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Argumentation Framework as an Educational Approach for Supporting Critical Design Thinking in Engineering Education

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Abstract

Rationale: In the context of engineering design of energy-efficient homes, effective decision-making involves integrating energy science and economic considerations. When faced with the complexity of ill-defined problems, engineering students often rely on trial and error rather than leveraging scientific knowledge. This study examines the educational impact of an Argumentation Framework, guiding students to apply scientific knowledge in design decisions critically. The evidence-based practice manuscript introduces a lesson design in engineering education to analyze and improve educational strategies, reflective practices, and instructional materials.

Assessment methods: This study outlines a lesson design utilizing the Argumentation Framework to support first-year engineering students in overcoming conceptual challenges while developing engineering projects. This approach was implemented in an Engineering Technology undergraduate course at a Midwestern university, whose curriculum covered foundational topics in Energy Science. The task involved designing a zero-energy home using Aladdin software, as an integrated CAD/CAE platform for design and simulation. Students documented their analysis, inferences, and decisions in a design journal with columns for factor, claim, evidence, and reasoning. Hence, this study explored how students integrate science knowledge and economic considerations in decision-making during an engineering project development, part of the lesson design.

Achievement of desired outcomes: Engineering students enrich from applying theoretical knowledge in practical design. This study introduces the Argumentation Framework involved in a lesson design approach, for first-year engineering undergraduate students, fostering critical thinking and practical application of theoretical knowledge in practical design. Emphasizing evidence-backed claims enables students to articulate compelling arguments, enhancing effectiveness in real-world applications. Sankey and Radar charts support these claims, facilitating reflection on how science knowledge guides energy-efficient home design and analyzing emerging trends in economic decision-making and energy science within students' designs.

1. Introduction

Addressing complex real-world situations requires integrating energy science knowledge and economic considerations in Engineering Design decision-making. Building on Vieira's insights [1], this study explores the intersection between scientific knowledge and economic factors in engineering design. Fostering structured and systemic thinking skills in this field poses diverse holistic educational challenges [2]. Recognizing the prevalent use of "trial-and-error" methods among first-year undergraduate students, the study proposes an approach by incorporating an Argumentation Framework [3] to seamlessly integrate scientific knowledge into nuanced decision-making processes in engineering design projects.

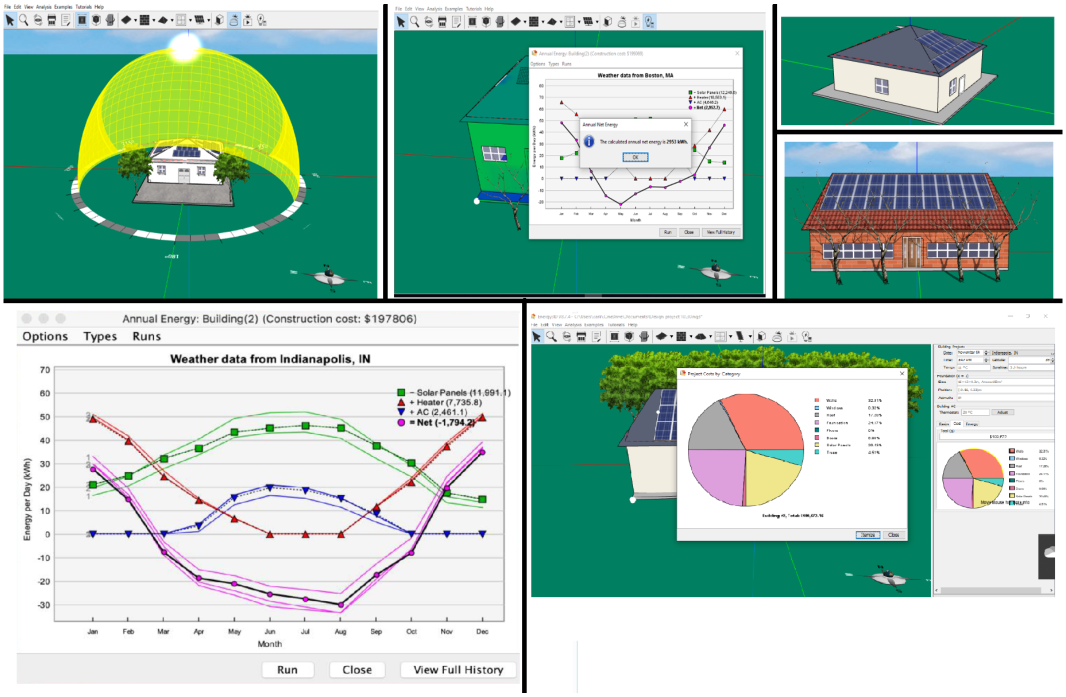
Numerous studies emphasize enhancing design education through argumentation, promoting collaboration, evidence-based decision-making, and critical thinking [4], [5], [1], [3]. Educators play a key role in introducing concepts like Claims, Evidence, and Reasoning. Incorporating language, literacy, and data in teaching strategies improves educational outcomes [4]. Additionally, note-taking fosters active listening and critical thinking [5], [6]. Ongoing analysis and adaptation of these approaches are essential to meet evolving needs in Engineering Education and enhance students' argumentation and problem-solving skills.

On the other hand, examining a simulation tool in engineering design, focusing on Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) capabilities, highlights the critical need for research on technology implementation, data collection, and analysis. This emphasis aims to enhance evidence-based decision-making in design and argumentation processes, contributing to improved outcomes in engineering education [7], [8], [1].

Incorporated in an Engineering Technology course at a Midwestern university, this study focused on a lesson design centered on a zero-energy home task using Aladdin software as a CAD/CAE platform. This CAD/CAE software supports inquiry-based learning in science and engineering by allowing users to design structures and simulate functions [9], [10]. Aladdin engages learners in inquiry about sustainable building and renewable energy design, using computer graphics and generative design, visualizing science concepts, and fostering informed arguments. Moreover, the software provides visual feedback, allowing students to conduct experiments and make informed design decisions by simultaneously rendering multiple simulations, enhancing inquiry-based design by enabling the comparison and analysis of various data-driven arguments [11], [12], [13]. Figure 1 illustrates some features that the software has, such as visualizations and information regarding cost, energy, and materials, among others.

Students actively participated by documenting informed decisions in a structured Design Journal, aligning with the Argumentation Framework of Claims, Evidence, and Reasoning. The study analyzed and emphasized academic pathway identification, technical problem-solving, and application of computational tools, highlighting key learning outcomes [11], [1]. The research delved into students' decision-making processes in designing energy-efficient homes, analyzing the consistency in documentation, and identifying recurring patterns in economic decision-making and the application of energy science principles. Thus, students documented their informed decisions following an Argumentation Framework to understand how they identified and pursued concepts or disciplines relevant to particular factors (e.g., energy efficiency, environmental considerations), using a CAD/CAE platform to aid in the analysis and

Figure 1: Example of features provided by Aladdin software



optimization of energy-efficient home designs. Consequently, this paper reflects on the following questions: How did students make decisions when designing energy-efficient homes? What trends emerged in students' design decision-making processes concerning economic decision-making and the incorporation of energy science knowledge?

This study assesses the impact of the Argumentation Framework on engineering design projects, contributing to Computer Science and Engineering Education literature. Aligned with the presented lesson design, the framework enhances critical thinking and problem-solving skills, providing valuable perspectives for applying scientific knowledge and economic considerations in real-world engineering contexts, aiming to support pedagogical approaches and address complex design challenges, especially in energy-efficient housing design.

2. Theoretical Framework

This study is grounded in the Argumentation Framework [3], which comprises three integral components: Claims, Evidence, and Reasoning. This framework guides students in engineering design projects, systematically connecting scientific knowledge with practical decision-making. The Claim represents the student's main viewpoint, supported by Evidence (facts, data, or examples) to enhance credibility. Reasoning explains how Evidence supports the Claim, amplifying the persuasiveness of the argument.

The Argumentation Framework cultivates reflective thinking and enhances problem-solving skills by emphasizing the link between theory and practical application in engineering decision-making. Integrating this framework encourages students to articulate and support their informed decisions effectively in real-world scenarios, aligning with broader educational objectives.

The study acknowledges students' challenges in connecting claims with supporting evidence, often characterized by a "trial and error" approach. However, by endorsing the adoption of the Argumentation Framework, the study suggests that students can transcend these challenges and develop more informed and substantiated arguments. This aligns with the belief that approaches grounded in applying scientific knowledge can offer a more efficient and effective means of constructing persuasive arguments. In embracing the Argumentation Framework, students not only enhance their critical thinking skills but also gain a structured methodology rooted in scientific principles, providing a more robust foundation for constructing compelling arguments applicable to real-world scenarios.

Furthermore, the study recognizes the role of the Argumentation Framework in structuring discussions about design iterations in engineering projects. Engineers can make claims about design changes and provide evidence from testing or analysis [5]. The Argumentation Framework emerges as a tool, guiding students toward a comprehensive skill set for successful engagement in engineering projects and problem-solving scenarios, addressing educational challenges and supporting engineering education in project-based and collaborative settings [2].

3. Methods

3.1. Context and participants

The study included a randomized sub-sample of 16 first-year engineering students out of a pool of 50 students randomly selected and analyzed from 248 students enrolled in the online 100-level course conducted via Microsoft Teams during the Fall 2020 semester due to COVID-19 restrictions. The random selection process aimed to ensure that the sub-sample was representative of the larger student population in the course. Applying this random sampling technique helps reduce bias and increases the likelihood that the findings from the sub-sample can be generalized to the broader student population in the course [14], [15]. Within the first two weeks, students utilized Aladdin software to design energy-efficient homes for a Midwestern city in the United States. The course emphasized learning outcomes in academic success, problem-solving, computational tool application, and awareness of professional standards in engineering technology.

The Engineering Technology course covered foundational concepts in electricity, mathematics, mechanics, programming, basic statistics, and professional development. It focused on conceptualizing heat transfer, solar radiation, heat flux, albedo, insulation, and energy conversion.

Utilizing Aladdin software, students documented their informed decisions in a Design Journal, focusing on Claim (i.e., prediction), Evidence (i.e., observation), and Reasoning (i.e., justification or rationale) [11]. The software facilitated the implementation of the design challenge, allowing students to create and modify virtual models of energy-efficient homes. This approach promoted effective argumentation, enabling students to support claims with Reasoning and Evidence.

The project design challenge was introduced midway through the 16-week semester, aligning with students' exposure to the project design process (i.e., problem identification, research, and requirements specification, concept generation, prototype and construct, product integration, and product testing), complementing their prior coursework in energy, electricity, and computer-aided design. With foundational knowledge, students integrated their learning from a co-requisite design-thinking course. In this course, they concurrently engaged in a group project's prototype and testing stages using Solidworks through three design-based models the students worked on. The timing of when the project was held (i.e., mid-semester) helped students gain prior theoretical and scientific knowledge necessary for the design challenge posed. The challenge encompassed two parts: (1) creating a simple home for familiarity with the design journal, augmentation framework, and Aladdin software, and (2) tackling a complete design challenge over one week. To work on the scaffolding process on the CAD/CAE platform, the instructors guided weekly recitation sections introducing Aladdin software features, supported by recorded videos related to the tool.

3.2. Lesson Design

This study employed a backward design process for the lesson, prioritizing intended learning outcomes before designing interventions. The goal was to foster informed-energy design decision-making, utilizing pedagogical principles and the Aladdin software [11]. The major intended learning outcomes were (1) Accurate energy knowledge and (2) Evidence of economical and energy-efficient designs.

To achieve these outcomes, the lesson design posed a design challenge that guided students through the process of implementing the four principles of the 4C/ID model, which were enacted via the Aladdin software [11], as follows:

1. Authentic Whole-Task Experiences: Students engaged in a design challenge to create a zero-energy home in Indianapolis.
2. Supportive Information: The learning management system, videos, and just-in-time help were utilized for energy-related concepts.
3. Aladdin Installation: The software installation, demo video, and file submission instructions conveyed the necessary information.
4. Part-Task Practice: A design exercise applied one energy concept to build an energy-efficient home.

Therefore, students used the CAD/CAE software (i.e., Aladdin) to support the engineering design process for a zero-energy home challenge in a Midwestern city, creating and modifying virtual models. As part of the prompt, the challenge incorporated specific details and constraints as follows:

1. Design Challenge Prompt:
    - Students were given a dual role as engineers and scientists working on a final design challenge to create a zero-energy home in Indianapolis, which would consume no net energy over the year.
    - Students were asked to think considering their dual role, as follows:

    - As engineers, students were tasked with designing a home that met specific constraints related to energy efficiency, cost, size, and aesthetics.
    - As scientists, students were required to investigate, observe, and explain the impact of design features on heat transfer, conducting small experiments and modifications to understand their effects on energy consumption and construction cost.

2. Design Constraints:
    - Energy Efficiency: The home should consume no net energy over a year.
    - Cost: The total cost of the home should not exceed $150,000
    - Size: The home should comfortably accommodate a four-person family, with specific area and height constraints.
    - Aesthetics: Design requirements included window placement, distance of tree trunks from the home, and solar panel placement.

3. Use of Aladdin Software:
    - The software provided a virtual platform for students to create, modify, and analyze the design of energy-efficient homes.
    - Students utilized the software to implement their design decisions, incorporating features such as solar panels, building orientation, and other energy-efficient elements.

Hence, integrating the dual role, the challenge prompted students to consider practical constraints and scientific principles related to energy efficiency in their design decision processes. The software facilitated visualization and implementation of design features, providing an experiential learning experience [2], aligning with the study's focus on promoting informed energy design decision-making.

3.3. Data Collection

The study analyzed design journals, documenting students' decisions using the Argumentation Framework —a sub-sample of 16 observations was randomly collected from 50 students, randomly selected and analyzed, out of 248 enrolled in the first-year course. The prompt involved an energy-efficient home design challenge using Aladdin software, aligning with course objectives. Students integrated energy concepts, design strategies, and economic analysis methods into their structured Design journals, employing the Claim-Evidence-Reasoning format for factors, arguments, predictions, observations, and justifications. The design journals adhere to a structured format comprising four key elements, as follows:

1. Factor: This section is the detailed description of features intended for modification in the design, outlining the step-by-step procedure.
2. Argue Prediction: Students presented a well-argued justification for modifying the chosen factor, articulating anticipated outcomes.

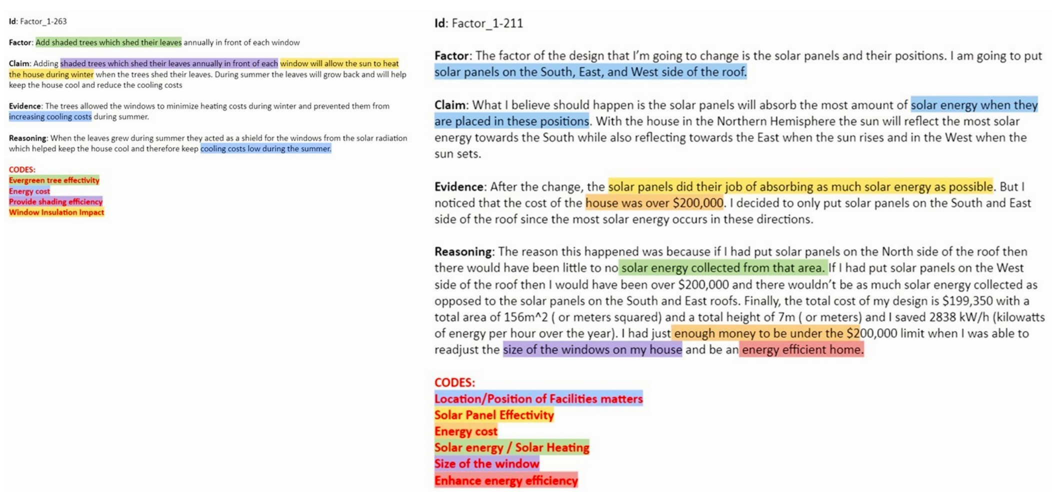
3. Observation (i.e., Evidence): This section provides a comprehensive account of the actual changes (i.e., tangible changes) observed in the Aladdin software.
4. Justification: The reasoning process behind the design decision is critically examined in this section. It delves into the critical examination of the reasoning process behind the design decision, connecting argued predictions with observed changes.

3.4. Data Analysis

The data analysis engaged a graduate Ph.D. student and an undergraduate student in a mentor-mentee relationship. Both researchers collaboratively categorized and revised data to understand students' decision-making from a sub-sample of 50 randomly selected students. The 16 students presented in this manuscript were randomly selected from this sub-sample.

At first, the researchers collectively hand-coded ten observations to determine a standard along the upcoming codification process collaboratively. Each observation comprised of a separated Design Journal of a student. Then, individually, each coded 20 additional observations, focusing on discerning students' claims, evidence, and reasoning in engineering design projects. The open hand-coding process resulted in categorized codes, revealing two overarching categories: Economic Design Decision-Making and Energy Science Knowledge. Visualizations like Sankey and Radar charts provided insights into emerging categories. Regular meetings addressed coding discrepancies, enhancing the study's credibility, trustworthiness, validity, and reliability. This process spanned ten weeks with reflexivity and discussion.

Figure 2: Codification process over the observations: Factor, Claim, Evidence, Reasoning



Id: Factor_1-263

Factor: Add shaded trees which shed their leaves annually in front of each window

Claim: Adding shaded trees which shed their leaves annually in front of each window will allow the sun to heat the house during winter when the trees shed their leaves. During summer the leaves will grow back and will help keep the house cool and reduce the cooling costs

Evidence: The trees allowed the windows to minimize heating costs during winter and prevented them from increasing cooling costs during summer.

Reasoning: When the leaves grew during summer they acted as a shield for the windows from the solar radiation which helped keep the house cool and therefore keep cooling costs low during the summer.

CODES:
Evergreen tree effectivity
Energy cost
Provide shading efficiency
Window Insulation Impact

Id: Factor_1-211

Factor: The factor of the design that I'm going to change is the solar panels and their positions. I am going to put solar panels on the South, East, and West side of the roof.

Claim: What I believe should happen is the solar panels will absorb the most amount of solar energy when they are placed in these positions. With the house in the Northern Hemisphere the sun will reflect the most solar energy towards the South while also reflecting towards the East when the sun rises and in the West when the sun sets.

Evidence: After the change, the solar panels did their job of absorbing as much solar energy as possible. But I noticed that the cost of the house was over $200,000. I decided to only put solar panels on the South and East side of the roof since the most solar energy occurs in these directions.

Reasoning: The reason this happened was because if I had put solar panels on the North side of the roof then there would have been little to no solar energy collected from that area. If I had put solar panels on the West side of the roof then I would have been over $200,000 and there wouldn't be as much solar energy collected as opposed to the solar panels on the South and East roofs. Finally, the total cost of my design is $199,350 with a total area of 156m^2 (or meters squared) and a total height of 7m (or meters) and I saved 2838 kW/h (kilowatts of energy per hour over the year). I had just enough money to be under the $200,000 limit when I was able to readjust the size of the windows on my house and be an energy efficient home.

CODES:
Location/Position of Facilities matters
Solar Panel Effectivity
Energy cost
Solar energy / Solar Heating
Size of the window
Enhance energy efficiency

The open hand-coding procedure generated codes for each observation and factor, as illustrated in Figure 2. Direct quotes, marked with a color scheme for clarity, represented the codes. Moreover, a matrix aligned emerging codes in rows and observations in columns, exemplified in Table 1 for some code abbreviations and meanings among the 32 emerging codes from the hand-coding process (see Figure 3). From the analysis of a sub-sample of 16 observations related to economic considerations, eight codes emerged —these are the codes and abbreviations that served as examples listed in Table 1. The matrix illustrated in Figure 3 represents the alignment for each observation/student with each code abbreviated following the Argumentation Framework.

Table 1: Abbreviations and meaning of the hand-codification

Abbreviation	**Code Meaning**
EC	Energy cost
EEE	Enhance energy efficiency
ITR	Improve temperature regulation
[...]	[...]
IUvI	Insulation U-value Impact
LIV	Lowering insulation value
REC	Reduce energy consumption
VHSC	Volumetric heat storage capacity
VSH	Volume & shape of the house

Figure 3: Hand-coded matrix for Claim, Evidence, and Reasoning

Claim										
Abbreviation	**248**	**256**	**276**	**292**	***	***	**319**	**221**	**267**	**294**
EC					***	***		X		
EEE	X	X		X	***	***				
ITR		X		X	***	***				
IUvI		X		X	***	***	X	X		X
LIV		X	X		***	***				
REC				X	***	***	X			
VHSC					***	***	X			
VSH					***	***		X		

Evidence										
Abbreviation	**248**	**256**	**276**	**292**	***	***	**319**	**221**	**267**	**294**
EC					***	***				
EEE				X	***	***				
ITR					***	***				
IUvI				X	***	***	X		X	X
LIV	X	X	X		***	***	X			
REC			X		***	***	X			
VHSC					***	***	X			
VSH					***	***				

Reasoning										
Abbreviation	**248**	**256**	**276**	**292**	***	***	**319**	**221**	**267**	**294**
EC					***	***		X		
EEE		X		X	***	***				
ITR		X		X	***	***				
IUvI		X		X	***	***	X	X		X
LIV		X	X		***	***		X		
REC				X	***	***	X			
VHSC					***	***	X	X		
VSH			X		***	***		X		

After completing matrices for the hand-coded process, an additional coding process was conducted to establish a rationale between the emerging codes. This led to the identification of four axial codes, as follows:

1. Energy efficiency and conservation
2. Insulation and thermal regulation
3. Design and space efficiency
4. Economic considerations

The codes were allocated to their corresponding categories, tabulated the observations, and reinforced the findings with quotes from the design journals associated with each category (see Figure 4). The resulting analysis is presented in the following section.

Figure 4: Axial Coding matrix representing the Rationale between the resulting codes

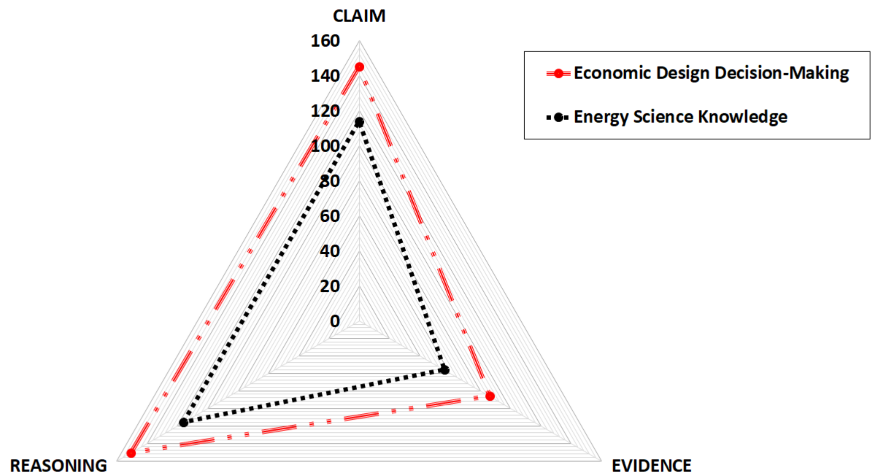
Rationale between codes				
Abbreviation	1. Energy Efficiency and Conservation	2. Insulation and Thermal Regulation	3. Design and Space Efficiency	4. Economic Considerations
EC				OK
EEE	OK			OK
ITR		OK		OK
IUvI		OK		OK
LIV		OK		OK
REC	OK			OK
VHSC		OK	OK	OK
VSH			OK	OK

4. Results and Discussion

From the resulting axial coding process, considering the frequencies along each category of analysis (i.e., Economic Design Decision-Making, and Energy Science Knowledge), Figure 5 illustrates a radar chart —also known as spider plot— representing the relationship between students' considerations on Economic Design Decision-Making and Energy Science Knowledge during the design challenge. The dashed red line represents "*Economic Design Decision-Making*", and the black dashed line represents "*Energy Science Knowledge*". Notably, students prioritized economic factors over scientific ones, as evidenced by the predominance of economic considerations in their arguments. In fact, Aladdin software might have influenced in this rely as it provide information regarding energy and cost outputs from the design. For instance, a student proposed adding south-facing windows to "*reduce energy costs*", demonstrating a holistic integration of technical and economic aspects. Hence, while integrating scientific principles, such as insulation and thermal regulation or environmental/geographical considerations, students tended to highlight economic sustainability as evidence for cost-effective solutions, apart from the arguments provided for claim and reasoning. This relationship is further visualized in Figure 6.

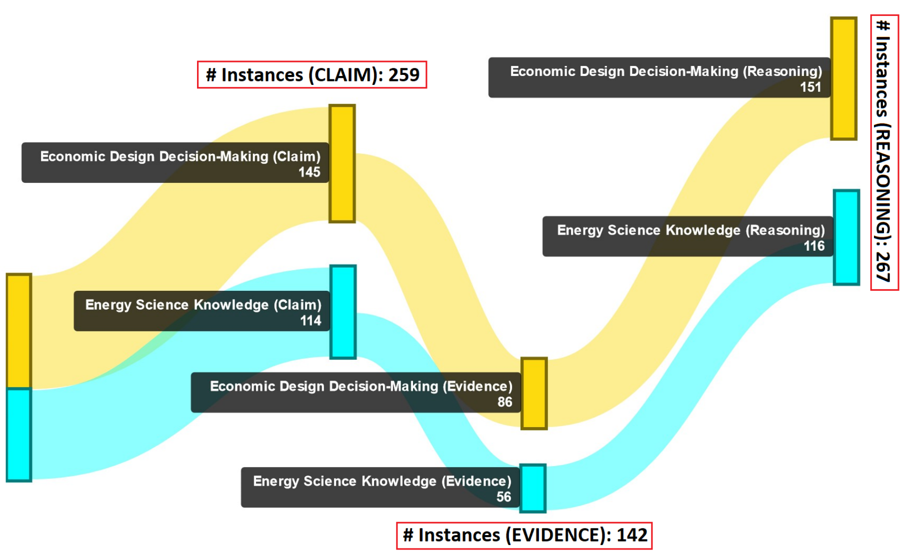
On the other hand, Figure 6 underscores a notable misalignment in the evidence process, revealing a discrepancy with a lower emphasis on economic factors compared to the *Claim* and *Reasoning* stages within the argumentation process. Despite advocating for an Argumentation Framework that integrates scientific knowledge, the study recognizes the importance of economic considerations in shaping the alignment of claims, evidence, and reasoning. This recognition prompts a call for a more nuanced approach, acknowledging that economic factors can

Figure 5: Spider Chart representing the distribution of Claim+Evidence+Reasoning between Economic and Scientific considerations



significantly impact the construction of arguments. For example, one observation highlighted a prioritization of economic considerations over energy conservation in its argumentation. The claim suggested the addition of shaded trees to "allow the sun to heat the house during winter when the trees shed their leaves," with the aim of "preventing increased cooling costs" during the summer. Despite scientific-centered argumentation is desired, this instance illustrates the importance of a balanced integration of both scientific knowledge and economic considerations, among further non-scientific knowledge, in constructing persuasive and well-rounded arguments.

Figure 6: Sankey Chart: Distribution of the Economic and Scientific Considerations along Claim, Evidence, and Reasoning following the Argumentation Framework



While certain students present well-aligned claims, evidence, and reasoning with quantitative support, not all exhibit this cohesion. For instance, one student argued, "*2838 kW/h was saved by changing the positioning of the solar panels*", enhancing credibility and enabling a more robust and nuanced argument. Nevertheless, within the analyzed sub-sample, it can be asserted that economic factors often sway decisions. Some initially discussed Energy Conservation but shifted their reasoning to Economic Considerations, indicating how students influenced their decisions (i.e., arguments) in engineering design projects. Figure 6 underscores the significant influence of economic considerations on aligning decision-making components, surpassing other factors, particularly energy science knowledge, in this specific context of lesson design. Again, it can be inferred that this influence might come from the information and plots provided by Aladdin software regarding the relation between energy and cost-effectiveness of the designs.

Furthermore, in CAD/CAE platforms (e.g., Aladdin), there is a need for simulation-based learning scaffolding facilitated by instructors, peers, or technology [9], [16]. Moreover, incorporating Artificial Intelligence or Machine Learning contributes to learners by generating precise, nuanced, efficient, and optimal solutions [17], [11], maximizing the utilization of CAD/CAE software and its generative design features.

5. Conclusions, Implications, Limitations, and Future Work

This study described a lesson design incorporating an Argumentation Framework, emphasizing its potential to enhance students' critical thinking, supporting the trade-offs for their decision-making processes, problem-solving abilities, and the practical application of scientific knowledge within engineering design projects. From this study, we could preliminarily say that integrating the Argumentation Framework fostered students to articulate persuasive scientific arguments and establish connections between theoretical knowledge and practical application in engineering design.

While the findings highlight the positive impact of this educational approach in guiding students toward informed decision-making in engineering design projects, a notable gap exists in the Evidence stage. Particularly, an observed tendency among students to prioritize economic constraints over theoretical scientific knowledge suggests a potential misalignment between the evidence presented and the related claims and reasoning. This discrepancy may be influenced by the reliance on the Aladdin software tool and its features, which serve as the CAD/CAE platform in the proposed lesson design.

Further research will be conducted to validate and reinforce the manuscript's claims, create targeted instructional materials, and develop strategies for seamlessly integrating the Argumentation Framework into diverse engineering education settings. The study will analyze how the Aladdin software influences students' prioritization of other contributing factors over scientific or theoretical knowledge, implementing targeted interventions, thus adjusting the instructional approach and refining the use of the tool. These efforts aim to strengthen the analysis of the lesson design's impact on learning outcomes and explore the potential integration of emerging technologies for enhanced effectiveness in specific educational contexts.

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