical Modeling
Mathematization	The students develop processes for quantifying, dimensionalizing, coordinatizing, categorizing, algebratizing, and systematizing relevant objects, relationships, actions, patterns, and regularities (Lesh & Doerr, 2003).
Measurement Process	The students develop measurement processes that relate to the key indicators proposed by Hagena (2015), identifying and distinguishing quantities of measurement, measuring, estimating and rounding, deciding whether to estimate, measure, or round, having knowledge about units of measurement, and having a set of meaningful benchmarks for these units.

Fig. 1. Codebook

The data from students' presentations 1 and 2 were segmented by sentences and subsequently coded using this codebook. The matrix resulting from the coding was then uploaded into the ENA Web Tool (1.7.0.) [38]. A visual analysis of the ENA models was performed. These graphs and results are presented in the following section.

Results

We defined the units of analysis as all data lines associated with a single value of Presentation (including Presentation 1 and Presentation 2), further subsetted by the type of student response, considering both verbal and written responses (Response.mode). Our ENA model included the codes listed in our codebook (Figure 1): *critical reflections*, *efficiency*, *design and technical*, *fluid properties*, *mathematization*, and *measurement*. We defined conversations as all lines of data associated with a single value of Response.mode, further subsetted by sentences.

The ENA model normalized the networks for all units of analysis before they were subjected to a dimensional reduction, which accounts for the fact that different units of analysis may have different numbers of coded lines in the data. For the dimensional reduction, we used a singular value decomposition, which produces orthogonal dimensions that maximize the variance explained by each dimension [39]. The networks were visualized through network graphs, where nodes represented the codes, and edges indicated the relative frequency of co-occurrence or connection between two codes. Each unit of analysis was thus represented by: (1) a plotted point indicating its network's location in the low-dimensional projected space, and (2) a weighted network graph. The following sections describe the results for Presentation 1 and Presentation 2.

Presentation 1 Results

In the first activity, students were tasked with evaluating and ranking four pumping systems based on usability for the residents in las colonias. The instructor briefly described the operation of each system, and the team produced the following ranking: first, ram pump; second, pump-tank; third, hydropneumatic systems; and fourth, manual water pump. Students developed their ranking based on factors such as the types of benefits and challenges for the communities; for example, system design, electrical energy consumption, efficiency in water supply, maintenance requirements. Below is an excerpt of the team's presentation 1 when describing some of the benefits that the ram pump brings to homes in las colonias in contrast to a pump-tank system:

> Sentence 8: It [ram pump] won't do any damage to the home and it only requires minimal maintenance.
> Sentence 9: It is easy to use and does not require electricity.
> Sentence 10: They will receive water much cheaper and they won't face long term damage to their bodies
> Sentence 11: This [pumps and tanks] could damage the home if the conditions are already rough.

This excerpt highlights the relationships between engineering constructs and critical reflections. In sentence 8, the students incorporate technical considerations regarding potential structural damage to houses, linking these to critical contextual considerations of the communities. Specifically, while ram pumps do not cause damage to houses, pump-tank systems do, due to the conditions of the houses. This is because the students identified that, in the real context of las colonias, many homes are low-cost or improvised constructions that cannot withstand heavy loads. The students also established connections between engineering design and critical reflections by selecting a pumping system with a simple design, prioritized low energy consumption, affordability for the communities, and the prevention of physical harm. Regarding physical harm, the students referred to las colonias context, where many residents have suffered back injuries from carrying water in buckets.

The ENA graph allowed us to identify the connections and co-occurrences of the constructs utilized by the students throughout their presentation. Figure 2 displays the ENA model for Presentation 1. The X-axis accounts for 81% of the data variance, while the Y-axis explains 11.4%. The *critical reflections* node is connected to the nodes for *design and technical knowledge*, *efficiency*, and *fluid properties*. The strongest connection observed was between *critical reflections* and *design and technical knowledge*, demonstrating that students most frequently used co-occurrences between these two constructs to address part 1 of the Ram Pump MEA. The large size of the *critical reflections'* node indicates that it played a relevant role in the majority of co-occurrences within the dataset of Presentation 1 [36]. It is important to note that the ENA model showed no connections with constructs related to mathematical knowledge.

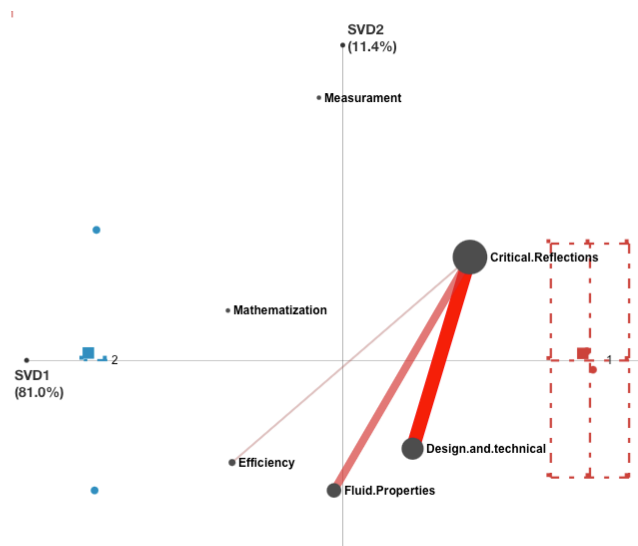

Fig. 2. ENA model from Presentation 1

Presentation 2 Results

Sections 2 and 3 of the Ram Pump MEA prompted students to engage in mathematical modeling processes to analyze the efficiency of the ram pump. In these activities, students were tasked with creating an efficiency manual for a pump and presenting their models in both written and verbal formats. In these activities, the students had the opportunity to physically interact with a real ram pump that was built by one of the researchers for the purposes of this study. Students manually collected data from the pump, made decisions about the variables involved to define its efficiency, and mathematically modeled the pump's efficiency. During their presentation 2, the students defined pump efficiency, described their data collection process, and detailed the technical considerations involved in constructing their models. Below is an excerpt from their presentation:

Sentence 53: We calculated efficiency as how much water was gained compared to the water wasted.
Sentence 54: Having a smaller comparison between both meant the ram pump was most efficient at that water level.

This excerpt reveals connections between constructs of mathematical and engineering knowledge. The mathematization processes, such as quantifying and measuring the amount of water, were related to engineering knowledge, particularly regarding efficiency. Additionally, the systematization and comparison of the ratio between water gained and water wasted were crucial for identifying the relationship between efficiency performance and the water level in the tank. The students' analysis of the pump's efficiency incorporated fundamental properties of fluid mechanics, including suction, discharge, and water losses. Based on their model, the team recommended that the community keep the ram pump's feed tank as full as possible.

The ENA model also provided insights into the co-occurrences of the codes throughout the team's presentation 2. Figure 3 shows that, after the modeling process, the students developed a network of connections linking *critical reflections, mathematics, and engineering knowledge*. The large size of the *mathematization* and *efficiency* nodes indicates that these constructs held a significant role in the majority of co-occurrences within the dataset of Presentation 2. Thick lines between the nodes for *mathematization* and *efficiency* highlight that the students' final model demonstrated stronger co-occurrences between these two constructs. Both nodes were also connected to *measurement processes* and *fluid properties*. Additionally, a co-occurrence was observed between *mathematization* and *critical reflections*, as well as between *efficiency* and *critical reflections*. This indicates that the team's model was also grounded in the relationship between these constructs.

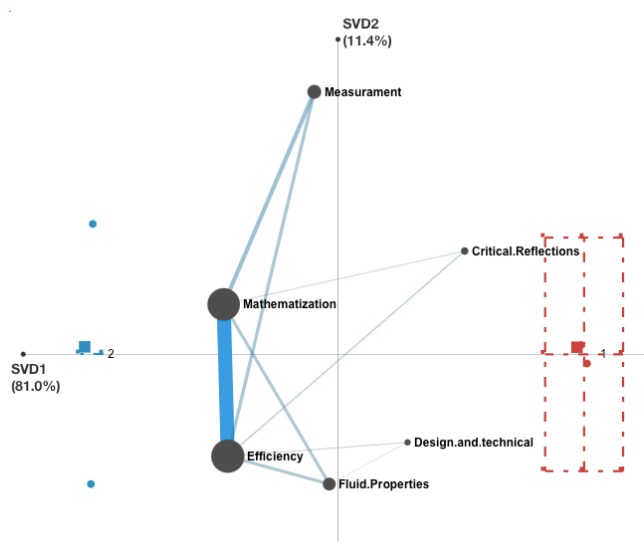

Fig. 3. ENA model from Presentation 2

Discussion and Conclusions

The ENA analysis allowed for the identification, through the data, that the Ram Pump MEA prompted students to integrate disciplinary knowledge of mathematics and engineering with critical reflections. During the first section of the activity, prior to interacting with the pump, students grounded their arguments in a blend of engineering knowledge and their critical reflections on las colonias. Notably, *critical reflections* emerged as the construct with the highest number of co-occurrences during the student presentations. Presentation 2 reveals that students continued to incorporate *engineering knowledge* and *critical reflections*, but they more heavily incorporated *mathematical knowledge* as they developed a metric for efficiency. The ENA model highlights that this process of mathematization played a significant role in the students' presentations, with the relationship between the constructs of efficiency and mathematization being particularly relevant. This finding aligns with the suggestions of Buede and Miller [3] and Dym et al. [4], who emphasize that mathematical modeling is intrinsically linked to engineering practices. Although to a lesser extent, the critical reflections node remained relevant in Presentation 2. This could be attributed to the students' focus on defining their data collection and modeling processes with greater depth; however, the connections to critical reflections provide evidence that continued to make reference to the context of las colonias. Further exploration of other student teams' data is necessary to provide a more thorough understanding of this aspect of the process.

The results underscore that the modeling process was fundamental for first-year engineering students in making informed recommendations for the communities in las colonias. This aligns with the ABET [8] learning outcomes, which highlight that engineering students should use mathematical knowledge to solve problems and be capable of making informed judgments within societal contexts.

This study contributes to the field of mathematical education in engineering by offering insights into how engineering students incorporate learning opportunities through modeling activities that promote the integration of disciplinary and societal knowledge. Furthermore, the findings underscore the importance of enhancing first-year engineering education with a sociotechnical and holistic approach [6, 10]. Given that this conference paper addresses a case study, we deem it essential for future research to explore disciplinary and societal formation with additional student teams to gain a more comprehensive perspective.

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