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Students' Use of The Engineering Design Process to Learn Science (Fundamental)

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Introduction

An engineering design-based curriculum was created to aid teachers in grades 4-8 in meeting the academic science standards for their state. The curriculum used the engineering design process (EDP) as a framework for learning and applying scientific principles. This paper explores how well the engineering design process serves as a framework for young students to learn science. An engineering-driven STEM unit, consisting of 14 (50-minute) class periods taught in a 6th-grade science class, requires students to work in teams to implement the EDP and learn scientific principles needed to meet a goal. Building on the real-world premise of a freight train derailing and spilling its cargo of various minerals into a lake, students plan, design, and iterate on decision tree processes for sorting, identifying, and recovering the spilled minerals to find the optimum solution. As students learn about mineral properties and the value of non-renewable mineral resources from the teacher's presentations, the information is used to support evidence-based reasoning for process design decisions. Data for this study consist of audio and video recordings of two groups of students as they refine and present their solution processes to retrieve the minerals from the lake. Innovative techniques are used to analyze the audio and video recordings. Digital twins are created for both the curriculum and the recordings of students' conversations. Then, a MATLAB program is written to count the number of times students used keywords from the curriculum when discussing their solutions. The word counts provide insights into how much students improve their understanding of scientific concepts as they develop their solutions.

Literature Review

Integration of science and engineering has long been studied as an approach to piquing student interest in science and providing both motivation and a framework for students to learn and apply scientific principles. The study reported in this paper explores the use of the Engineering Design Process (EDP) as a framework for learning science in a middle school classroom. This section of the paper presents a review of the literature on approaches to the integration of science and engineering as well as the relationship between student interest in a topic and their desire to learn more about that topic.

Integration

Integrated STEM education allows students to make connections among the disciplines of STEM[1], but presently, there are many forms of this integration with no universally adopted model[2]. This contributes heavily to the inconsistent application of engineering at the K-12 levels[3], [4]. A sampling of some options proposed by a researcher [5]are sequenced, parallel, partial, enhanced, and total approaches for STEM Integration that have demonstrated some effects on science learning[6]. In all of these models, what has been accepted is the importance of the design process in providing students with a meaningful context for identifying multiple solutions to be applied to problems.[7], [8], [9], [10].

Although there has not been an agreed way to do integrated engineering and science, there is, however, an accepted tool for measuring the effectiveness of integrated curriculums (STEM-Integration Curriculum Assessment)[1], based upon a STEM Integration framework[11] that identified skills and dispositions of engineering knowledge and practice for K-12 curricular frameworks[12]. Multiple researchers report from their findings that engineering can be the integration vehicle for the STEM disciplines [13], resulting in improved student learning and motivation. These benefits are not without challenges, however, and two of the most influential factors challenging science and engineering integration are #1) the lack of guidance for teachers on how to integrate the subjects[11], [13] and #2) the limited knowledge and experience base in engineering of K-12 teachers who, as a result, need scaffolding and support when preparing to teach concepts for their grade levels[1], [14]. The Engineering Design Process (EDP) is one framework that seems to help teachers by providing specific points to measure student learning of science concepts [14]. A benefit of using EDP is that requirements to meet an objective can be established early on for a project that can be used to guide student learning as they develop designs and solutions.

Student Interest

Several studies demonstrate that interest has a direct relationship to a student's attention in class and desire to learn more about a subject [15], [16] which is why it is believed students that show interest in STEM at the middle or high school levels are more likely to complete a degree in STEM fields[17]. There are specific engineering design-based research projects that challenge this [8] [18], [19], [20], [21], but overall, researchers agree and emphasize the need to capture broader audiences to increase interest in STEM fields [7]. However, the lack of teacher experience in engineering has caused a majority of students to have no exposure to or formal experience with engineering [9], [22]. Researchers observing students with no experiential learning in engineering as a basis to draw from for unfamiliar challenges report diminished student interest in the field[23]. Another significant challenge for many teachers is finding quality curriculum materials that allow students an authentic engineering experience of having to iterate and improve on their designs. [8], [24].

There are several studies that examined student-teacher interactions and the impact on student interest in science/engineering[25], [26], [27]. The studies are grounded in discourse[4] analysis showing the ways that teachers have spoken and presented information have a significant impact on student interest in science and engineering [28]. An example from one case study showed that the number of prompts by the teacher for design justifications had an impact on the amount of science used by two different groups performing the same exercise[24]. Additional investigations of classroom demonstrations performed by teachers with follow-on experiments that allowed students to take ownership of their engineering designs and intellectual creativity show positive impacts on student interest[29]. There is broad acceptance that additional studies are needed into the subject, examining specific aspects of questioning strategies and how the presentation of new knowledge impacts student interest and class discussion[4].

Taking into consideration the views and perspectives about engineering and science integration and factors impacting student interest in learning, there is an opportunity to explore the research question:

> "How well can the engineering design process serve as a framework for learning science by middle school students."

The following sections describe an approach to answering this research question by examining what occurred when middle school students used the Engineering Design Process (EDP) to accomplish a specific objective. Measuring the scientific literacy gained by the students through the use of the EDP provides evidence of its viability as a framework for learning science.

Methodology

Introduction

This section presents the methods and procedures to answer the question, "How well can the engineering design process facilitate learning of science by middle school students?". This is a case study of two teams from a middle school classroom that use the engineering design process as a framework for learning scientific principles. The students' goals are to plan, design, and evaluate a decision tree process to recover, sort, and identify minerals from a lake following a train derailment spilling the cargo of minerals. Students' solutions reflect the increase of their team's scientific literacy over the multiple sessions of the STEM curriculum.

Setting

The {name redacted} project developed a suite of 13 integrated STEM curricula for grades 4 – 8. The curricula are hands-on engineering design challenges that integrate grade-appropriate mathematics and science content, mapping to Next Generation Science Standards and Common Core State Standards for Mathematics for engineering and discipline-specific standards. Each unit was written by a team of teachers and developed in conjunction with curriculum researchers from the {name redacted} project. The design projects in each unit vary in context and in terms of the mathematics and science concepts needed to create an adequate solution. Yet, within all the variations, each unit is an authentic engineering design challenge. Each unit has undergone an extensive design research cycle to ensure quality.

During the final years of the {name redacted} project, new teachers went through a week-long summer professional development to learn to implement one of the units. Then, research was conducted in their classrooms. This study comes from one of the teachers who participated in this implementation portion of the study. At the time of data collection, she was an elementary school licensed teacher with a middle school science endorsement, had a master's degree, and had 20+ years of experience. This was her first time implementing this curricular unit, but she had experience implementing other STEM integration curricula.

The school the teacher taught in was a highly rated public suburban school in the Midwestern United States. It had approximately 825 students in grades 5-6, with a student-teacher ratio of 18 to 1. It was ranked as the most diverse public school in its district, with approximately 30% of students of color and 25% of students receiving free or reduced-price lunch. Two teams were selected from the middle school class based on parental consent to participate in the study and the talkativeness of students.

Class Curriculum

The engineering design-based STEM integration unit implemented in this study consists of 14 (50-minute) class periods. It builds on the realistic premise of a freight train derailing and spilling its cargo of various minerals into a lake. Students use the engineering design process to learn scientific principles that help them to plan, design, and evaluate ways to recover, sort, and identify spilled minerals. As they learn about mineral properties and the value of non-renewable mineral resources from the teacher's presentations, students use evidence-based reasoning to make design decisions. Mineral properties and identification tests provide the basis for this engineering-driven STEM unit that addresses the Next Generation Science Standards and Common Core State Standards for Mathematics, as shown in Table 1. The minerals to be sorted and recovered are listed in Table 2 with their associated point values. The minerals with larger values represent greater difficulty in sorting and recovering and require deeper scientific knowledge of their properties.

Table 1.NGSS and Common Core Standards

Next Generation Science Standard	**Common Core State Standards-Mathematics**
5-PS1-3: Make observations and measurements to identify materials based on their properties.	CCSS.MATH.CONTENT.8.EE.B.5: Graph proportional relationships, interpreting the unit rate as the slope of the graph. Compare two different proportional relationships represented in different ways.
MS-ETS1-1: Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions	CCSS.MATH.CONTENT.HSS.ID.C.7: Interpret the slope (rate of change) and the intercept (constant term) of a linear model in the context of the data
MS-ETS1-2: Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem	
MS-ETS1-3: Analyze data from tests to determine similarities and differences among	

several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.	
MS-ETS1-4: Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.	

Each session empowered the students to connect eight notional machines into decision trees based on their capabilities and operating limitations to sort and identify minerals by their eight characteristics for points.

Table 2 Minerals and Points

Mineral	**Points**
Bauxite	4
Biotite	4
Calcite	4
Feldspar	10
Galena	8
Gold	15
Graphite	4
Hornblende	5
Magnetite	4
Muscovite	5
Pyrite	4
Quartz	7
Talc	3
Wood	0
Plastic	0

The machines in Table 3, Machine Description, have an associated cost to process each mineral and a probability of success for the sorting and identification task.

Table 3. Machine Description

Machine	Description	Note(Probabilities)
Magnet (1 point per mineral)	This machine separates materials that are magnetic from those that are non-magnetic.	This machine is very accurate. It rarely misses any magnetic pieces
Color Detector (1 point per mineral)	This machine sorts materials into two groups: light colored and dark colored	Because some minerals are not very light but also not very dark, this machine sometimes sorts incorrectly. About 1 out of every 10 pieces is sorted wrong.
Streak Sensor (1 point per mineral)	This machine sorts materials into two groups based on whether the streak is light or dark in color.	For some minerals, the streak will vary in color, and this makes it hard for the machine. About 2 out of every 10 pieces are sorted wrong
Crusher (2 points per mineral)	This machine tests the hardness of materials according to the Mohs hardness scale.	This machine has trouble separating minerals whose hardness is within one above or below another mineral on the Mohs hardness scale.
Shape Detector (1 point per mineral)	This machine separates materials that fracture from materials that cleave.	For about 1 out of every ten minerals, this machine puts the mineral in the wrong category.
Reflector (3 points per mineral)	This machine shines light on materials to separate them into three groups based on their luster: metallic, dull, or glassy.	Some minerals can have two of the three lusters (e.g. metallic to dull). The machine has trouble sorting these. Minerals with two or more lusters are sorted into groups unpredictably
Density Calculator (3 points per mineral)	This machine allows you to sort materials into four groups based on the density of the materials (all in g/cm3): 0 to 1.0, 1.1 to 2.9, 3.0 to 4.9, and 5.0 or more	xx
Human Power (5 points per mineral)	Human power allows you to hire people to sort out one material by hand.	Besides being expensive, it is also very time consuming to use human power.

Figure 1 Decision Tree depicts a graphical illustration of the decision tree that allows several alternatives to be chosen. The decision tree models made by the students begin with which machine to start with and move to the right, branching into the states of nature for success or failure of sorting or detecting the minerals, which then branch into the next machine with success or failure probabilities.

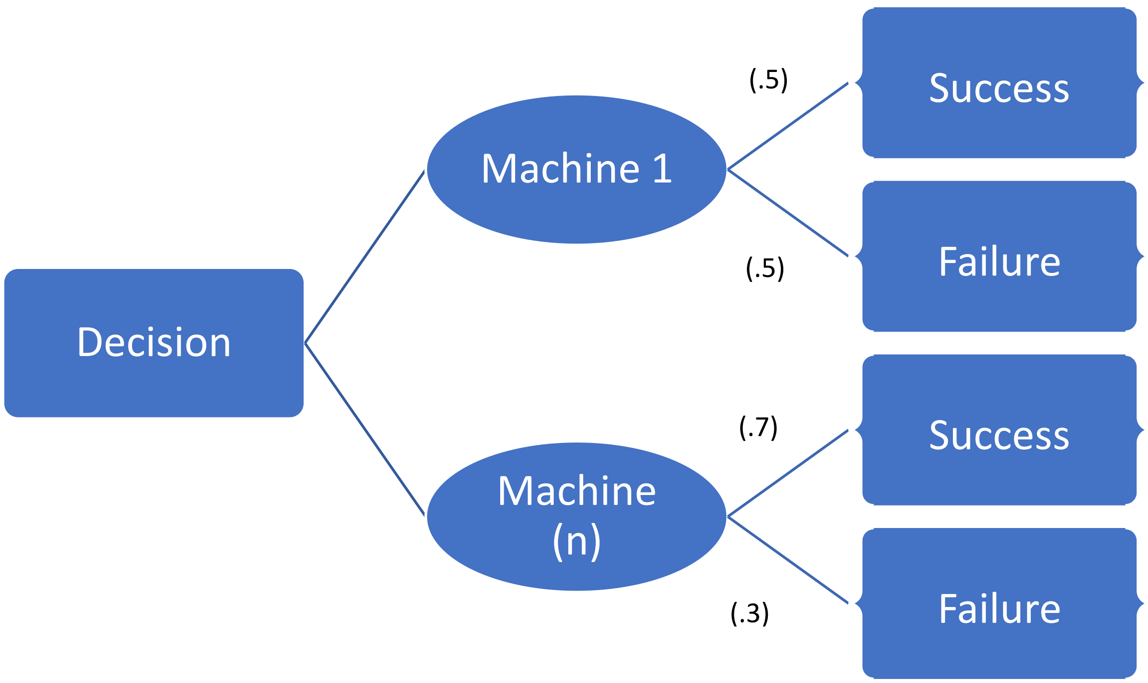


Figure 1 Decision Tree

Data Collection/Analysis Methods

The researcher is a "participant-observer" collecting data through multiple unstructured recorded video observations, recorded audio, and digital pictures of the sessions in a controlled natural classroom setting. The students knew they were being recorded as they designed and refined their processes as the teacher presented new scientific material.

The data from the two teams had methods and coding schema applied in the same way to reveal their reasons and rationale for designing their solutions based on the science learned. Data was gathered with the goals of:

> #1 Answering the question of what engineering design tradeoffs occurred as science knowledge increased while students refined their solutions using the EDP? [4], [7]
>
> #2 Gaining an understanding of what science was discussed and learned while using the EDP in each class session [4], [24].

As the data is comprised of audio, video, and imagery, a hybrid style of deductive and inductive coding was applied for the individual sets. The first step was to establish predetermined deductive codes, using both the literature review and the research question, for a code map[24] to use for the initial review of the different data sets. As the reviews occurred, inductive coding was also employed to capture new codes that emerged. The predetermined and discovered codes were grouped for categorization. The specific use of coding methods, descriptive and value coding, for the video, audio, and images is shown in Table 4, Coding Matrix.

Table 4 Coding Matrix

	Descriptive Coding	Value Coding
Video	X	X
Audio		X
Image	X	

Word frequency counts, and probabilities of shared terms between curriculum and team dialogue were compared to explore student gains in science while using the engineering design process.

Content

The focus of this section is describing the mixed methods approach used to examine team discussions to reach solutions during the last three sessions of the curriculum, which was when students were designing their solutions. A MATLAB model of the course content was generated as a “digital twin” of the mineral mayhem curriculum. This model was used as a baseline to compare the words used in the curriculum with those used in the separate teams' recorded dialogues as they developed their decision trees for solutions to the mineral mayhem challenge. The workflow explanation in this section uses the curriculum as the data set to explain the process, but the procedures were also utilized for the team conversations. Figure 2 displays the MATLAB program’s workflow and the objectives for each step. The same process was used to create the “digital twin” of the curriculum and the students’ conversations.

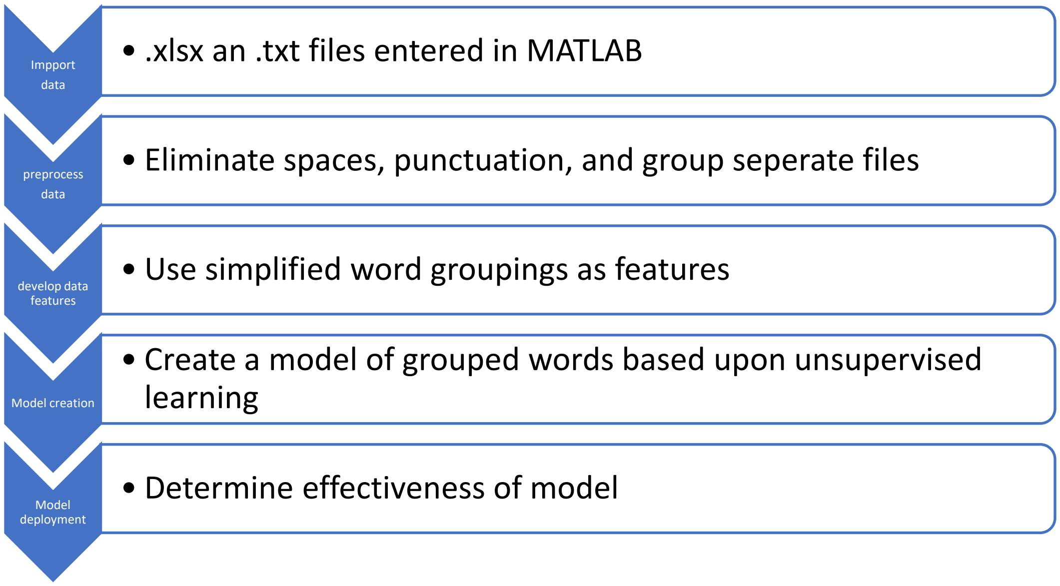
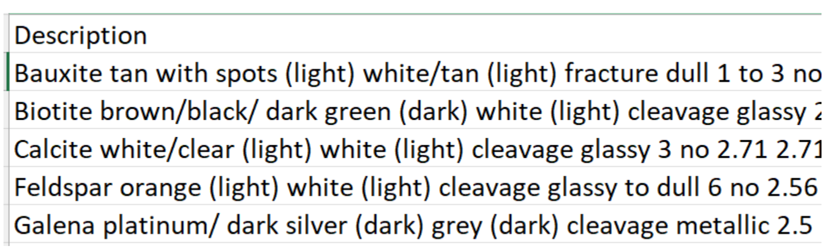


Figure 2 Program Workflow

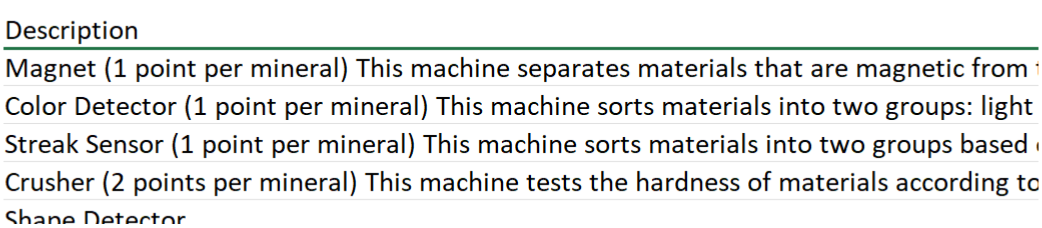
Importing of Data

A data store was created in MATLAB that holds all the raw files for the curriculum and team conversations. The data is comprised of 3 separate Excel files that describe the properties and features of the minerals, machines, and learning sessions described in the curriculum. A portion of each file is depicted in Figures 3-5.



Description
Bauxite tan with spots (light) white/tan (light) fracture dull 1 to 3 no
Biotite brown/black/ dark green (dark) white (light) cleavage glassy
Calcite white/clear (light) white (light) cleavage glassy 3 no 2.71 2.71
Feldspar orange (light) white (light) cleavage glassy to dull 6 no 2.56
Galena platinum/ dark silver (dark) grey (dark) cleavage metallic 2.5

Figure 3 Mineral Excel file



Description
Magnet (1 point per mineral) This machine separates materials that are magnetic from
Color Detector (1 point per mineral) This machine sorts materials into two groups: light
Streak Sensor (1 point per mineral) This machine sorts materials into two groups based
Crusher (2 points per mineral) This machine tests the hardness of materials according to
Shape Detector

Figure 4 Machine Excel file

Description
off the rails.Identify the engineering design problem. Students will be client memo, which orients them to the problem of sorting minerals reclaimed from a lake after a train to the engineering design process and will conduct research on the im • Research mineral value and importance. • Describe economic, social, and ethical considerations related

Figure 5 Lesson Excel file

The program first imports the curriculum data files (minerals.xlsx, machines.xlsx, and lessons.xlsx) from the data store and combines all three into one .txt file.

Preprocess

The documents can be viewed as a matrix where each line represents a row of a matrix with a string of characters that all reside in the first column. The dimension of the matrix is m x 1. A subfunction to the main program was created to preprocess the data files to synchronize and align the data for use in the analysis of the team conversations. The beginning of this subfunction converts all of the text in the combined file to lowercase. This is because the computer will recognize an upper-case word and a lower-case case as two separate words. For example, the terms “Mineral” and “mineral” are two separate and distinct words that would result in an inaccurate frequency count when a search was performed. Tokenization is then performed, and each word of the row is placed into its own column. This changes each line from being a m x 1 vector to an m x n vector, where n is the number of words(tokens) in the row. A pointer reference system that allows for indexing can now be used for each word in a line. Figures 6, Before Tokenization, and 7, After Tokenization, display the process results.

Row	Column 1	Dimension
1	“Off the rails. Identify the engineering”	1X1

Figure 6 Before Tokenization

Row	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Dimension
1	“off”	“the”	“rails”	“identify”	“the”	“engineering”	1X 6

Figure 7 After tokenization

Once tokenization is complete, all punctuation is removed from each word. The total number of words is then reduced by eliminating what are known as “stop words”. Examples of such words are “the,” “and,” and “its.” The removal of both short (two characters) and long words (greater than 15 characters) is then performed. If there is an empty row, this is removed as this slows processing time down. The process of lemmatization or grouping the inflections or variants of a word and using only the root form is performed. An example is “running” and “ran,” which are from the base word “run.”

Figure 8, Pre- and Post-processed document, shows a sample of applying the above steps to the curriculum files. Notice that all words are lowercase and lemmatized, and punctuation, stopwords, and short and long words have been eliminated, allowing for tokenization. The number of tokens is shown to the left of the row.

```
textdata = 33x1 string
    "Properties of minerals, identifcation methods f
    "Engineering design process, Environmental & Civ
    "off the rails.Identify the engineering design p
    "Let’s Sort it Out. Identify similarities and di
    "Which Mineral is That? Conduct tests of mineral
    "Discovering Density.Measure the volume of irreg
    "Go with the Flow. Identify the criteria and con
    "Engineering Design Challenge. Create a process
```

```
 7 tokens: property mineral identifcation method r
12 tokens: engineering design process environment
43 tokens: off rail identify engineering design pr
34 tokens: sort identify similarity difference mir
44 tokens: mineral conduct test mineral property r
59 tokens: discover density measure volume irregu
62 tokens: flow identify criterion constraint engi
49 tokens: engineering design challenge create pro
```

Figure 8 Pre and post-processed document

Develop Data Features

The key to analyzing the text is establishing features from the document for the computer to recognize and take action on. For the purpose of this program, a distinct feature is the grouping of unique words from the curriculum’s vocabulary into what is referred to as n-grams. An n-gram is a set of n number of words that convey meaning; an example of bi-grams (n-gram with n =2) to convey an idea could be “bad weather” or “rain clouds.” These groupings are combined to establish a model object in MATLAB that allows the words to be compared/contrasted with another model. The Mineral Mayhem tri-gram object model (MinMaybag, n=3) and its properties are shown in Figure 9, Mineral Mayhem Bag of tri-grams object model. The original raw data with dimensions (m x n) of 33 x 1 became a model with the dimensions of 33 rows by 579 columns. The 579 columns are a string of 3 words, shown in the model's “Ngrams” property.

```
MinMaybag =
  bagOfNgrams with properties:

          Counts: [33x579 double]
      Vocabulary: ["property"    "mineral"    "identifca
          Ngrams: [579x3 string]
    NgramLengths: 3
       NumNgrams: 579
```

Figure 9. Mineral Mayhem Bag of Tri-grams Object Model

A wordcloud of the tri-grams is depicted for reference in Figure 10, MinMay Wordcloud. The size of the words reflects their frequency and, therefore, emphasis in the document.

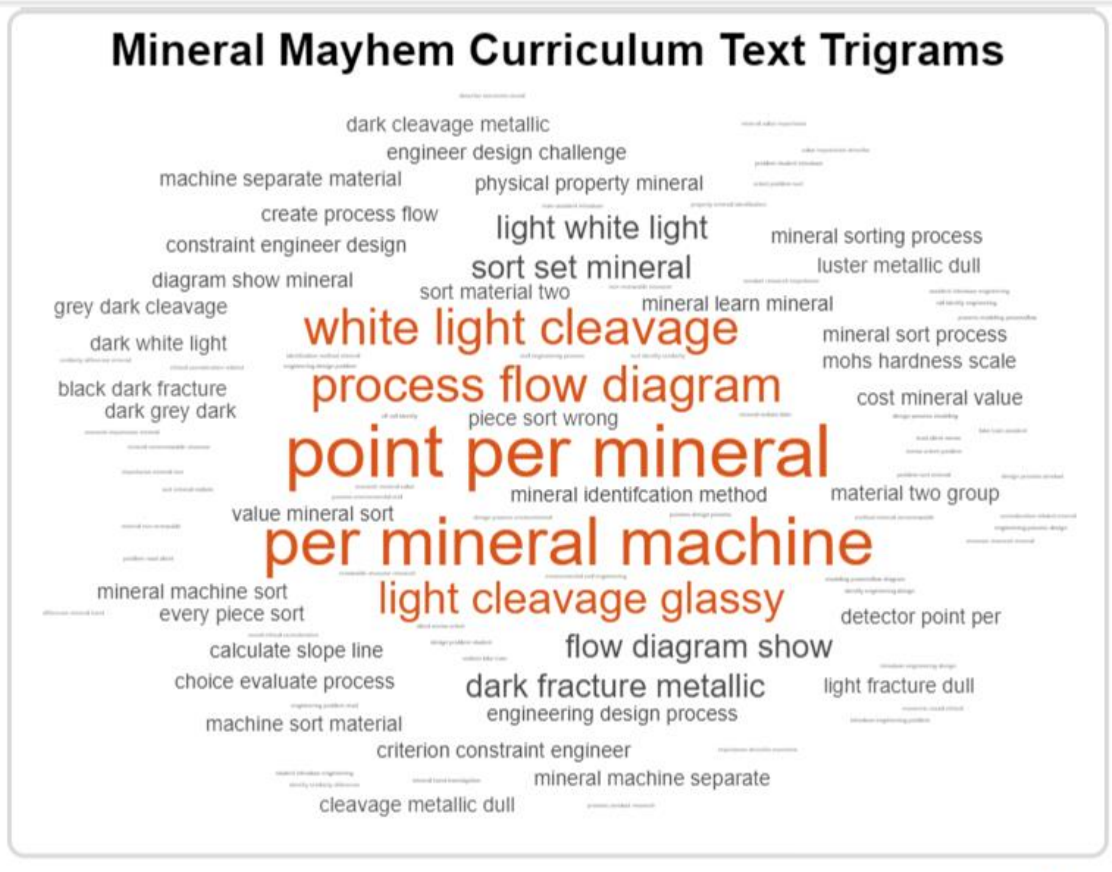


Figure 10. MinMay Wordcloud

Discussion and Results

Model Deployment

Deploying the model has the objective of determining similarities between the baseline curriculum model and the team conversation data documents [30], [31]. The assumption is that there are patterns to be recognized in the curriculum model's top words used within each team's 50-minute session conversation. The words that are identified will be counted in the team conversations. Students establish methodologies for recognizing minerals based on what they have learned. From this knowledge, they develop recovery processes motivated by points for each mineral correctly collected, identified, and accounted for. This can be used as one form of insight into the curriculum's influence on the team's decision processes and also an indicator of whether student learning of science occurred through the use of the structured EDP [30], [32], [33]. The comparison and analysis of the three final days (11,12 and 13) of the curriculum against team dialogue is performed.

Day 11 Target Group 1 and 2

After preprocessing the conversation for Target Group 1, the result was a 2,824 x20 matrix. Target Group 2's preprocessed conversation produced a 2097x20 matrix. The overall word counts reflecting the curriculum terms used in both teams' discussions for day 11 are shown in Figure 11, Both Teams' Wordcounts Day 11. A preliminary review shows the two groups have differing approaches that can be inferred from their word counts. Target Group 1(TG1) focused on cost, influenced by the recovery processes constraining their gains and profit. The specific minerals were of less concern; the way the team would attempt to recover them was the objective. By contrast, Target Group 2's (TG2) discussions centered around specific minerals and how to exploit their properties for recovery. The cost was not a high priority of their initial concerns. TG1's initial design solution resulted in an overall score of -10. Their discussion points of cost, different attempts(try), shape, color, and design comprised 63% of their discussion. TG 2's initial design solution resulted in an overall score of -17. Their discussion points of different attempts(try), color, feldspar, magnetite, and shape design comprised 58% of their discussion. Of note, TG 2's mineral of focus had the highest value (Feldspar) of 15 points if it were to be recovered, but this was the mineral of lowest concern by TG 1.

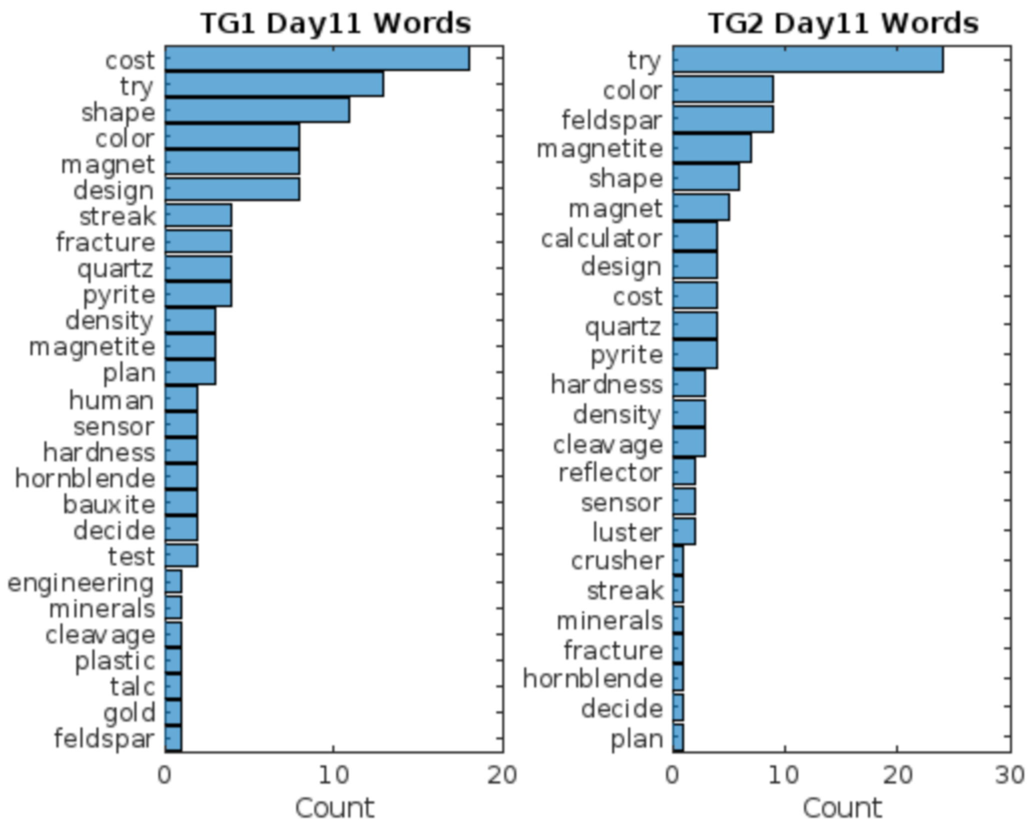


Figure 11. Both Teams' Wordcounts Day 11

Figure 12 shows TG1's Day 11 word count next to a photograph of their process design as it appeared on Day 11. Figure 13 provides the same information for TG2.

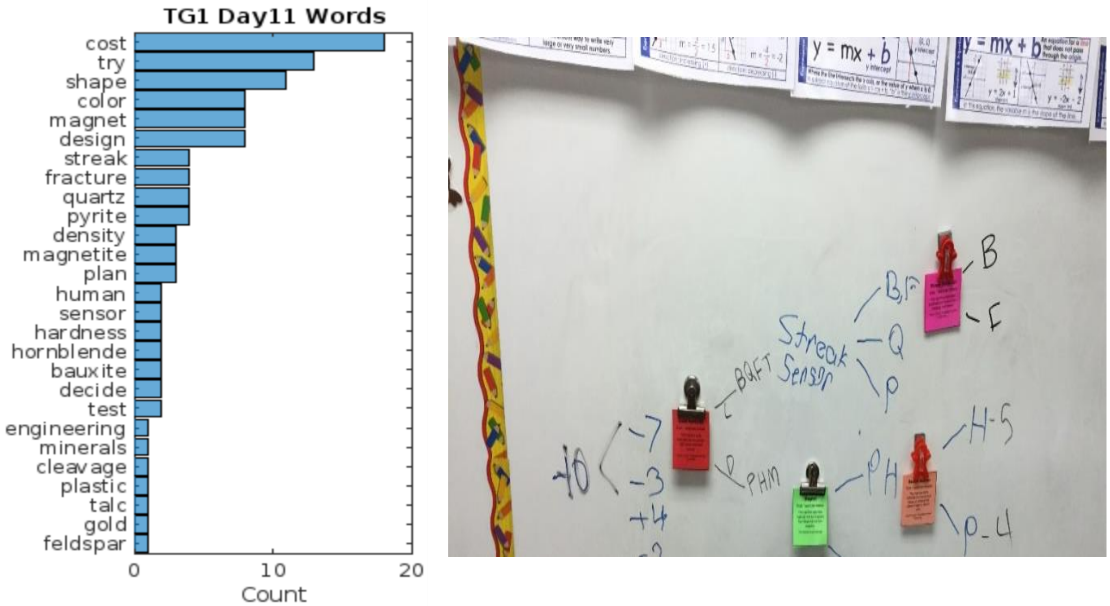


Figure 12 TG1 Day 11 Words and Photo of Solution

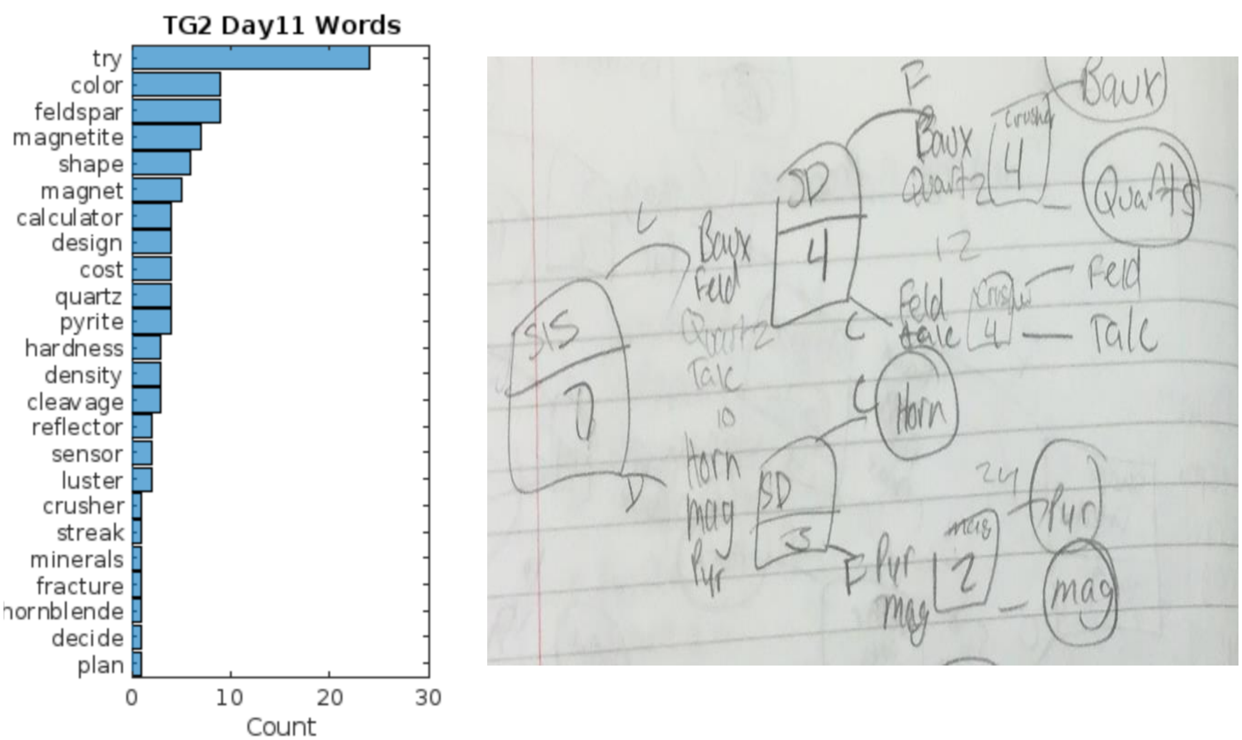


Figure 13. TG2 Day 11 Words and Photo of Solution

Day 12 Target Group 1 and 2

On Day 12, as student groups refined their solutions, Target Group 1's preprocessed discussion produced a 1,617x20 matrix, and Target Group 2 produced a 997x20 matrix. Both teams had substantially fewer words on Day 12 than day 11. Day 12 results show a shift in priorities by both teams to items that did not provide any points but actually would take points away if they were unable to be recovered. Influenced by the "client" letter that responded to their day 11 designs, the request to remove plastic and wood gave guidance on what to prioritize. This is reflected as both teams spent much time discussing the plastic and wood and the approaches to eliminate them. TG1 recognized that density would be a strong differentiator between minerals and these two much lower-density items. Figure 14 shows the word counts for both teams on Day 12.

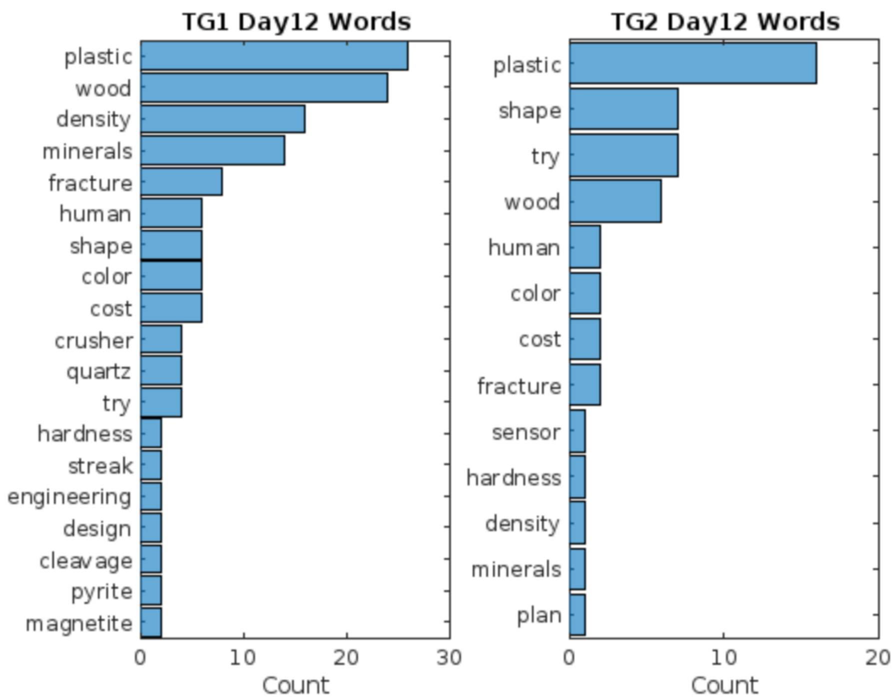


Figure 14 Both Teams Wordcounts Day 12

The teams spent a significant amount of time comparing the density properties of plastic, wood, and minerals. TG1 discussions were focused on the recognition of plastic and wood and the impacts of being able to eliminate them. The tradeoff of being able to detect minerals, while still being able to identify and sort plastic and wood, became a permanent design requirement for the team. Their solution resulted in -3 points, which was an improvement from their initial design score of -10. While TG2 recognized the need to eliminate plastic and wood, their solution choice used the shape to discern these objects from minerals. The main terms were approximately 63% of the discussion. TG2's range of terms decreased from the initial day as well, with no discussion of specific minerals and limited discussion of properties and processes for recovery. A great deal of time was dedicated to exploring whether plastic and wood had any shared properties that could be recognized. The team's overall design resulted in -10, which was an improvement from their day 11 design score of -17. Of note, their solution became more focused on solving the plastic and wood issues, spending 54% of the discussion on these terms.

Day 13 Target Group 1 and 2

On Day 13, the preprocessing actions for Target Group 1 generated a 1,962x20 matrix, while Target Group 2's conversation produced a 2258x20 matrix. Day 13 reflected significant maturity in both teams' designs and approaches for the sorting and recovery processes. Of note. they both could recognize and remove wood and plastic, giving them extra points for their solutions. The top three points of discussion by both teams were plastic, wood, and minerals, which account for a significant percentage of the discussions by both teams. TG1 produced a solution that generated an overall score of +9 for recovery. This is a 19-point increase from the initial one from day 11. TG2's overall solution was +9 as well, increasing from day 11 by 26 points. Figure 15 shows the Day 13 word count for both target groups. Figures 16 and 17 show the word counts next to photos of the solutions.

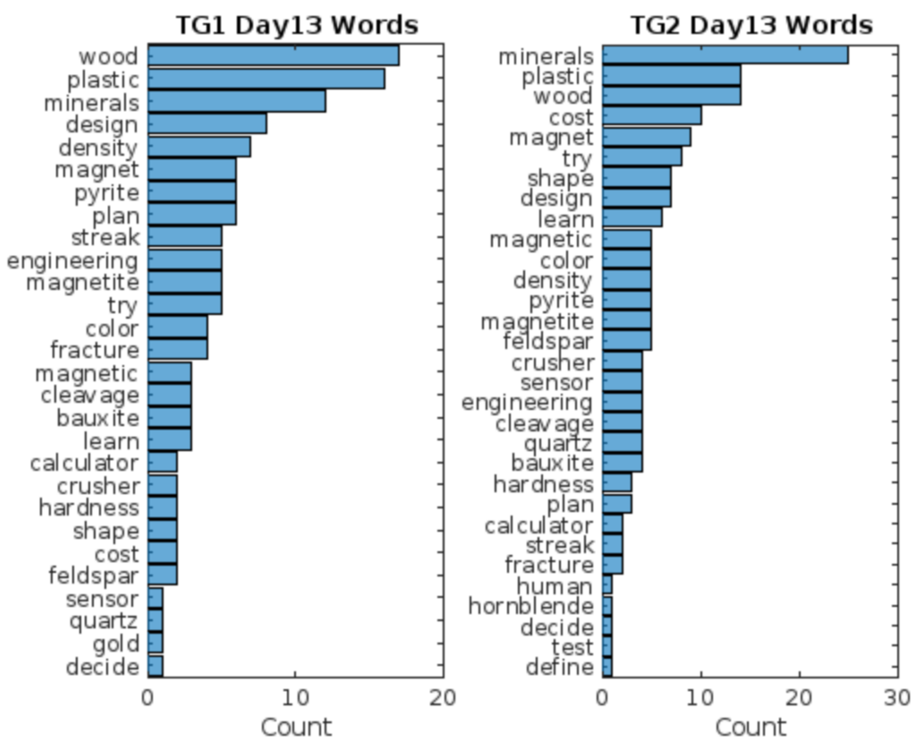


Figure 15 Both Teams Wordcounts Day 13

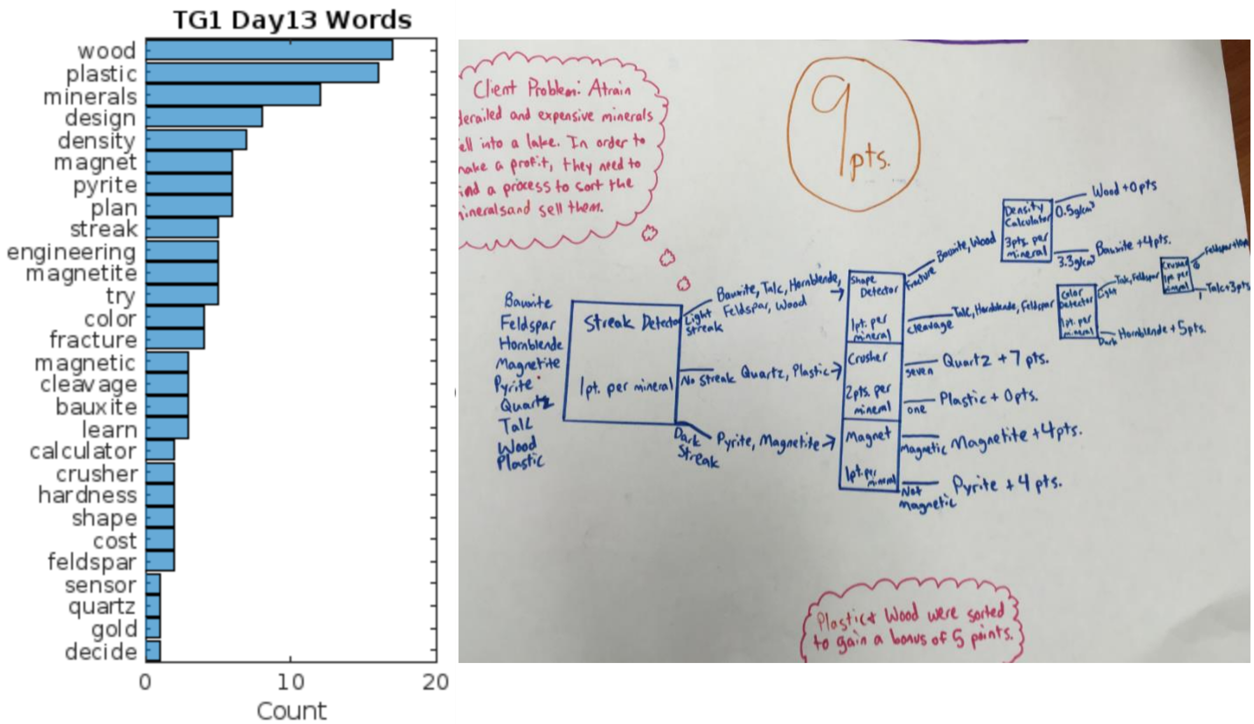


Figure 16 TG1 Day 13 Words and Solution

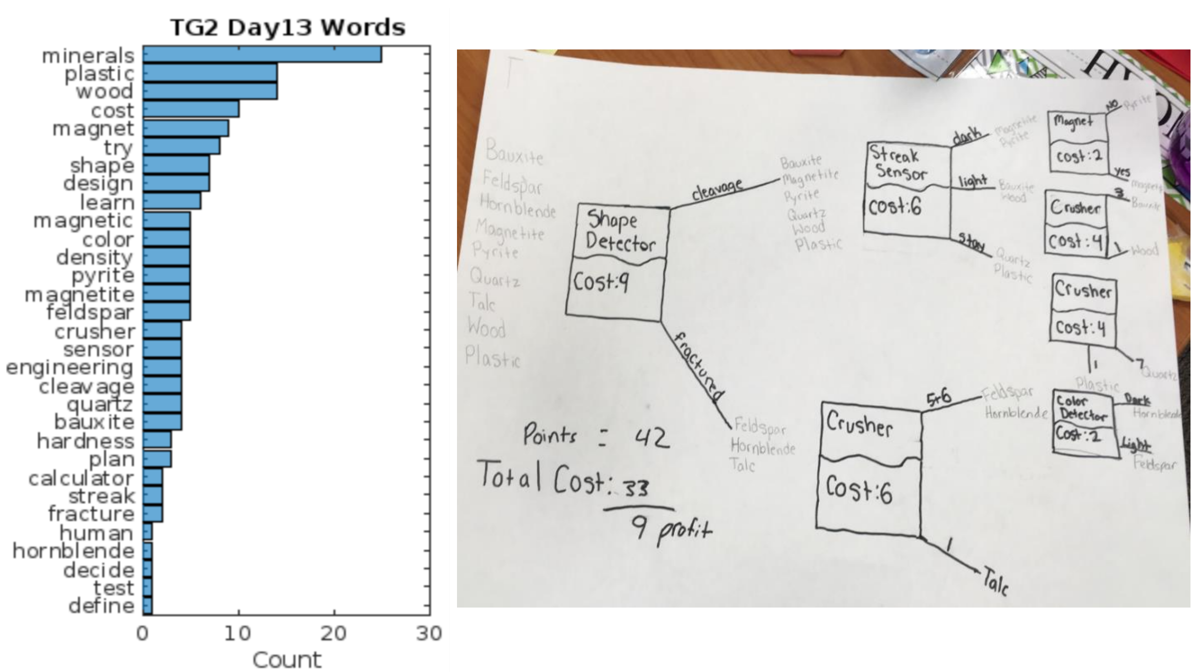


Figure 17 TG2 Day 13 Words and Solution

Conclusion

It is evident from the teams' solutions that design tradeoffs were occurring over the final stages of the curriculum. The indication is that as both teams executed the EDP, they recognized that additional scientific knowledge was needed to identify minerals. The more difficult minerals to be recovered required an understanding of higher levels of science or the coupling of scientific areas to meet objectives. There were gains in multiple scientific areas, which shows that learning did occur. The scientific area that showed the most significant discussion increase for TG1 was the subject of density, accounting for only 2% of the Day 11 discussion but jumping to 12% and 10% for days 12 and 13. Once the team recognized and understood this characteristic for mineral identification, this became a design parameter the team centered on. This is evidenced in their final design in the upper corner, which uses this to eliminate plastic and wood, gaining them extra points. TG2 benefited when the team stopped attempting random machine sequences and focused on the design of a solution backed by science. The team's use of the word "try" was at 41% on day 11, and reviewing the audio and video files exposed the high number of attempts of randomly connecting machines by the team. This took a severe decrease to 7% on day 13, and the team had justifications for the choices made.

A review of the different changes that resulted in overall positive scores for their final designs suggests that the EDP enabled both teams to perform design tradeoffs for profit and make these decisions based on the science acquired from the lessons. It can be stated that student scientific literacy increased over the multiple sessions of the STEM curriculum that was structured through the use of the Engineering Design Process.

Future efforts

In recent years, there has been an increased importance of having the capability to search large archival databases that contain elements of different types, such as photos, video, audio, and textual data. There are opportunities for the Mineral Mayhem curriculum to be further explored from additional perspectives. An argument could be made that the digital twin model could be used to explore methodologies of thematic[34]and discourse[35] analysis being applied to the teams. Machine learning and Deep Learning could be utilized for the datasets. One particular application is the classification of input data through supervised learning. A deep learning convolutional neural network(CNN) potentially could be used to establish a sentiment classifier of the conversations about the curriculum.

Another future effort could be to train a sentiment classifier that assigns a numerical score to a piece of text to indicate whether the sentiment is positive or negative about performing the EDP to learn science. This would attempt discourse analysis [35], [36], [37] to understand the opinions and feelings of the team members as ideas are exchanged to reach a consensus on solutions. The patterns of discourse and conversations amongst team members provide insight into their understanding of the constraints, valuations, and objectives that influence their design decisions in the real-world context of problem-solving.[37] The social interactions of team members progressing through the engineering design process could also be explored. The value is recognized in understanding how the team builds to an agreed-upon approach for the challenges before them.[35], [36], [37] Examining the discussions allows for an understanding of the final design processes accepted by each team.[36], [38].

References

[1] S. S. Guzey, T. J. Moore, M. Harwell, and M. Moreno, "STEM Integration in Middle School Life Science: Student Learning and Attitudes," *J. Sci. Educ. Technol.*, vol. 25, no. 4, pp. 550–560, Aug. 2016, doi: 10.1007/s10956-016-9612-x.

[2] D. A. R. Bybee Rodger W., "Scientific Literacy, Science Literacy, and Science Education," in *Handbook of Research on Science Education, Volume II*, Routledge, 2014.

[3] S. S. Guzey and W. Li, "Engagement and Science Achievement in the Context of Integrated STEM Education: A Longitudinal Study," *J. Sci. Educ. Technol.*, vol. 32, no. 2, pp. 168–180, Apr. 2023, doi: 10.1007/s10956-022-10023-y.

[4] M. L. Aranda, R. Lie, S. Selcen Guzey, M. Makarsu, A. Johnston, and T. J. Moore, "Examining Teacher Talk in an Engineering Design-Based Science Curricular Unit," *Res. Sci. Educ.*, vol. 50, no. 2, pp. 469–487, Apr. 2020, doi: 10.1007/s11165-018-9697-8.

[5] M. M. Hurley, "Reviewing Integrated Science and Mathematics: The Search for Evidence and Definitions From New Perspectives," *Sch. Sci. Math.*, vol. 101, no. 5, pp. 259–268, May 2001, doi: 10.1111/j.1949-8594.2001.tb18028.x.

[6] S. Guzey, T. Moore, and M. Harwell, "Building Up STEM: An Analysis of Teacher-Developed Engineering Design-Based STEM Integration Curricular Materials," *J. Pre-Coll. Eng. Educ. Res. J-PEER*, vol. 6, no. 1, Jun. 2016, doi: 10.7771/2157-9288.1129.

[7] S. Selcen Guzey, T. J. Moore, and G. Morse, "Student Interest in Engineering Design-Based Science," *Sch. Sci. Math.*, vol. 116, no. 8, pp. 411–419, 2016, doi: 10.1111/ssm.12198.

[8] M. Harwell, M. Moreno, A. Phillips, S. S. Guzey, T. J. Moore, and G. H. Roehrig, "A Study of STEM Assessments in Engineering, Science, and Mathematics for Elementary and Middle School Students," *Sch. Sci. Math.*, vol. 115, no. 2, pp. 66–74, 2015, doi: 10.1111/ssm.12105.

[9] S. Brophy, S. Klein, M. Portsmore, and C. Rogers, "Advancing Engineering Education in P-12 Classrooms," *J. Eng. Educ.*, vol. 97, no. 3, pp. 369–387, 2008, doi: 10.1002/j.2168-9830.2008.tb00985.x.

[10] "Engineering in K-12 Education," NAE Website. Accessed: Apr. 14, 2023. [Online]. Available: https://nae.edu/24860/Engineering-in-K12-Education

[11] T. Moore, A. Glancy, K. Tank, J. Kersten, K. Smith, and M. Stohlmann, "A Framework for Quality K-12 Engineering Education: Research and Development," *J. Pre-Coll. Eng. Educ. Res. J-PEER*, vol. 4, no. 1, May 2014, doi: 10.7771/2157-9288.1069.

[12] G. H. Roehrig, E. A. Dare, E. Ring-Whalen, and J. R. Wieselmann, "Understanding coherence and integration in integrated STEM curriculum," *Int. J. STEM Educ.*, vol. 8, no. 1, p. 2, Jan. 2021, doi: 10.1186/s40594-020-00259-8.

[13] M. Stohlmann, T. Moore, and G. Roehrig, "Considerations for Teaching Integrated STEM Education," *J. Pre-Coll. Eng. Educ. Res. J-PEER*, vol. 2, no. 1, Apr. 2012, doi: 10.5703/1288284314653.

[14] M. M. Hynes, "Middle-school teachers' understanding and teaching of the engineering design process: a look at subject matter and pedagogical content knowledge," *Int. J. Technol. Des. Educ.*, vol. 22, no. 3, pp. 345–360, Aug. 2012, doi: 10.1007/s10798-010-9142-4.

[15] C. S. Dweck, *Self-theories: their role in motivation, personality, and development*. in Essays in social psychology. Philadelphia, PA: Psychology Press, 1999.

[16] K. A. Renninger, S. Hidi, and A. Krapp, Eds., *The Role of interest in learning and development*. Hillsdale, N.J: L. Erlbaum Associates, 1992.

[17] A. V. Maltese, C. S. Melki, and H. L. Wiebke, "The Nature of Experiences Responsible for the Generation and Maintenance of Interest in STEM," *Sci. Educ.*, vol. 98, no. 6, pp. 937–962, Nov. 2014, doi: 10.1002/sce.21132.

[18] A. Redmond, J. Thomas, K. High, M. Scott, P. Jordan, and J. Dockers, "Enriching Science and Math Through Engineering: Enrichment Through Engineering," *Sch. Sci. Math.*, vol. 111, no. 8, pp. 399–408, Dec. 2011, doi: 10.1111/j.1949-8594.2011.00105.x.

[19] G. J. Kelly and C. M. Cunningham, "Epistemic tools in engineering design for K-12 education," *Sci. Educ.*, vol. 103, no. 4, pp. 1080–1111, Jul. 2019, doi: 10.1002/sce.21513.

[20] Ş. Purzer, J. Strobel, and M. E. Cardella, Eds., *Engineering in pre-college settings: synthesizing research, policy, and practices*. West Lafayette, Ind: Purdue University Press, 2014.

[21] K. Bethke Wendell and C. Rogers, "Engineering Design-Based Science, Science Content Performance, and Science Attitudes in Elementary School," *J. Eng. Educ.*, vol. 102, no. 4, pp. 513–540, Oct. 2013, doi: 10.1002/jee.20026.

[22] M. Dalal and A. Carberry, "Understanding anchors associated with secondary school students' engineering design experiences," *Clive Dym Mudd Des. Workshop XII*, Jan. 2021, Accessed: Jan. 23, 2023. [Online]. Available: https://par.nsf.gov/biblio/10294645-understanding-anchors-associated-secondary-school-students-engineering-design-experiences

[23] J. Mangold and S. Robinson, "The engineering design process as a problem solving and learning tool in K-12 classrooms," in *Association for Engineering Education - Engineering Library Division Papers*, Atlanta, United States: American Society for Engineering Education-ASEE, Jun. 2013, p. 23.1196.1-23.1196.14. Accessed: Jul. 03, 2023. [Online]. Available: https://www.proquest.com/publiccontent/docview/2317889206?pq-origsite=primo&parentSessionId=1eQSpjZ2YY4OaaUr4gjnBa35sdfs0xsvAyRcYFGcRmw%3D

[24] E. A. Siverling, E. Suazo-Flores, C. A. Mathis, and T. J. Moore, "Students' use of STEM content in design justifications during engineering design-based STEM integration," *Sch. Sci. Math.*, vol. 119, no. 8, pp. 457–474, Dec. 2019, doi: 10.1111/ssm.12373.

[25] N. M. Alozie, E. B. Moje, and J. S. Krajcik, "An analysis of the supports and constraints for scientific discussion in high school project-based science," *Sci. Educ.*, p. n/a-n/a, 2009, doi: 10.1002/sce.20365.

[26] D. S. Pimentel and K. L. McNEILL, "Conducting Talk in Secondary Science Classrooms: Investigating Instructional Moves and Teachers' Beliefs," *Sci. Educ.*, vol. 97, no. 3, pp. 367–394, May 2013, doi: 10.1002/sce.21061.

[27] A. W. Oliveira, "Improving teacher questioning in science inquiry discussions through professional development," *J. Res. Sci. Teach.*, vol. 47, no. 4, pp. 422–453, Apr. 2010, doi: 10.1002/tea.20345.

[28] L. B. Resnick, C. S. C. Asterhan, S. N. Clarke, and R. Correnti, Eds., *Improving Teaching at Scale: Design for the Scientific Measurement and Learning of Discourse Practice*. Washington, DC: American Educational Research Association, 2015.

[29] D. H. Palmer, "Student interest generated during an inquiry skills lesson," *J. Res. Sci. Teach.*, vol. 46, no. 2, pp. 147–165, Feb. 2009, doi: 10.1002/tea.20263.

[30] C. Frankfort-Nachmias, D. Nachmias, and J. DeWaard, *Research methods in the social sciences*, Eighth edition. New York, NY: Worth Publishers, a Macmillan Education Company, 2015.

[31] M. D. White and E. E. Marsh, "Content Analysis: A Flexible Methodology," *Libr. Trends*, vol. 55, no. 1, pp. 22–45, 2006.

[32] S. Stemler, "Emerging Trends in Content Analysis," 2015, pp. 1–14. doi: 10.1002/9781118900772.etrds0053.

[33] M. Bengtsson, "How to plan and perform a qualitative study using content analysis," *NursingPlus Open*, vol. 2, pp. 8–14, Jan. 2016, doi: 10.1016/j.npls.2016.01.001.

[34] R. A. B. Rodrigues, J. W. Paul, and J. S. Cicek, "Entering the Discipline of Engineering Education Research: A Thematic Analysis," presented at the 2021 ASEE Virtual Annual Conference Content Access, Jul. 2021. Accessed: Oct. 23, 2023. [Online]. Available: https://peer.asee.org/entering-the-discipline-of-engineering-education-research-a-thematic-analysis

[35] J. P. Quintana-Cifuentes, S. Purzer, this link will open in a new tab Link to external site, M. H. Goldstein, and this link will open in a new tab Link to external site, "Discourse Analysis of Middle School Students' Explanations during a Final Design Review (Fundamental)," in *Association for Engineering Education - Engineering Library Division Papers*, Atlanta, United States: American

Society for Engineering Education-ASEE, Jun. 2019. Accessed: Nov. 29, 2023. [Online]. Available: https://www.proquest.com/docview/2314001357?pq-origsite=primo
[36] R. Eggert, A. Joshi, S. Mehrotra, Y. V. Zastavker, and V. Darer, "Using discourse analysis to understand 'failure modes' of undergraduate engineering teams," in *2014 IEEE Frontiers in Education Conference (FIE) Proceedings*, Oct. 2014, pp. 1–5. doi: 10.1109/FIE.2014.7044436.
[37] S. Selcen Guzey and M. Aranda, "Student Participation in Engineering Practices and Discourse: An Exploratory Case Study," *J. Eng. Educ.*, vol. 106, no. 4, pp. 585–606, 2017, doi: 10.1002/jee.20176.
[38] J. M. Case and G. Light, "Emerging Research Methodologies in Engineering Education Research," *J. Eng. Educ.*, vol. 100, no. 1, pp. 186–210, 2011, doi: 10.1002/j.2168-9830.2011.tb00008.x.