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Assessing Learning in Mathematical Sensemaking Electromagnetism Instructions among Rwanda Polytechnic Students at Huye College

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ABSTRACT

In the realm of electromagnetic (EM) courses in engineering, many studies have reported students' learning difficulties related to mathematical frameworks representing physical phenomena. Students' learning engagement and learning gains are not satisfying. The present study assessed first-year engineering students' behavioural engagement and perceived learning gains in mathematical sensemaking electromagnetism instructions at RP-Huye College. Within a single-case research design, a six-weeks intervention incorporating mathematical sensemaking instructions, supported by physical experimentation and computer simulations, was implemented to 61 first-year engineering students who were enrolled in the department of electrical and electronics engineering. All enrolled students were purposively recruited to participate because this target population was less than 100. Data were collected through classroom observations, which used the behavioural engagement related to instruction (BERI) and a post-topic evaluation, which used a semi-structured questionnaire. Data analysis involved the use of graphs, descriptive statistics and inductive thematic analysis. Findings revealed that students were mostly engaged during mathematical sensemaking by hands-on and simulation-based activities, particularly in topics related to electromagnets, where engagement levels peaked at 7.5 in average. Conversely, lecture-based tasks, especially on magnetic forces and electromagnetic induction, recorded the lowest engagement at 6.2 in average. The post-topic assessment on perceived learning gains showed that students had highly positive perceptions on their learning experiences (M=4.82, SD=0.48) and recognized the significance of EM in engineering (M=4.85, SD=0.38). These numerical results were complemented by students' narrations, which indicated that they gained particular attention about specific EM formulas and how they can apply them in engineering. However, the present study also noted that further refinement in instructional design, particularly by incorporating specific dimensions of mathematical sensemaking, could optimize learning outcomes for EM courses in engineering. Additionally, formal assessments of students' mastery and experimental studies can benefit future work.

Keywords: Computer Simulations, EM Instructions, Mathematical Sensemaking, Physical Experimentation

I. INTRODUCTION

Research has shown that students' mathematical ability affects positively their performance in electromagnetism (EM) courses. It was evidenced that adequate knowledge of mathematics is a must for the understanding and application of EM concepts (Okey & Gladysibibo, 2015, p. 47). Nevertheless, students' learning difficulties in EM courses have been consistently reported in engineering education contexts, raising an epistemic curiosity for understanding how engineering students learn EM topics. According to Bollen et al. (2017, p. 13), some students may use inaccurate mathematical relations in EM due to the lack of a deeper understanding of the physics involved. This gap between mathematical representations and the deeper understanding of the physics in EM courses can lead to students' difficulties in problem-solving in engineering contexts.

Cutri et al. (2015, p. 2) insisted that, without the use of active learning strategies in EM instructions, engineering students may rely solely on mathematical deductions without understanding the real physics. This is also in the same view as Zhao and Schuchardt (2021, p. 1), who stipulated that students who only rely on algorithmic and procedural approaches struggle to make sense of the real science of some physical phenomena. Further, talking about inadequate treatment of Maxwell's theory in EM courses, Massa et al. (2020, p. 51) claim that engineering students can lose self-confidence and motivation to understand physical phenomena and concepts described by Maxwell's equations, leading to passive and boring learning process. This shows that, without efficient treatment of mathematical representations embodying physical meaning in EM concepts, engineering students become unable to make inferences from mathematics to real-world physical phenomena. In this case, there is a lack of mathematical sensemaking which could help them in making connection between mathematics and EM phenomena.

As physicists and engineers use mathematics in problem-solving, "mathematical sensemaking is viewed as a reasoning that leverages coherence between formal mathematics and conceptual understanding" (Kuo et al., 2020, p. 1). According to Galili (2018), mathematical knowledge that builds solid understanding of physics concepts can be categorized in algebraic and geometric knowledge domains. For algebraic domain, mathematical sensemaking requires students to make inferences from mathematical equations to variables in a physical phenomenon. On the other hand, mathematical sensemaking means that students are able to make a coherent connection between graphical and figural representations and physics concepts. In EM courses, students' learning difficulties can be linked to the lack of mathematical sensemaking about algebraic and geometrical domains.

In traditional instructions, lecturers tend to skip the deep mathematical representations of EM concepts by either employing qualitative descriptions, using robust mathematical demonstrations of EM phenomena or just immersing students in application sessions without a rigorous manipulation of variables. In this case, the instruction becomes more theoretical or qualitative and does not cater about students' mathematical sensemaking for deep understanding of the subject. For example, Campos et al. (2023) found that first-year engineering students at a Mexican university struggled to use correct symmetry in calculating both electric and magnetic fields in line with Gauss' and Ampere's laws, respectively. This is an evidence that these students lacked mathematical sensemaking for connecting geometrical representations and algebraic knowledge in problem-solving. Algebraic knowledge domains require students' analysis through the manipulation of variables whereas geometrical domain necessitates the use of visual objects.

In Rwanda, some studies show that there is an overemphasis on theoretical instruction over practical training, which can lead to engineering students' low interest in the courses and employability prospects (Hakizayezu & Maniraho, 2022). It was reported that 88% of 150 technical and vocational education and training (TVET) graduates had learning difficulties because their training was too theoretical and not enough practical. An equal number of graduates also mentioned that they did not have the fundamental skills needed for work. In an interview, a TVET trainer expressed these feelings, pointing out that as long as practical training is still scarce in schools, it is unrealistic to anticipate improved employability rates among graduates. These results may reveal that, in STEM subjects, it is difficult for students to have meaningful learning within theoretical instructions.

Table 1

Some Reports about Hands-on Practical Skills for Rwandan TVET Students

Topic	Feedback	Source
1. Perceptions of TVET graduates and trainers on **practical instruction** at school.	Not sufficient. More practice is needed for more employability	(Hakizayezu & Maniraho, 2022)
2. TVET schools in promoting employability through **hands-on skills** (job search, creation and sustainability).	Workshop-based training is needed for more employability	(Rukundo & Sikubwabo, 2021)
3. IPRCs students' satisfaction survey including the acquisition of **practical skills** either in industry or in training workshops or labs.	Many students are satisfied but improvement in time allocated to practical sessions is worthy doing	(Rwanda Polytechnic, 2021)
4. National employment policy harnessing education and employability skills including Rwanda Polytechnic's focus on **hands-on practical skills**.	Hands-on practical skills will prepare students for the competitive world. Traditional theoretical knowledge is obsolete	(Ministry of Public Service and Labor, 2019)
5. Factors hindering the acquisition of **practical skills** in Rwandan TVET schools, Rwanda Polytechnic.	Many theoretical courses and less lecturers' assistance	(Rwamu, 2019)

The present study aimed to assess first-year engineering students' behavioural engagement and perceived learning gains in mathematical sensemaking electromagnetism instructions at Huye College. Specifically, it intended:

1. to determine first-year engineering students' behavioural engagement levels in mathematical sensemaking electromagnetism instructions.
2. to assess the extent to which first-year engineering students perceive their learning gains in mathematical sensemaking electromagnetism instructions and areas in which students perceive these learning gains.

To achieve these specific objectives, the present research has followed the corresponding research questions, formulated based on the specific objectives:

1. How do first-year engineering students' behavioural engagement levels change during mathematical sensemaking electromagnetism instructions?
2. To what extent and in what areas do students perceive learning gains after completing the mathematical sensemaking electromagnetism course?

II. LITERATURE REVIEW

2.1 Empirical review

2.1.1 Teaching and Learning Electromagnetism in Engineering

Throughout engineering education, EM and related topics are fundamental subjects since they form the basis for so many technological developments. Specifically, in electrical and electronics engineering, students need to deal with properties and characteristics of field quantities and their interaction with matter in order to address different engineering challenges (Lager et al., 2020). According to Almudi and Ceberio (2015), EM courses can help engineering students in making conclusions about electromagnetic induction (EMI) by assessing the conceptual relevance and validating their reasoning about EM phenomena in general. Moreover, it was confirmed that solid training in classical EM forms foundational pillars in electrical engineering (Lager et al., 2020, p. 15). In telecommunication engineering, EM courses lead to students' skills about wireless communications, transmissions, radar, antenna, microelectronics and sensors (Espinosa et al., 2021). This shows that the overall performance of electrical and electronics engineering students can be modelled by investing in transformative teaching and learning of EM courses.

However, the assimilation of EM concepts has been reported to be a learning difficulty for engineering students (Cutri et al., 2022). For example, Zuza et al.(2014, p. 1) claim that first-year engineering students barely understand the fundamental concepts of electromagnetic induction (EMI) in traditional instructions. In the same study, an instructional strategy combining experimentation and theoretical interpretation has been implemented and improved students' reasoning about EMI. With a similar vision, in the study conducted by Notaroš et al. (2019), it was claimed that traditional instructions relying heavily on mathematics do not offer opportunities for visual and active learning. Due to this, the said study implemented hands-on electromagnetics instructions computer-assisted MATLAB-based activities for fostering engineering students' creativity. As a result, this strategy prompted students' engagement during electromagnetics assignment and above 70% of 28 students gave positive feedback about the strategy.

Engineering students' learning difficulties about EMI phenomenon is manifested in other contexts, showing its common existence. A research carried out at three universities in Europe to investigate science and engineering students' understanding of the electromagnetic force (emf) concept in relation with EMI phenomenon, it was found that not more than 10% of participants could differentiate between the concepts of emf and potential difference (Zuza et al., 2016). The study found that most students understood magnetic flux and induction but struggled to connect these concepts to induced emf and, very often, confused emf with potential difference. In another study conducted at university pre-service physics students, it was revealed that students also confuse the formula of motional induced emf ($\varepsilon = BLv$) and the formula for Laplace's magnetic force ($F = IBL$) (Kocakülah, 2022).

Apart from EMI, studies also show that engineering students face learning challenges in relation with the use Gauss' law of flux and Ampere's law of magnetic field. A descriptive study conducted on 322 engineering students completing an EM course at one private Mexican university, it was found that students struggle in using the symmetry for Gauss' law in electricity and Ampere's law in magnetism (Campos et al., 2023). The study findings recommended active learning activities which can develop students' physical thinking and ability to calculate electric field and magnetic field.

Recent research has explored effective methods for teaching EM courses in engineering, bridging the gap between abstract concepts and real-world applications. For example, to better equip electrical engineering students with knowledge and skills for addressing real engineering problems in EM subject, González et al. (2023) opted to use the backward design (BD) methodology. This choice was made for fostering engineering students' argumentative, interpretative and proactive competences in EM subject by explaining the causes of EM phenomena, formulating hypotheses about EM phenomena and applying EM concepts in real engineering problems. Since this methodology requires students to test hypotheses through experimentation and observation, it can be thought that those students with good mathematical abilities can easily achieve the learning outcomes within this BD methodology in EM courses.

Further, a study using investigative science learning environments (ISLE) with less focus on mathematics during hands-on activities proposed by Wilson et al. (2020) can raise questions in the engineering contexts. Although this strategy can help students without strong background in mathematics, real engineering problems impose the combination of both qualitative and quantitative descriptions in problem-solving, indicating a central role played by mathematical descriptions of EM phenomena. In science classes, opportunities should be opened for students to grapple with the mathematically represented scientific concepts through mathematization, deduction, translations and analogical reasoning (Karam, 2014, pp. 5–10). The tendency of some EM instructors to only focus on conceptual treatment of EM concepts can still lead to engineering students' inability to deal with real engineering problems. The mathematics used to describe EM phenomena should be given equal treatment, especially in the engineering contexts.

2.1.2 Mathematical Sensemaking in Electromagnetism and Related Physical Sciences

Mathematical sensemaking is an instructional strategy which has been recommended in physical sciences, particularly, in EM courses. Zhao and Schuchardt (2021) provided different dimensions of mathematical sensemaking while working with mathematical equations in science:

Math-procedure sensemaking
Math-rule sensemaking
Math-structure sensemaking
Math-relation sensemaking
Math-concept sensemaking

Students' learning difficulties in EM courses, as reported in different studies, can be discussed within this framework. For example, two research studies found that engineering students struggle in understanding and applying Gauss' law ($\oint \vec{E} \cdot d\vec{A} = \frac{Q_{en}}{\varepsilon_0}$) due to their inability to handle the geometrical nature of Gaussian surfaces and confusion between different charge distributions (Campos et al., 2023; Hashish et al., 2020). Primarily, this can show that some engineering students had the problem of sensemaking about mathematical structures related to the symmetrical nature of surfaces representing electric flux.

Failing to understand the symmetrical nature of EM concepts can also lead to other learning difficulties in problem-solving procedure. This was exemplified in the study conducted on both undergraduate physics and engineering students at two universities from Spain and Uruguay about Ampere-Maxwell's law (Suárez et al., 2024). In the application of Ampere-Maxwell's law [$\oint \vec{B} \cdot d\vec{l} = \mu_0 \left(I_c + \varepsilon_0 \frac{d}{dt} \int \vec{E} \cdot d\vec{A}\right)$] beyond Ampere's law ($\oint \vec{B} \cdot d\vec{l} = \mu_0 I_c$) limitations, the study found that the majority of students struggled to interpret the concept of magnetic field circulation in relation with the provided surfaces. These results show that students' difficulty in math-structure sensemaking (surface nature) has led to their inability to understand and apply the math-concept of circulation.

It is true that all mathematical representations for EM concepts contain mathematical relations with standard rules and procedures, for which students need to have sensemaking about. For example, the application of Gauss' law and Ampere's law in problem-solving for EM phenomena requires students to understand the concept of closed integral with associated rules and procedures for surface and line integration respectively. Nevertheless, it was shown that some students may have difficulties in working with the principle of superposition in the Gauss' law contexts (Li & Singh, 2018). These students could not be able to determine the net electric field from a discrete charge distribution. This study has revealed that students' difficulties in applying Gauss' law are related to the lack of mathematical sensemaking in terms of concepts, rules and procedures about vector operations on electric fields.

The lack of mathematical sensemaking in EM courses has already impeded the learning process for both physics and engineering students. In the topic of EMI effect, it has been revealed that, without a proper mathematical sensemaking about the Faraday's and Lenz' laws ($emf = -N\frac{d\Phi_B}{dt}$), students experience difficulties in interpreting the negative sign and the rate of change of the magnetic flux in the expression (Hoe et al., 2024). As it was revealed, some students use the term "oppose" as if the original magnetic flux opposes the induced magnetic flux. These students were lacking a proper understanding of the mathematical concept of rate of change and its symbol, as it is represented in the expression. According to Zuza et al. (2014), the efficient way of addressing engineering students' difficulties with Faraday's law is to employ both experimentation and explanatory theory models, which strengthens the mathematical sensemaking.

Learning physics in the engineering contexts is considered as a way in which students build solid understanding of scientific structures making real systems, for them to have critical thinking abilities in problem-solving. It is argued that calculations in physics can offer precision and safety from argumentative errors (Kuo et al., 2020, p. 7). This shows a foundational role of mathematical sensemaking in physics courses for engineers. Particularly, Gaunkar and Mina (2018) found that the performance of engineering students in EM courses can be improved when instructional strategies which foster students' understanding mathematical concepts used in EM courses. Some studies have highlighted some scenario in which students' lack of mathematical sensemaking has led to wrong inferences. For example, in a study about gravity and free fall conducted on high school students in Ghana, it was found that many students relied on the equation ($W = mg$) to say that an object with bigger mass will fall faster than the object with smaller mass. It is clear that there was a lack of mathematical sensemaking in the situation.

2.2 Theoretical Review

The present study was guided by the constructivist-based experiential learning, for modelling engineering students' learning environments. As it is seen in Morris' (2020, p. 7) study, the Kolb's 1984's experiential learning cycle models students' learning by providing concrete examples, creating reflective observation opportunities, fostering abstract conceptualization and immersing students in active experimentation. In the present study, real engineering equipment like electromagnets, generators, bulbs and wires helped to provide concrete examples. Using mathematical equations and rules, students had the opportunity to predict the change in some variables whereas mathematical concepts like coefficients, closed integrals or line integrals were conceptualized through visualizations. Moreover, students were allowed to actively repeat experiments, either using computer simulations or hands-on activities. In this view, the present study intended to increase engineering students' mathematical sensemaking in EM through their learning experiences.

III. METHODOLOGY

3.1 Research Design and Study Setting

The current study employed a single-case research design for assessing first-year engineering students' learning during mathematical sensemaking electromagnetism lessons, as it is described by Ridder (2017). It consisted of a six-weeks intervention characterised by mathematical sensemaking classroom activities blended with either physical experimentation or with computer simulations. The intervention was followed by a post-evaluation targeting students' perceptions about their learning. Teaching and learning was guided by the performance criteria prescribed in the electromagnetic course, in the part of electromagnetism (demonstrate electrostatic phenomena, examine the effect of direct electric current in circuits, demonstrate magnetic phenomena and determine the induced emf based on electromagnetic induction laws).

Table 2

Some Mathematical Representations and Discussed Applications

Concepts	Formula	Experimentation	Application
1. Electrostatic force on charged particles	$\vec{F} = q\vec{E}$	GeoGebra simulations	Deflecting plate systems
2. Gauss' law of electric flux	$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{en}}{\varepsilon_0}$	PhET Simulations, Physics monster Simulations	Electric fields for straight cables
3. Ohm's law in DC	$V = IR$	PhET simulations and Hands-on activities in the workshop	Electrical circuit analysis
4. Ampere's law of magnetic field	$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{en}$	Hands-on activities using straight conductors	Magnetic fields for straight cables
5. Field of electromagnets	$B = \mu_0 nI$ (solenoid) $B = \frac{\mu_0 NI}{2r}$ (circular coils) $B = \frac{\mu_0 I}{2\pi d}$ (straight wire)	JavaLab simulations, Hands-on activities in the workshop with coils, magnetic needles and iron rods	Electric bell, Near-field communication
6. Ampere's force between two current wires	$F = \frac{\mu_0 I_1 I_2 l}{2\pi d}$	GeoGebra simulations	Magnetic interaction in electrical systems
7. Lorentz magnetic force on a charged particle	$F = qvBsin\theta$	GeoGebra simulations	Cathode Ray Tubes
8. Laplace's magnetic force on a current wire	$F = IlBsin\theta$	GeoGebra simulations, observation of physical moving-coil meters and the loud speaker	Moving-coil meters, loudspeakers
9. Magnetic torque in motors	$\tau_B = IANBsin\theta$	GeoGebra simulations, Hands-on activities in the workshop with the DC Motor	Electrical motors

10. Faraday's law and Lenz' law of EMI, mutual induction	$emf = -N\frac{d\Phi_B}{dt}$ $V_S = -M\frac{dI_P}{dt}$	PhET simulations, GeoGebra Simulations, JavaLab Simulations and Hands-on activities with AC generator and Transformer	Electrical power generation and Transmission

3.2 Sample and Data Collection

The target population in the present study was sixty-one (61) first-year engineering students who were enrolled in a one-semester 2023/2024 course of engineering electromagnetics and wave optics at Rwanda Polytechnic-Huye College, in the electrical and electronics department. Since this number was less than a hundred (100), all students were purposively recruited to participate in the study, as it is advised by Martínez-Mesa et al (2014). Data collection involved classroom observations using the behavioural engagement related to instruction (BERI) instrument (Lane & Harris, 2015). BERI is a practical and objective classroom observation protocol which provides information about students' behavioural engagement level at any time during an instruction.

During the instruction, the trainer had to switch from one instructional activities to another based on the prescribed learning objectives and classroom interactions. These activities included lecture (LE), Questions (QU), teacher movement (TM), discussing real world examples (RW), demonstration (DE), hands-on (HO) and computer simulation (CS). The students' engagement level was then recorded by observing the number of students engaged in a group of 10. After the completion of topic, a semi-structured questionnaire was administered to students for gathering their perceived learning gains during the course. The questionnaire was composed by ten (10) five-point Likert scale questions and one open-ended question about students' perceived learning gains.

3.3 Data Analysis

Data analysis involved the calculation of the average engagement levels of students for each activity during the 50-minute mathematical sensemaking instruction. These levels were compared using scatter charts for figuring out differences and similarities between two related topics. For the ease of representation, every instructional activity has been coded to make clear visualization in the scatter plots. On the other hand, the Likert scale data about students' perceived learning gains have been analysed by calculating arithmetic means and standard deviations for the point scores. Moreover, the classification has been done with reference from the scoring range as presented in Table 3. Moreover, qualitative responses have been analysed using the inductive thematic analysis.

Table 3

Scoring Range for the Five-Point Likert Scale Data

Description	Value	Range
Strongly Disagree (SD)	1	1.00-1.80
Disagree (D)	2	1.81-2.60
Neutral (N)	3	2.61-3.40
Agree (A)	4	3.41-4.20
Strongly Agree (SA)	5	4.21-5.00

IV. FINDINGS & DISCUSSION

The present study assessed first-year engineering students' behavioural engagement and perceived learning gains in mathematical sensemaking electromagnetism instructions. Classroom observations and a post-topic evaluation were carried out to collect data from 61 students who participated in the study. The data have been analysed using both quantitative and qualitative methods and the corresponding results are presented in the next sections.

4.1 Students' Behavioural Engagement Levels

Figure 1 represents the average 2 to 5-minute observational segments task-related students' engagement levels for the instructions about static electricity and current electricity. It can be observed that the highest students' engagement level in both instructions is 9, recorded for computer simulations in both topics whereas the same level is exclusively particular for hands-on tasks in the current electricity and for demonstration in static electricity. On the other hand, the lowest students' engagement level is found as 3 for the lecture-based task in the topic of static electricity.

Apart from the clearly defined points denoting the highest and lowest levels of students' behavioural engagement, Figure 1 also shows that students are generally more engaged within the current electricity classroom session as opposed to static electricity. The data indicate that the entire session devoted to static electricity had an average engagement level of 6.3, whereas the session devoted to current electricity had an average engagement level of 6.8, which is somewhat higher.

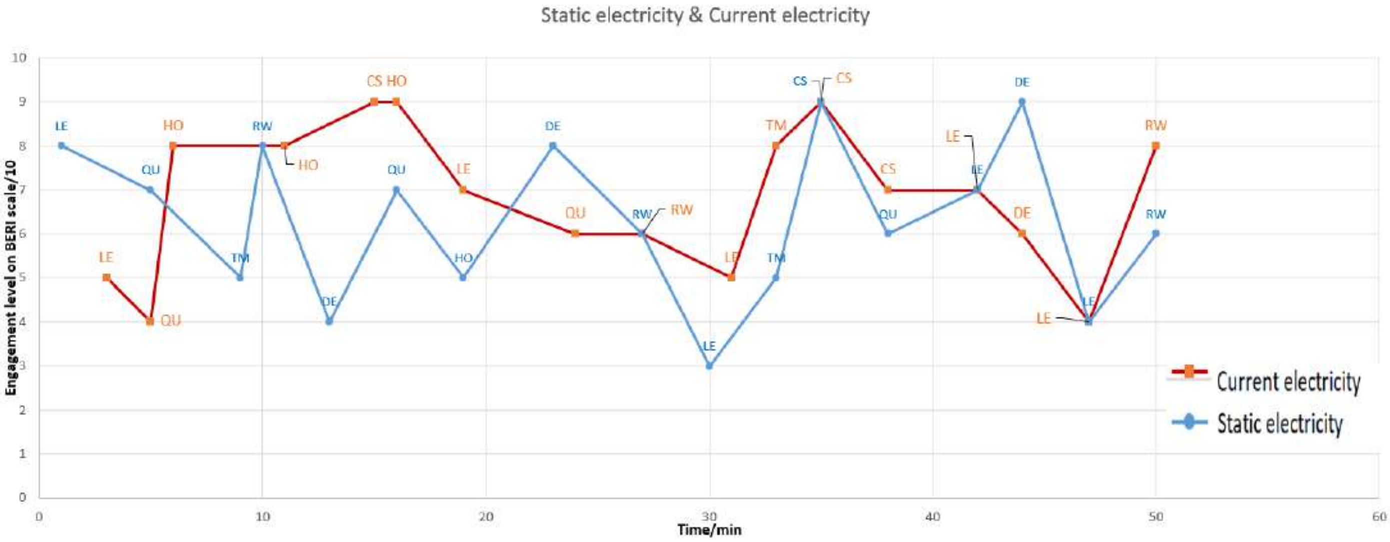

Figure 1
Comparing Students' Engagement about Static vs. Current Electricity

For the part of electromagnets and motors with generators, Figure 2 shows that the highest engagement level is 10, recorded when students were involved in the hands-on tasks during the about electromagnets. In the same instruction, demonstration and hands-on tasks scored the second highest levels (9) whereas questions and lecture activities scored the lowest levels (6). However, in the topic addressing the laws of magnetic forces and electromagnetic induction, encompassing applications such as motors and generators, the peak engagement level reached 9, which was recorded during demonstrations. Conversely, the lowest engagement level, recorded at 3, was observed during activities involving questions and lectures.

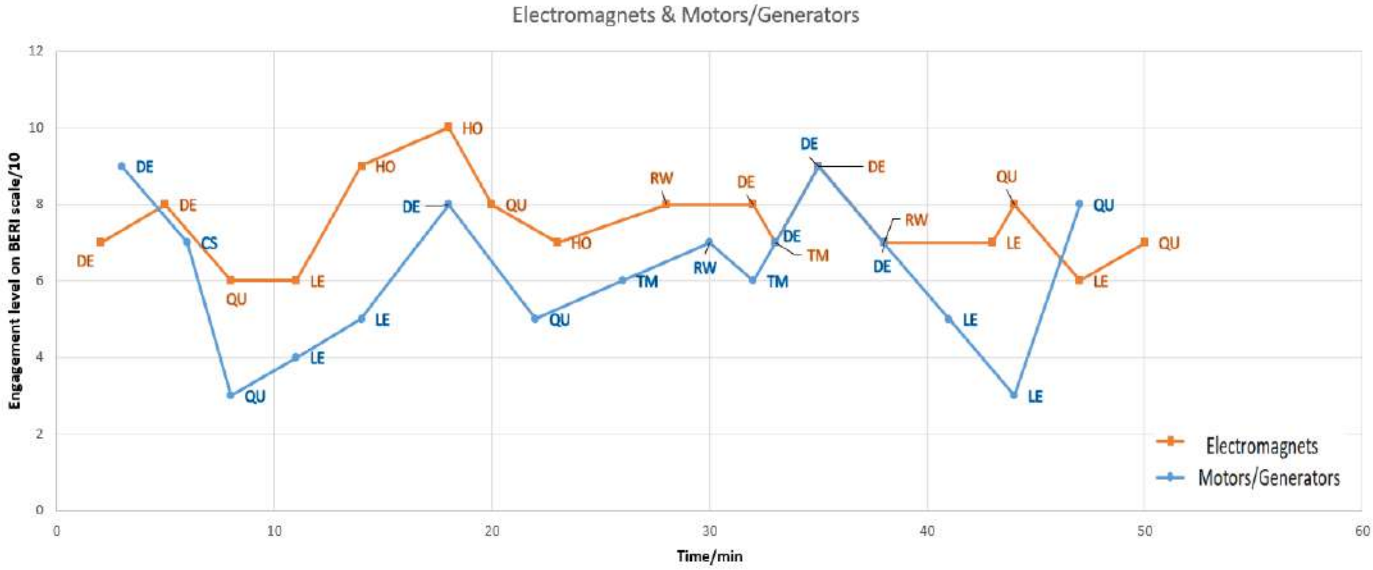

Figure 2
Comparing Students' Engagement about Electromagnets vs. Motors and Generators

In essence, Figure 2 reveals a notable trend in terms of engineering students' behavioural engagement. It indicates that a greater number of scatter points associated with the instructional segment on electromagnets tend to be above when juxtaposed with those corresponding to the instruction focused on the application of magnetic forces and electromagnetic induction. This pattern is complemented by the computed engagement levels of students for the two instructions, with the former registering 7.5, while the latter scored 6.2. Even on the overall consideration, from Figure

1 and Figure 2, it is observed that first-year engineering students were more engaged during the instruction about the topic of electromagnets compared to other topics.

4.2 Students' Perceived Learning Gains

From a post-topic evaluation, Table 4 summarizes the first-year engineering students' perceived learning gains about the students' learning experiences whereas Table 5 provides main results of students' perceived learning gains about the importance of EM in engineering. Moreover, the qualitative data are presented in three (3) themes.

Table 4

Perceived Learning Gains about Students' Learning Experiences within EM Lessons

Item focus	M	SD
Knowledge gained in EM	4.85	0.36
Application of EM in engineering	4.84	0.42
Further learning in EM	4.77	0.50
Collaboration with classmates	4.77	0.64
Revise my learning goals	4.85	0.48
Average	**4.82**	**0.48**

As it is indicated in Table 4, higher scores on students' perceived learning gains are related to the role of EM lessons in stimulating students' revision of their learning goals (M=4.85, SD=0.48) and the overall knowledge in EM (M=4.85, SD=0.36). On the other hand, students appreciated the learning experiences in relation with the application of EM in Engineering (M=4.84, SD=0.42). Although there is no big difference with the highest scores, the lowest scores are observed on how lessons fostered students' engagement in the planning for further learning (M=4.77, SD=0.50) and improved collaborative learning in the course (M=4.77, SD=0.64). The overall score on first-year engineering students' perceived learning gains from their learning experiences, (M=4.82, SD=0.48), indicates that these students had highly positive learning experiences during the mathematical sensemaking lessons in EM course.

Table 5

Perceived learning Gains on the Importance of EM in Engineering

Content covered	M	SD
Electrostatic forces	4.82	0.43
Electromagnets	4.85	0.36
Resistor networks and Ohm's law	4.92	0.33
Magnetic forces	4.85	0.36
EMI	4.80	0.40
Average	**4.85**	**0.38**

Table 5 summarizes the scores of students' responses on five-point Likert scale items related to students' perceived learning gains on the importance of EM course in engineering. These data demonstrate a consistent high levels of agreement across various course components grouped in the covered content. Table 5 indicates that the section on resistor networks and Ohm's law garnered the highest agreement (M=4.92, SD=0.33). It shows that these engineering students managed to relate the practical activities in the classroom to the real use of mathematical formulas and Ohm's law in electrical and electronics engineering.

Further, through the mathematical sensemaking lessons on electromagnets and magnetic forces, students' awareness about the importance of EM in Engineering was improved. This is indicated by their positive agreement on the importance of electromagnets (M=4.85, SD=0.36) and magnetic forces (M=4.85, SD=0.36). Furthermore, the importance of electrostatic forces (M=4.82, SD=0.43) and EMI (M=4.80, SD=0.40) were appreciated after the completion of the course. The overall average for perceived learning gains across all components stands at a high level (M=4.85, SD=0.38), suggesting a consistent and relatively positive perception among students regarding the importance of the EM course in engineering.

The open-ended question that followed the Likert scale items in the questionnaire has helped to get valuable insights for answering one part of the second research question: "…what specific areas do students perceive learning gains after completing the mathematical sensemaking electromagnetism course?". Fifty-nine (59) qualitative responses from students were subjected to an inductive thematic analysis.

Theme 1: Content Knowledge Gained in the Electromagnetism Lessons

Through the students' responses, there was a consistent consideration of the knowledge gained through the mathematical sensemaking lessons of EM course. In their expressions about the confidence of understanding of the course, some have even specified the points of understanding. For example, one respondent said: "I know how emf is generated by using electromagnetism". This expression is much related to students' practical activities conducted about Faraday's law and Lenz' law of EMI effect ($emf = -N\frac{d\Phi_B}{dt}$). The same understanding was also mentioned by many other respondents in different narrations. Additionally, another respondent wrote: "Help us to know how to connect in series, parallel combination circuit and to find results".

Students' responses also revealed how they understood how to use different formulas and laws in electromagnetism. One respondent attested a deep understanding of interaction between electric current and magnetic field by stating: "I can explain the formula for interaction between electric current and magnetic field". This is the confirmation of their meaningful understanding of the Laplace's magnetic force on a current-carrying wire ($F = IlBsin\theta$). Moreover, some respondents did not mention their understanding with specific topics, but expressed that they gained important knowledge in general. For example, one respondent said: "My confidence about electromagnetism is improved because I have understood where electromagnetism is applied and some precautions I can keep while doing electromagnetism practices".

Theme 2: Awareness of the Role of Electromagnetism in Engineering

Through the classroom activities focusing on the mathematical sensemaking, the participants figured out how the course helped them to link theories, concepts and laws of electromagnetism to electrical and electronics engineering practices. Some of them have described this at the superficial level, without citing the concrete examples. This was seen in the expressions like "as we have seen in the module, there are multiple ways of applying electromagnetism concepts in engineering field, although I haven't done anything yet. But soon, I will try. Thanks" and "in physics, electromagnetism has created a great revolution in field of engineering application and caused a great impact on various fields such as electrical engineering, electronics, telecommunication, medical, industrial, space and so on".

On the other hand, respondents mentioned specific instances where they had applied or plan to apply the acquired skills in engineering such as correcting home generators, fans, and creating machines using EM principles. For example, one respondent said: "For instance, in electrical engineering, electromagnetism is crucial for designing electric generators and transformers. In electronic engineering, it is integral to the functioning of devices like motors and sensors". Linking EM and the design of electrical generators and transformers, these students were highlighting their improved understanding the EMI effect ($emf = -N\frac{d\Phi_B}{dt}$) and mutual induction in a transformer ($V_S = -M\frac{dI_P}{dt}$). Moreover, based on the mathematical sensemaking lessons conducted in EM, the qualitative responses showed that students solidified their understanding of the working principles of motors and sensors as used in electronics engineering.

There were many other evidences that mathematical sensemaking lessons helped students to recognize the application of EM in electrical and electronics engineering. Another student stated: "I am confident in electromagnetism and I will use electromagnets in creating magnetic field like in designing transformers and motors". This response pertains to the application of electromagnets in electrical engineering. A similar response was observed in the expression: "For instance, I have successfully integrated electromagnetic principles into designing efficient motors, leveraging both electromagnets and electromagnetic induction". These responses indicate how students raised the awareness of applying EM in the engineering field.

Theme 3: Stimulated Continuous Learning in Electromagnetism

This theme revolves around the students' ideas about their further learning and improvement in their inquiry about EM as a result of their learning experiences. Some respondents expressed a commitment to deepen their understanding of EM concepts and principles, motivated by their meaningful learning experienced through mathematical sensemaking lessons. For example, one student said: "understanding the formulas in EM will help me to read books and learn more about the working principles of electrical systems". This statement indicates that the mathematical sensemaking lessons in EM have reduced the engineering students' independent learning obstacles, fostering more curiosity about the application of EM in electrical and electronics engineering.

In the same line, students compared their learning experiences before and after the mathematical sensemaking lessons in EM. One student said: "Before this course, I was struggling to interpret the information about EM systems on different websites, but now I feel confident that I will use the information from different websites in my learning and practical journey". This indicates that engineering students had better learning experiences in these lessons and it triggered students' motivation for continuous learning about the application of EM in engineering. This was also complemented by other respondents claiming that they would continue to dive in hands-on practical investigations to get more knowledge and skills about EM. Overall, these instructions have significantly enhanced students' engagement and enthusiasm for the subject.

4.3 Discussions

The present study assessed first-year engineering students' behavioural engagement and perceived learning gains in mathematical sensemaking electromagnetism instructions. Focus was on the application of EM in electrical and electronics engineering. Classroom observations revealed higher engagement levels during hands-on and computer simulation instructional activities, for different occasions. On the other hand, lecture-based tasks have continuously scored lower levels of students' behavioural engagement. The topic of electromagnets showed the highest engagement level at 7.5 while the topics related to magnetic forces and electromagnetic induction recorded the lowest at 6.2.

Furthermore, a post-topic evaluation revealed a strong and positive students' perception about their learning experience (M=4.82, SD=0.48) and a solid recognition of the importance of electromagnetism in electrical and electronics engineering (M=4.85, SD=0.38). In all cases, students' qualitative responses provided supporting arguments for both their recorded engagement levels and Likert scale scores of their perceived learning gain. They also provided a precision of learning experience within mathematical sensemaking instructions in terms of EM content, learning decisions and its applications in electrical and electronics engineering.

Combining all findings together, the present study revealed the ability of mathematical sensemaking instructions to foster first-year engineering students' active learning in electromagnetism and motivation to pursue additional learning in the subject. High levels of engagement can reveal students' enthusiasm and epistemic curiosity triggered by the constructivist-based experiential learning environments, especially for the topic of electromagnets. Electromagnets are common features in many electrical and electronic devices and systems, as sources of magnetic fields for different effects. This means that, by allowing students to manipulate some variables modelled by mathematical expressions for electromagnets, students had the opportunity to link theory and real engineering problems and this helped them to make sense of these mathematical representations.

The use of real engineering tools and equipment for experimentation, rather than conventional laboratory equipment, has helped in the realization of concrete engineering contexts within EM course. As it was already recorded that Rwandan TVET students learn better within application-based environments, it is clear that mathematical sensemaking was established without much theory. Therefore, the findings of the present study align with those in Kuo et al. (2020), calculation-concept crossover approaches were influential in fostering students' engagement in mathematical sensemaking physics instructions. In the same view as this study, the present study has focused on practical activities through hands-on, computer simulations and demonstrations to create this connection between calculation and EM concepts, yielding similar results. The behavioural engagement and perceived learning gains can also be explained based on the connection between mathematical sensemaking and scientific sensemaking, as proposed by Sirnoorkar et al. (2023, p. 3). With this, engineering students were given the opportunity to blend mathematical expressions with EM concepts and practical activities were presented to them for direct real-world experience.

A recurring trend across the covered topics is that students often become passive when the instructor shifts to a lecture format or asks questions. This passivity may reflect a transition period where students move from engaging activities to a less interactive lecture style, which might not effectively maintain their engagement. Alternatively, students' lack of responsiveness during questions time could indicate incomplete understanding of some electromagnetism concepts being discussed.

However, the highest engagement level recorded about the topic of electromagnets embodies some particularity. This has been thought to originate from students' use of Ampere's law to learn electromagnetic concepts from their own student-made electromagnets. In this topic, students had the opportunity to build their own electromagnets like iron-cored solenoid, circular coil, toroid and just a straight conductor using wires and iron cores. They were very happy and curious because they could link the theoretical expressions and their observations. This has similarity with physical science teachers' observations that practical investigations involving sketching and comparing the magnetic field produced by different electromagnets increases students' sensemaking about electromagnetism concepts (Samuel, 2017).

Students' strong and positive perceptions of their learning experience and gains stem from innovative instructional activities that effectively bridge mathematical representations with physical concepts and the underlying principles of system operation. This connection is grounded in a framework that highlights the interplay between mathematical and physical sensemaking in science learning (Gifford & Finkelstein, 2020, pp. 5–6). Since engineering students are naturally inclined to understand how things work in real-world settings, hands-on experimentation has significantly enhanced their cognitive abilities to grasp and apply mathematical expressions. This, in turn, has deepened their understanding of electromagnetic systems. Similarly, Gaunkar and Mina (2018) found that meaningful learning in EM courses requires to engage engineering students in reflective practices, which have been achieved by designing mathematical sensemaking supported by experimentation.

V. CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

The purpose of the present study was to assess learning in mathematical sensemaking electromagnetism instructions among first-year engineering students at RP-Huye College and this has been achieved through objective classroom observations about students' engagement levels and a post-topic evaluation of students' perceived learning gains. Classroom observations have revealed non-uniform students' engagement levels, but these levels were remarkably high and significant during hands-on activities and computer simulation activities. Particularly, the topic of electromagnets has recorded the highest students' engagement level compared to other topics. Nevertheless, engagement levels were seen to drop to lower levels when the instructor switches classroom activities to lecture time or asking questions. Higher engagement levels have demonstrated the ability of mathematical sensemaking instructions to establish active learning for engineering students who previously considered EM courses as theoretical subjects. The post-topic evaluation about engineering students' perceived learning gains during mathematical sensemaking EM instructions has also revealed strong and positive perceived learning gains. These indicated students' improved understanding of the subject and its precise applications in electrical and electronics engineering. Further, students' qualitative responses have provided precision and examples of students' learning gains in EM, supporting both their engagement levels and positive perceived learning gains. Since these instructions were realized by incorporating experimentation to support mathematical sensemaking, the findings in the present study suggest that to leverage mathematical sensemaking in EM courses within engineering contexts, there must be learning models focusing on experimentation and real-world experiences to foster engineering students' engagement and achievement of learning outcomes.

5.2 Recommendations

Despite the favourable results observed in the present study, it is important to acknowledge some limitations and recommendations from these limitations and overall results. First of all, due to time and logistic constrains, the present study employed a single-case research design and it could not be possible to compare the effectiveness of mathematical sensemaking with other instructions. The study also relied on observation data and self-reported learning gains. The study could not measure the depth and width of students' mastery of electromagnetism content and evaluate the growth of students' ability of problem-solving in the subject. Therefore, the following recommendations can be captured by readers:

There is a need to embed mathematical sensemaking strategies and frameworks in physics curricula, especially in EM courses. Engineering students should be taught to become problem solvers and be able to handle electromagnetic problems which involve mathematical formalism. This will help to bridge the gap between mathematical theory and engineering applications.

Physics teachers in engineering education should establish active learning and students' engagement in physics courses by modelling mathematical sensemaking instructions with adequate strategies which brings real-world engineering problems. They should not skip mathematical representations used to describe physical phenomena, rather it is important to find the mechanism of triggering mathematical sensemaking. Regular assessment for learning should also be in EM courses. Future work can focus on experimental studies which may involve different dimensions of mathematical sensemaking tailored to specific and real-world EM problems.

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