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Relationships of Abstraction and Application Complexity in the Attainment between Mathematics and Electrical Engineering Modules in Diploma Courses of South Africa

Kavita Behara
Department of Electrical Engineering, Mangosuthu University of Technology
Durban, South Africa

Kayode Timothy Akindeji
Smart Grid Research Centre, Department of Electrical Power Engineering,
Durban University of Technology
Durban 4001, South Africa

Gulshan Sharma*
Department of Electrical Engineering Technology,
University of Johannesburg
Johannesburg 2006, South Africa

Abstract. In South Africa, universities are under pressure to meet increasing targets for student enrolment in engineering disciplines and fields. This has resulted in many students being enrolled in engineering programs without possessing the minimum required mathematical skills and understanding to tackle the challenging engineering disciplines. Hence, the engineering disciplines have a high student attrition and failure rate. This study aimed to evaluate the complex relationship of abstraction and application between mathematics attainment and principles of electrical engineering attainment by the students enrolled in diploma courses in technical universities of South Africa. A blend of quantitative and qualitative data was used. Legitimation code theory (LCT) was used to determine the complexity of higher learning levels. The relationships between six core courses in the Electrical Engineering curriculum were investigated to analyze the knowledge building from mathematics modules to principles of electrical engineering modules. The problem-solving, analytics, and abstract mathematical skills developed in these modules impact the overall progression into principles of electrical engineering courses at different levels for diverse students. The research examines the theoretical foundation, student performance, and practical

*Corresponding author: *Gulshan Sharma, gulshanmail2005@gmail.com*

application of mathematical ideas in electrical engineering using curriculum documents, student academic records, and interviews with electrical engineering lecturers. The study found a weak correlation between the two modules and examined how resources, cultural attitudes, and pedagogy affect student achievement. The results indicate an unexpected negative and fragile correlation between the lower mathematics and engineering modules at high levels. The LCT analysis showed the disconnect between the mathematics courses and the principles of electrical engineering in both the level of abstraction used in the studies and the extent of application principles taught.

Keywords: abstraction; diploma courses; electrical engineering; legitimation code theory; mathematics

1. Introduction

Mathematics is a vital and recognizable element in engineering disciplines because of its application in problem-solving, design, and synthesis in advanced engineering technology (Pepin et al., 2021). At the university level, most engineering programs rely heavily on students' mathematical knowledge and skills, and their application is an essential indicator for students at all levels of academic fulfilment (Li & Schoenfeld, 2019). Engineering combines pure mathematics with practical applications in various electrical engineering courses (Bolstad et al., 2022). Electrical engineering principles rely heavily on mathematical concepts such as differentiation, integration, matrices, determinants, vectors, complex numbers, measurement, and statistical analysis.

The demand for skilled engineers in South Africa is soaring, fueled by the country's technological- and economic-advancement ambitions. However, the current state of engineering education presents a formidable obstacle. Unequal access to quality education, high student dropout rates, outdated teaching methods, limited industry collaboration, and inadequate resources paint a picture of a system struggling to meet the nation's needs (Carrim, 2022).

The multifaceted challenges impact access, pedagogy, industry relevance, and infrastructure. Students from underprivileged backgrounds face limited opportunities, often lacking the academic preparation or support systems necessary to navigate the demanding curriculum. Traditional teaching methods fail to engage students, leaving them unprepared for the practical application of engineering concepts. A disconnect exists between the academic curriculum and the needs of the industry, leaving graduates underequipped for the professional world (Nyoni, 2022). South Africa's journey towards a robust engineering education system is long and arduous, but the collective efforts of stakeholders – government, universities, industry, and professional bodies – offer a glimmer of hope. By addressing these challenges head-on, South Africa can equip itself with the skilled workforce necessary to drive its technological advancements and take its rightful place as a leader in the global engineering landscape (Nyoni, 2022).

In South Africa, there is pressure for universities to meet increasing targets for student enrolment in engineering disciplines and fields (Tjønneland, 2017). As a result, many students are enrolling in engineering programs without many of the requisite mathematical skills (Tsui & Khan, 2023) and understanding to tackle the challenging engineering disciplines. Hence, there is a high student failure and attrition rate in the engineering disciplines (Bengesai et al., 2021). Much of this has been attributed to students' underpreparedness for basic mathematical skills and the level of these skills (Kapoor, 2020). The "heterogeneity of today's student groups", as Hennig et al. (2015) pointed out, requires curricular and pedagogical change, paying particular attention to "didactical considerations and technical implementation" (p. 1). More recently, there have been concerns about how the structure of the engineering program might help or hurt students' chances of success (Young & Muller, 2014). The importance of students' attainment in mathematics for success in engineering programs has been well established by Ro et al. (2017). However, many of the studies that emphasized the need for engineering students' mathematical abilities either referred to the importance of pre-engineering mathematics (i.e., achieving high marks in mathematics at the school level) (López-Díaz & Peña, 2021; Pepin et al., 2021, Pertegal-Felices, 2020; Winberg et al., 2018) or assumed that mathematics (with other basic sciences) underpins the engineering sciences in curricular progression (Kallia & Sentance, 2021). The relationship between mathematics and the engineering sciences becomes more troubled when both disciplines need mathematical tools to be taught simultaneously, as in many technical engineering diplomas (Meda & Swart, 2018). In such cases, the relevance of the mathematical concepts taught is crucially essential to avoid what van der Wal et al. (2017) called "mathematics [becoming] an island with limited relevance". The literature suggests a generally poor alignment between mathematics courses and engineering sciences. For example, many engineering sciences require mathematical expertise, which will sometimes be imparted in mathematics courses only at a later stage. This mathematical expertise is of particular concern in the South African context, where many students enter engineering programs without the desired levels of mathematical attainment and knowledge (Kehdinge, 2019).

In such cases, greater alignment between the mathematics course and the engineering modules is intended to support and benefit students (Craig, 2021; Steve et al., 2022). In a study that examined the mathematical errors in electrical engineering courses, Faezeh et al. (2023) showed an excellent example of alignment and recommended ways of improving the alignment across the mathematics course to enable an appropriate alignment between mathematical concepts and engineering applications. The content of these exercises includes, for example, ordinary differential equations of first and second order (in a task on oscillating circuits) or complex numbers (in a task on alternating current). These topics arise from the application of Kirchhoff's rules to electrical circuits with time-varying currents flowing through resistors, capacitors, and inductors. It is well known and reported in the literature that students' motivation for studying complex modules, such as mathematics, is an essential factor and "a robust predictor of performance" (Arshad & Romatoski, 2021). Thus, mathematics should not only be learned to be relevant to engineering problem-solving; it should also engage students.

Furthermore, it was found that the lack of student engagement in mathematics courses for engineering significantly contributed to student failure and attrition (Ginting, 2021; Shay, 2020). Students tend to value authentic tasks (what they expect in an engineering program) compared to school mathematics, which students often experience as unrealistic, unauthentic, and meaningless regarding questions and exercises (Cook, 2021). They think that it is of no use to them. A comparative study of engineering programs in South Africa and Europe found a striking lack of relevance to the South African context (Kloot & Rouvrais, 2017). Teaching mathematics in a way that engages students in authentic tasks and ensures that there is alignment between the mathematical concepts and tools required by the engineering sciences and the provision of mathematics courses is likely to involve academic staff who teach mathematics for engineers (Botejara-Antúnez et al., 2022).

Given the above discussion, it has been observed that there is a great need to investigate and analyze the relationship between students' attainment in mathematics and electrical engineering modules in an electrical engineering diploma program using reliable data. Thus, this study investigates the relationship between students' attainment in mathematics and electrical engineering modules across an electrical engineering diploma program to determine the curricular elements that might constrain students' progress. Three research questions (RQs) guided this study:

- **RQ1:** What is the diploma program's relationship between mathematics and electrical engineering?
- **RQ2:** What is the relationship between students' attainment in mathematics and attainment in electrical engineering modules?
- **RQ3:** What strategies can enhance the correlation between students' mathematical proficiency and their performance in electrical engineering courses?

The rest of the research is organized subsequently. Section 2 presents the conceptual framework and foundation for this research work, and Section 3 the research design. Section 4 presents the research results, and Section 5 offers a discussion on the research results and their consequences. Finally, the manuscript ends in Section 6 with a conclusion and recommendations for future work.

2. Conceptual and Theoretical Framework

The correlation between students' mathematical proficiency and their performance in electrical engineering courses is a multifaceted phenomenon that has received significant attention in academic research. It is widely acknowledged that students with advanced mathematical abilities are more inclined to excel in electrical engineering studies. This is because mathematics serves as the fundamental basis for numerous concepts imparted in electrical engineering. An illustration of this can be seen in the field of electrical engineering, where students are required to possess the capacity to comprehend and effectively employ principles derived from calculus, differential equations, and linear algebra.

The “complex relationship of abstraction and application” in engineering education refers to the intricate interplay between theoretical knowledge and its practical implementation (Winberg et al., 2018). This relationship can be understood through two key concepts. First, *abstraction* refers to stripping away unnecessary details and focusing on the concepts and principles underlying a phenomenon or process. In engineering, this involves learning theoretical frameworks, mathematical models, and scientific laws that govern the behavior of systems and technologies. Second, *application* refers to translating theoretical knowledge into concrete actions and solutions to real-world problems. It involves applying learned concepts to design, develop, and operate engineering systems, considering practical constraints, limitations, and specific contexts.

2.1 Conceptual Framework

The conceptual framework for this research is based on the complex relationship of abstraction and application between the attainment of mathematics and that of principles of electrical engineering. The interconnection between mathematics and electrical engineering is comprehended by employing the conceptual framework of legitimation code theory (LCT). The learning and cognitive theory is a theoretical framework that significantly emphasizes how information is represented and legitimized. Within mathematics and electrical engineering, the notion of LCT posits that students must possess the capacity to comprehend and effectively employ mathematical principles within the framework of electrical engineering difficulties. It implies that students must be able to effectively bridge the gap between the abstract terminology used in mathematics and the tangible language utilized in electrical engineering. Several studies have identified a positive correlation between attainment in mathematics and attainment in electrical engineering modules. For example, research by Hwang and Son (2021) has revealed that students’ academic performance in mathematics exhibited the highest correlation with their achievement in an introductory engineering course. According to related research conducted by Cabuquin and Abocejo (2023), it was observed that students who enrolled in a more significant number of mathematics courses exhibited a higher probability of completing engineering programs.

The relationship between mathematics and electrical engineering is intricate and multifaceted, characterized by a blend of abstraction and application complexity (Winberg et al., 2018). Mathematics is the foundation for electrical engineering, providing the tools and concepts necessary to understand and analyze complex electrical systems. The level of abstraction in mathematics concepts varies, with some concepts being more concrete and directly applicable to real-world problems. In contrast, others are more abstract and require a deeper understanding of mathematical principles.

In electrical engineering, the application of mathematics becomes increasingly complex as students progress through the diploma program. Initial courses introduce fundamental concepts such as circuit analysis, drawing upon basic mathematical principles like algebra and trigonometry. As students advance, they encounter more sophisticated concepts such as differential equations, electromagnetic fields, and control systems, which demand higher mathematical abstraction and problem-solving skills.

The conceptual framework for understanding the relationship between mathematics and electrical engineering attainment in diploma courses is presented in Figure 1.

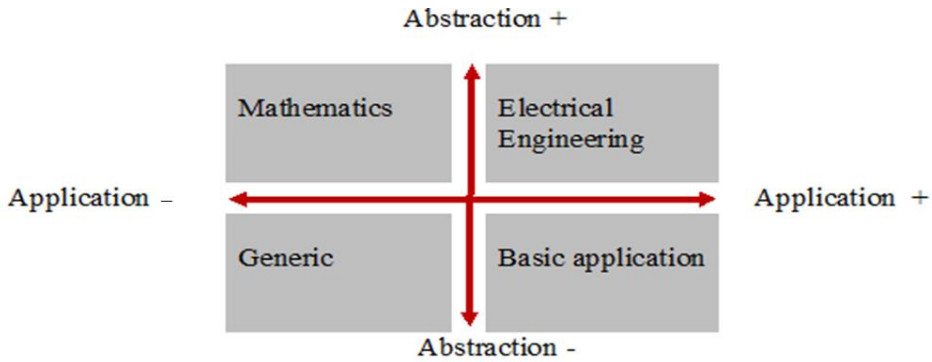

Figure 1: Abstraction and application on the semantic plane

The literature on teaching mathematics for electrical engineering has suggested that relevance and alignment are essential issues to consider. The literature, however, does not consider the disciplinary differences between mathematics and electrical engineering (or the engineering sciences more generally). For this reason, the study drew on LCT (Maton, 2014), a sociological framework that seeks to identify the knowledge structures underpinning practices. In the case of mathematics for electrical engineering, the knowledge structures refer to mathematics knowledge structures and electrical engineering knowledge structures. Mathematics could be understood as a pure, complex discipline with a high level of challenge, and engineering as a hard-applied discipline with an equally high level of challenge. LCT provides a way of understanding mathematics for electrical engineering as the relation between abstraction and application.

LCT comprises five dimensions (Maton, 2014), namely semantics, specialization, autonomy, temporality, and density. This study drew on semantics that understands the pure disciplines, such as mathematics, as abstract, with a tendency to be decontextualized, and fields such as electrical engineering as applied and strongly contextualized but using highly conceptual mathematical tools. Semantics can be diagrammatically represented as a plane in which the X-axis represents higher and lower application levels, and the Y-axis represents higher and lower abstraction levels, as shown in Figure 1. Four quadrants are created within the semantic plane, dependent on the relative strengths of the pure and applied relations. A quadrant is created that foregrounds basic applications, such as a generic problem-solving process or simplified engineering problems, where there is a more robust application and weaker abstraction. Where there are weaker levels of application and stronger levels of abstraction, a quadrant is created for the pure disciplines that, in this study, foreground pure mathematical knowledge. In the plus/plus quadrant, both abstraction and application combine, showing that the challenge of the engineering sciences comprises drawing on the tools and language of mathematical abstraction to solve complex engineering problems. In the minus/minus quadrant, neither abstraction nor application is evident, resulting in a generic or non-specific quadrant. Maton (2014) argued that if electrical engineering is characterized by complex problem-solving, it would be difficult for students to move directly from mathematics to electrical engineering without having experience in fundamental problem-solving. Drawing on the explanation by LCT, we would thus not expect students to be able to instantly transfer knowledge from pure mathematics to electrical engineering without what Maton (2014) called a "semantic wave", as shown in Figure 2. The concept of a semantic wave (Maton 2014) is adopted in this study. It is referred to as a "learning wave", emphasizing that it is representative of the progression of learning experiences in a course. Thus, a successful transfer of knowledge from mathematics to electrical engineering would happen through step-by-step training in the primary application of essential mathematical tools before students could succeed in the more complex forms of problem-solving using complex mathematical tools.

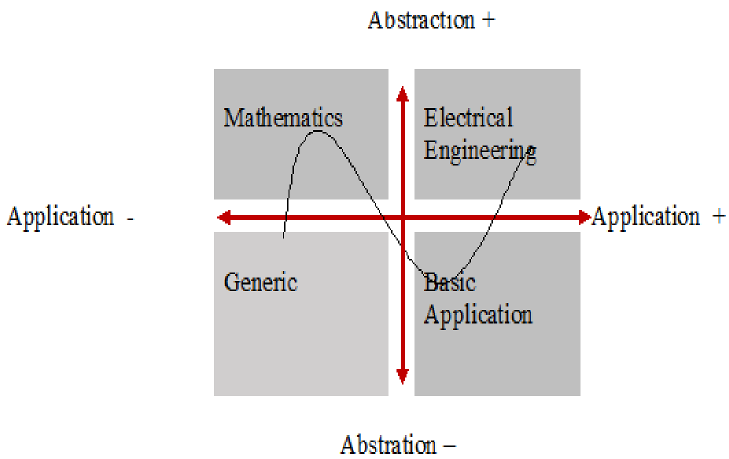

Figure 1: A semantic wave showing how mathematical tools could be transferred to electrical engineering

3. Research Design

3.1 Research Site

The site selected for this study is the university of technology in South Africa. The university was chosen as it has one of the most significant numbers of electrical engineering students (±250) in the country and has two intake periods in both the first and second semesters, which adds to the teaching challenges. As discussed in the introduction, a university of technology in South Africa has more challenges than other universities in the country, including a highly diverse student intake and many underprepared students achieving mathematical skills (Coetzee & Mammen, 2017; Fomunyam, 2019). The electrical engineering program investigated in this work is a three-year diploma program. The universities of technology and diploma programs in South Africa have the same or similar structures. Other traditional universities offer many similar core courses, such as mathematics and electrical engineering, in both the first and second semesters to account for the two intake periods and the high failure rates across these courses.

Table 1 shows the basic curriculum structure of the National Diploma in Electrical Engineering and credit allocation to the modules. The structure and credits would be the same in all electrical engineering diplomas in South Africa, as these courses are accredited by the Engineering Council of South Africa (ECSA). All are required to have the minimum credit values for the basic sciences (including mathematics), engineering sciences (such as electrical engineering), practical training, and general courses, as detailed in ECSA standards (E-P- 02). As seen in Table 1, three mathematics courses and three electrical engineering courses were the focus of this study. Together, these comprise 62 credits of the 360-credit diploma, with 30 credits given to mathematics and 32 to electrical engineering modules.

Table 1: Structure of National Diploma in Electrical Engineering and credit allocation to the courses

<table>
<tr><th rowspan="2">Year of study</th><th rowspan="2">Semester</th><th rowspan="2">Mathematics</th><th rowspan="2">Basic science</th><th colspan="2">Engineering science</th></tr>
<tr><th>General</th><th>Discipline specific</th></tr>
<tr><td rowspan="2">One</td><td>S1</td><td>Math 1 (10)</td><td>Physics (10)</td><td>Communication Skills (5)
Computer Skills (5)</td><td>Electrical Engineering I (10)
Electronics I (10)
Digital Systems I (10)</td></tr>
<tr><td>S2</td><td>Math 2 (10)</td><td></td><td></td><td>Electrical Engineering II (10)
Electronics II (10)
Digital Systems II (10)
+1 Specialization (10)</td></tr>
<tr><td rowspan="2">Two</td><td>S3</td><td>Math 3 (10)</td><td></td><td></td><td>Digital Systems III (12)
Software Design II (12)
Control Systems II (12)
+1 Specialization (12)</td></tr>
<tr><td>S4</td><td></td><td></td><td></td><td>Software Design III (12)
+4 Specialization (48)</td></tr>
<tr><td rowspan="2">Three (WIL)</td><td colspan="5">Practical 1 (44)</td></tr>
<tr><td colspan="5">Practical 2 (48)</td></tr>
<tr><td colspan="6">WIL: work-integrated learning</td></tr>
</table>

3.2 Data Sources

The present study relied on three sources of data. The first data source comprised the curriculum documents (including course outlines and student guides). These course outlines show the topics/concepts taught in mathematics and electrical engineering. The second data source was the students' academic records showing their attainment in mathematics and electrical engineering. The third data source comprised interviews with two lecturers who taught electrical engineering and mathematics modules. The interviews took place following the analysis of data from the first two data sources to gain insights into the research results.

3.3 Data Collection Methods

The research design for this study comprised three parts. The first is a study of the curriculum outcomes for the mathematics and electrical engineering modules, following the methodology developed by Meda and Swart (2018). The second part analyzed students' mark attainment across these modules using basic statistical methods to investigate correlations between student grades in mathematics and electrical engineering courses. This was done to identify potential learning challenges across the courses. The third part consisted of eliciting the responses of two lecturers who teach electrical engineering courses for clarification and a plausible explanation of the results.

3.4 Data Analysis Methods

First, regarding analysis of curriculum outcomes, the outcomes of the mathematics and electrical engineering courses were studied and compared to identify areas of alignment and misalignment.

Second, concerning course results and correlation, course results were obtained for 2014 to 2019, with separate results lists for semesters 1 and 2. The results were structured according to student numbers and percentage marks obtained for the course. The average mark and highest and lowest were calculated and standard deviations of these marks were computed. The assumption in the National Diploma in Electrical Engineering, which offers mathematics and electrical engineering modules simultaneously, is that mathematics is a supported module. There would be alignments across levels, such as Mathematics 1 and Electrical Engineering 1. However, as the analysis of the curriculum documents showed, this was not the case; the most significant curricular alignment is between Mathematics 1 and Electrical Engineering 3, hence the addition of correlations across levels. Thus, six correlations were performed between the student marks of engineering courses and their mathematics prerequisite courses to determine the relationship between attainment in mathematics and attainment in the engineering courses. The average and highest marks in these courses were also compared.

Lastly, the interviews were artifact-based, in which the lecturers were asked to clarify or offer plausible explanations for the results found in the curriculum alignment and correlation studies.

3.5 Analysis of Application of the Conceptual Framework to the Research Results Solution

The research results were synthesized drawing on the LCT concepts of abstraction and application and how these concepts could be woven together in creating appropriate alignment across the Mathematics and Electrical Engineering curricula. The synthesis focused on positioning the learning that occurs in courses on the semantic plane, using course syllabus information and input from electrical engineering lecturers to establish the extent of how abstract or applied significant elements of the course were. The key modules were awarded weaker (-) or stronger (+) levels of abstraction and application, using the structure outlined in Table 2 and the inputs of the two participating electrical engineering lecturers to guide the process.

Table 2: Levels of abstraction and application coding

Abstraction label	Level of abstraction	Application label	Level of application
--	Concrete, simple terms	--	Distinct from application
-	Concrete, more complex terms	-	Largely separate from the application
+	Connection to the concrete, low abstract terminology	+	Some/vague use of application contexts
++	More abstract descriptions, moderately complex abstractions	++	Descriptions strongly connected to a particular application or application domain
+++	Highly abstract use of complex abstractions	+++	Strongly related to specific application considerations

4. Research Results

The research results are presented in two sections. The inputs of the electrical engineering lecturers are not reported separately but are integrated into the discussion below, as the interviews were based on an initial analysis of the results. In the first section, the content of the mathematics and electrical engineering courses was identified and compared across three levels; secondly, the academic performance of six student cohorts across the mathematics and electrical engineering courses was measured and analyzed.

4.1 Conceptual Model of the Relationships between Mathematics and Electrical Engineering Modules Attainment

This section identifies the relationship between key mathematics and electrical engineering course outcomes. The two electrical engineering lecturers identified modules of the mathematics and electrical engineering courses as "killer modules", that is, modules with high rates of student failure and attrition. The critical course outcomes for the course are shown in Figure 3. The results have been simplified; for example, the outcome *second order homogeneous and non-homogeneous linear differential equation and general solutions of differential equations* have been simplified to *differential equations* (M3.5). The links and arrows show the mathematical tools and processes in which students are trained and taken up in the electrical engineering courses. As can be seen, there are many cases of misalignment. For example, trigonometry (M2.1), needed to set up measuring systems in Electrical Engineering 1 (E1.3), is only offered in Mathematics 2. Matrices, fundamental to almost all the Electrical Engineering 3 applications, are presented in Mathematics 1 (M1.2). While it is noted that several mathematical concepts are helpful across the Electrical Engineering curriculum, the linkages show only the key or essential connections – many of these are not offered in the Mathematics curriculum, while they are needed in the Electrical Engineering curriculum. According to the two lecturers interviewed, there might also be a challenge with the concept level offered. For example, when a concept such as the *determinant of a square matrix, co-factors and inverse of a matrix* is provided at Level 1 in mathematics, this might not be sufficiently complex for its application in Electrical Engineering 3. There is thus considerable room for improving the alignment across the modules. While mathematical modules provide much of the "thinking skills" for electrical engineering, there could also be a difficulty with mathematical topics irrelevant to the electrical engineering application or more than the electrical engineering requirement, which places an unnecessary burden on the student.

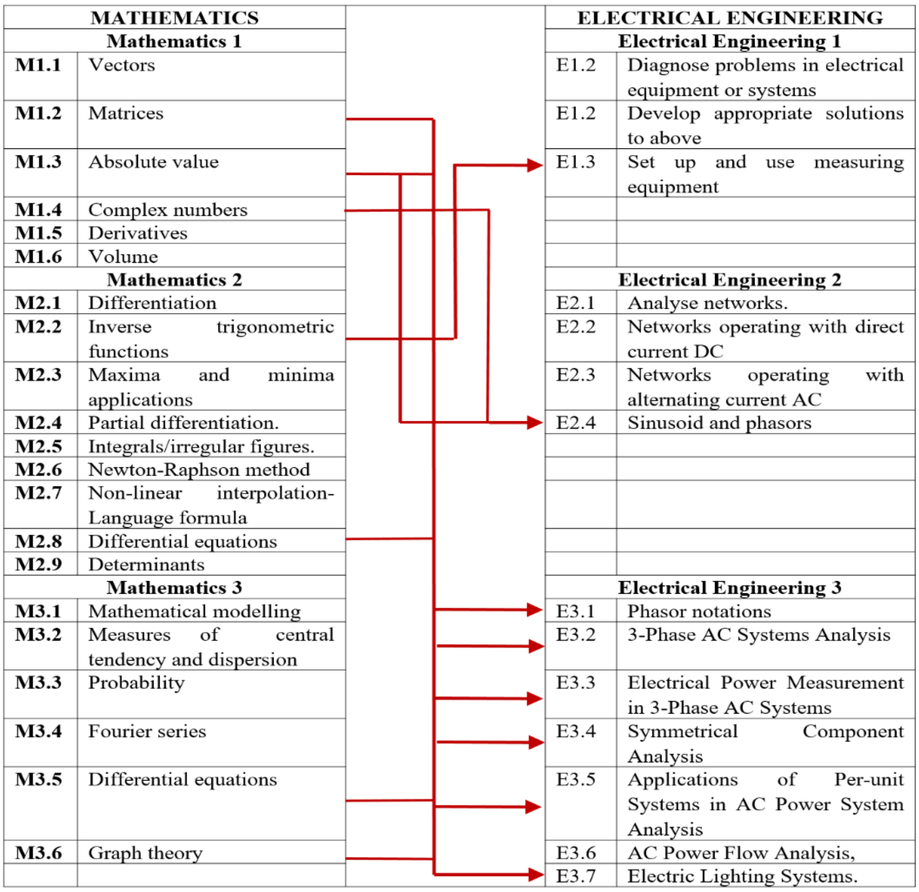

Figure 3: Key relationship between the mathematical tools and electrical engineering applications

The conceptual model of the relationship between mathematics attainment and electrical engineering attainment is shown in Figure 4.

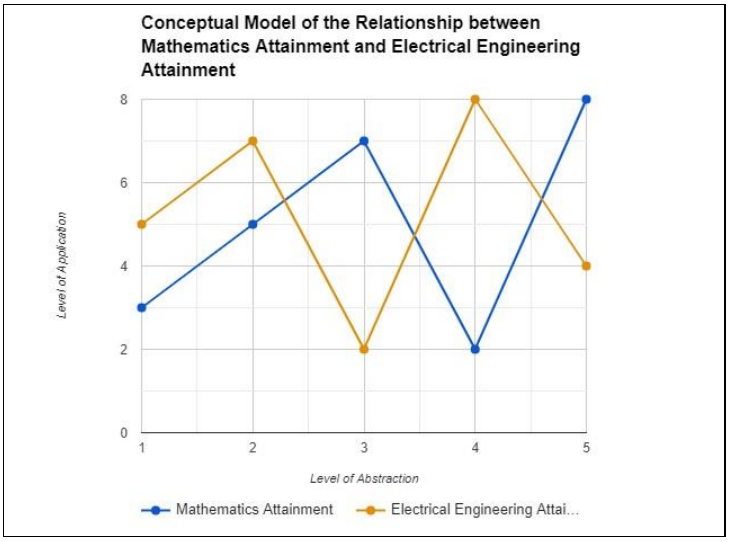

Figure 4: Conceptual model of the relationship between mathematics attainment and electrical engineering attainment

The relationship between abstraction and application complexity between the mathematics and electrical engineering modules is shown in Figure 5.

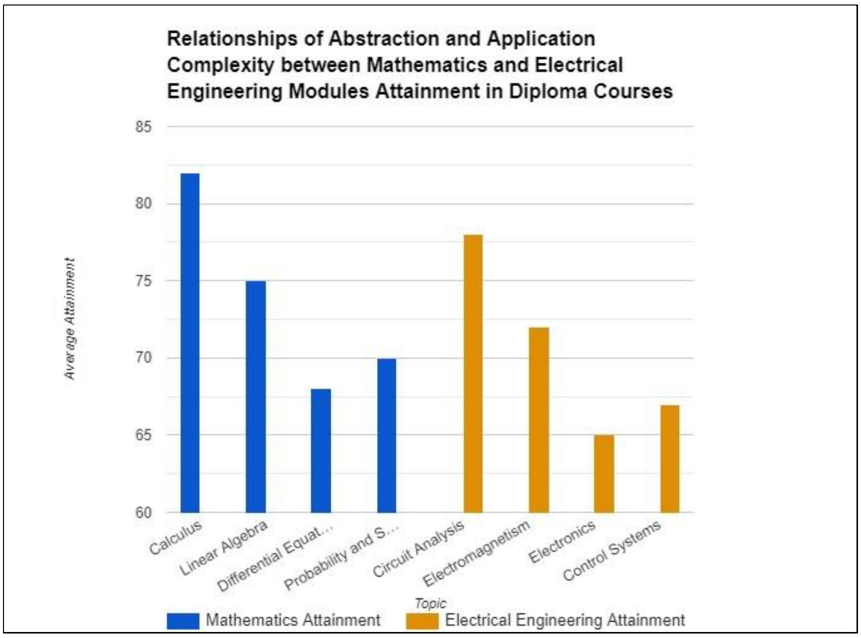

Figure 5: Relationship of abstraction and application complexity between the mathematics and electrical engineering modules

The level of abstraction in mathematics concepts varies, and applying mathematics in electrical engineering requires a balance between abstract understanding and practical problem-solving skills. As students progress through electrical engineering programs, the application of mathematics becomes increasingly complex. Initial courses introduce fundamental concepts such as circuit analysis, drawing upon basic mathematical principles like algebra and trigonometry. As students advance, they encounter more sophisticated concepts such as differential equations, electromagnetic fields, and control systems, which demand higher mathematical abstraction and problem-solving skills.

In the modern world, balancing technical skills and other critical abilities such as creativity, communication, and interpersonal effectiveness is necessary for success in many fields, including mathematics, engineering, and related STEM disciplines. Technical proficiency is essential for figuring out complex issues and creating creative solutions, but it is insufficient to succeed in today's dynamic, collaborative work environments (Darling-Hammond et al., 2020). A substantial proportion of technical and social abilities depends on the job and profession. General guidelines dictate that STEM professionals should build a solid foundation in both domains. Technical skills may comprise 60% to 70% of the essential competencies, while social skills may comprise 30% to 40%. This ratio ensures that individuals have the technical knowledge and interpersonal abilities to collaborate, communicate, and lead in their industry (Boylen et al., 2023).

4.2 Student Performance across Mathematics and Electrical Engineering Modules

Students' performance across the mathematics and electrical engineering modules is analyzed in this section. Correlations were performed between the students' marks of engineering courses and of mathematics prerequisite courses to determine the relationship between their attainment in mathematics and electrical engineering. The difference between the average and highest marks of these courses was also compared. It was hypothesized that very weak correlations exist between prerequisite and subsequent courses. The average course results for mathematics and electrical engineering from 2014 to 2019 are shown in Table 3.

Table 3: Average results of the courses

Year	Semester	Math 1	Math 2	Math 3	EE 1	EE 2	EE 3
2014	S1	59.6%	47.0%	65.2%	49.4%	50.8%	60.3%
	S2	86.5%	69.3%	68.3%	62.3%	37.5%	43.2%
2015	S1	78.7%	82.0%	60.5%	52.1%	54.8%	53.5%
	S2	85.0%	88.9%	67.7%	88.7%	70.7%	37.7%
2016	S1	60.6%	58.6%	71.8%	59.3%	43.5%	65.1%
	S2	75.3%	59.6%	78.4%	87.4%	44.5%	68.7%
2017	S1	71.1%	45.9%	54.7%	65.2%	40.5%	52.0%
	S2	60.4%	38.5%	73.8%	41.7%	49.0%	63.5%
2018	S1	59.8%	83.6%	61.9%	78.2%	72.9%	92.2%
	S2	78.5%	59.1%	64.1%	61.9%	80.6%	90.9%
2019	S1	51.8%	32.3%	71.7%	57.9%	80.4%	37.0%
	S2	66.4%	52.8%	66.7%	68.4%	24.2%	56.8%

The minimum and maximum course results from 2014 to 2019 are shown in Table 4. These results show a wide range between the minimum and maximum marks, showing that some students perform excellently. The low marks indicate that some students have a significant challenge or do not deregister from the course before writing the exam. Six correlations were done between engineering courses and their prerequisite mathematics courses. They were: Mathematics 1 (Math 1) and Electrical Engineering 1 (EE 1); Math 1 and Electrical Engineering 2 (EE 2); Mathematics 2 (Math 2) and EE 2; Math 2 and Electrical Engineering 3 (EE 3); Mathematics 3 (Math 3) and EE 3; and Math 1 and EE 3.

Table 4: Minimum and maximum marks for each year and all modules

Year	Range	Math 1	Math 2	Math 3	EE 1	EE 2	EE 3
2014	Max	95%	93%	97%	93%	73%	86%
	Min	9%	2%	4%	15%	20%	14%
2015	Max	96%	98%	98%	93%	81%	78%
	Min	11%	19%	7%	27%	24%	24%
2016	Max	94%	99%	94%	84%	81%	81%
	Min	20%	5%	8%	24%	24%	26%
2017	Max	99%	98%	97%	82%	72%	82%
	Min	10%	3%	14%%	26%	9%	14%
2018	Max	99%	100%	98%	95%	85%	88%
	Min	5%	15%	10%	30%	18%	33%
2019	Max	97%	98%	100%	95%	92%	83%
	Min	10%	6%	10%	11%	11%	35%

The results of the correlations are shown in Figure 6.

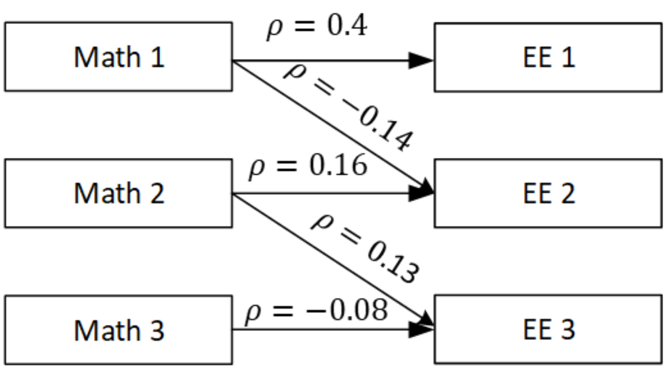

Figure 6: Correlation between mathematics and electrical engineering courses

The correlations reveal positive and negative relationships between mathematics and engineering courses. For example, the relation between Math 1 and EE 1 was significantly positive (ρ = 0.4), which suggests that a general understanding of the topics covered in Math 1 was needed for students to succeed in EE 1 despite the apparent lack of alignment between the topics in the Math 1 curriculum and applications of EE 2. However, a weak negative correlation (ρ = -0.14) between Math 1 and EE 2 suggests that either the Math 1 concepts were not needed for EE 2 or that those that might have been needed were not retained. It speaks to a possible pedagogical need for methods that depend less on rote learning and improve long-term retention of mathematical concepts. There was a weak positive relationship ($\rho = 0.16$) between Math 2 and EE 2, suggesting a positive but insignificant relationship between Math 2 and EE 2. This implies that the concepts learned in Math 2 were not particularly relevant to students' needs for mathematical tools in EE 2, as seen in Figure 6. The weak correlation could also suggest curricular misalignment, which seems to be the case but would need further investigation.

Furthermore, there was a weak positive relationship ($\rho = 0.13$) between Math 2 and EE 3, again suggesting that either the Math 2 concepts are not required in EE 3 or that there is poor retention of mathematical concepts. There was a weak negative correlation ($\rho = -0.08$) between Math 3 and EE 3. The mathematical concepts at Level 3 seem to be more than required for the EE 3 applications. This suggests that the concepts and tools provided by Math 3 were irrelevant to EE 3 or that there was curricular misalignment, which would need to be investigated. When the results of Math 1 were correlated with that of EE 3, there was a slight negative correlation. As the tools provided by Math 1 are fundamental to the applications of EE 3, this suggests that either the mathematical tools were insufficient or that students had not retained the concepts learned in Math 1. Where a negative relationship exists between a support module (e.g., Mathematics 3) and the module to be supported (e.g., Electrical Engineering 3), it could suggest that the support module's demands create a high cognitive load, which is often caused when the support module is not aligned with the target module. The correlations have raised several issues concerning the complex relationship between mathematics and engineering. In the sections that follow, this relationship is further analyzed.

5. Discussion

5.1 Analysis: Abstraction and Application across Mathematics and Electrical Engineering Modules Space

The core of the research revolves around investigating the relationship between the attainment of mathematics and electrical engineering in diploma courses in South Africa. Specifically, the research aims to understand how the level of abstraction in mathematics concepts and the application complexity of electrical engineering modules influence student attainment. This study delves into the intricate connections between these two disciplines, examining how mathematical foundations, problem-solving skills, and application of abstract concepts to real-world problems contribute to students' success in electrical engineering courses. To gain more insight into the relationships between these courses, an LCT analysis of how abstraction and application varied across the content of the two modules was done.

Table 5 shows the relative levels of abstraction and application of the material learned, where + or – indicates that abstraction or application is stronger or weaker in the course topic. We focused on the relations between courses with negative and low correlations to see to what extent the level of abstraction differed between these. We started with inspecting the connection between Math 1 and EE 2. The Math 1–EE 2 correlation showed a significant increase in the level of abstraction between the courses and the application – Math 1 involves lower levels of abstraction in the form of algebra and introductory calculus. According to the interviewees, these topics were taught with few contextual examples, and simple examples irrelevant to the engineering discipline were mainly used. This allowed students to focus on understanding the mathematical principles without knowing much about the context. However, the delivery of content in EE 2 was markedly different from that of Math 1. From the start of the course, the students had to contend with more challenging scenarios incorporating contextual complexities. Thus, students had to understand both higher levels of abstraction and breadth of application complications.

Table 5: Relative levels of abstraction and application of the material learned

Course topic	Abstraction	Application
Math 1 – algebra	+	-
Math 1 – calculus	++	--
Math 2 – first order differential equations, matrices	++	-
Math 2 – vector calculus	++	--
Math 3 – high-order differential equations, complex numbers	+++	-
Math 3 – Laplace transforms, Fourier series, probability, statistics	+++	+
EE 1 – potential difference, resistance temperature, electro-motive force	+	+
EE 1 – Maxwell's theories, Thevenin's theorem	++	+
EE 2 – sinusoids and phasors	+	+
EE 2 – AC power analysis, three-phase circuits analysis	++	+++
EE 3 – three-phase systems, power factor correction	+++	++
EE 3 – Electrical power measurement, end voltage computation, DC distribution	+++	+++

Figure 7 illustrates the learning waves plotted for Math 1 and EE 2 start at different application levels. Math 1 begins at a very low (-) application level; in contrast, EE 2 starts at a higher abstraction (+) level. This suggests that students progressing from Math 1 to EE 2 may experience a noticeable jump in the level of abstraction and discourse utilized in the courses. The EE 2 lecturer may expect students to understand a higher level of abstraction than that at which they have been trained during previous courses. In terms of application, there is an even more significant disconnect. Math 1 had very few engineering concepts and contexts encountered, whereas in EE 2, the course began with the expectation that students understood various fundamental contextual issues of engineering. Thus, this could be another stumbling block for students to succeed.

Regarding the topics covered, Math 1 algebra and calculus were covered abstractly without electrical engineering examples. In contrast, in EE 2, AC power analysis and three-phase circuit analysis topics were highly abstract and deeply application specific. The level of abstraction tends to increase as the course progresses to greater complexity to explain more complex concepts. However, as the level of abstraction increases, the abstract concepts become more porous, using more stylized and simplified representations to replace the increasing complexity of application principles. A similar trend is seen in many of the connections between mathematics and engineering modules. Students' mathematics learning tends to become less grounded in concrete engineering principles, which are essential to enable the student to develop integrated knowledge.

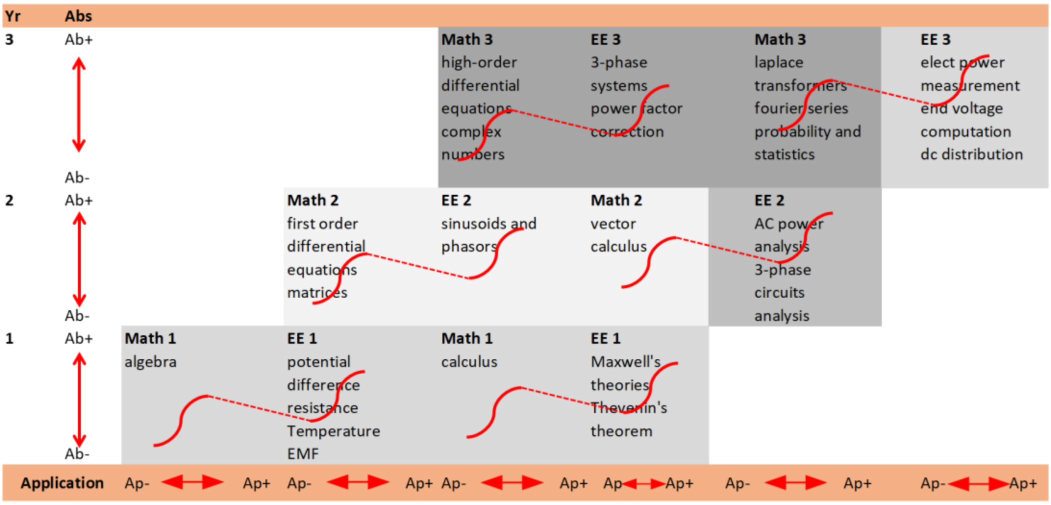

Figure 7: The semantic wave across mathematics and electrical engineering modules

On the other hand, the learning can become too specific and not easily transferrable to different contexts if all the learning experiences are firmly grounded in specific contextual examples. Therefore, it is beneficial that the interconnection between mathematics and engineering modules incorporate appropriate "learning waves", ensuring that the learning does not become too porous or distinct from reality. The learning waves for each course have been plotted in Figure 7 to illustrate the learning progression between different courses. This helps to see where the exit points, at the abstract and application level, are compared to the entry points of other courses. The dotted lines are intended to help understand the relative relation in abstraction between the courses. The learning curves closer to the left correspond to less application-oriented course content, whereas curves further to the right are more application oriented. The Math 3 and EE 3 relation had a weak negative correlation of -0.08. The learning waves of these two courses show significant differences in the levels of abstraction and application between Math 3 and EE 3. The EE 3 content started at a higher level of abstraction than where Math 3 finished, but it needs to be emphasized that these courses run simultaneously. As such, the students beginning EE 3 will have much higher levels of complexity to handle, for which the Math 3 course would not have been able to prepare them.

5.2 Limitation to the Research

Overall, the current research on the relationship between the attainment of mathematics and electrical engineering in diploma courses in South Africa provides valuable insights into the importance of a strong foundation in mathematics for success in electrical engineering. However, it is essential to acknowledge the research limitations and obstacles and address these issues in future studies to further our understanding of this complex relationship. A limitation of our research is limited scope, as the study focused on diploma courses in South Africa, and the results may thus not be generalized to other education systems. In addition, the study primarily relied on quantitative data, which may not capture the full complexity of the relationship between mathematics and electrical engineering attainment. Some obstacles include lecturer training, technological infrastructure, curriculum development, cultural and socio-economic factors, and adopting new pedagogies.

5.3 Exploring Factors Influencing Success in Electrical Engineering

Although mathematics is the foundation of electrical engineering, it is essential to include other elements to comprehend student performance fully. We can assess their efficacy in engaging and facilitating student understanding by examining various teaching methods, such as conventional lectures and interactive learning. This analysis allows us to determine the most successful tactics for promoting student engagement and comprehension. Furthermore, analyzing the effects of teacher training programs demonstrates how the expertise of instructors directly leads to enhanced student achievements.

Student backgrounds have a substantial impact beyond the dynamics of the classroom. Students' preparedness, motivation, and access to resources are influenced by their prior educational experiences, socio-economic status, and cultural background, which affect their performance. Through comprehending these varied origins, focused interventions and support initiatives can be formulated that accommodate individual requirements and tackle potential obstacles to achievement. Moreover, the accessibility and quality of educational resources, such as textbooks, online materials, and laboratory equipment, substantially impact student learning. Examining the availability of resources might reveal potential areas of disadvantage for pupils, impeding their advancement. Looking at the function of technology, such as instructional software and online simulations, can also yield significant observations into how technology can improve learning experiences. By extending our research beyond the relationship between variables, we can better understand the intricate interaction among several factors that influence students' attainment in electrical engineering. Through the implementation of longitudinal studies, the collection of data from various populations, and mixed methods research, valuable insights may be acquired into the enduring effects of interventions and efficient strategies be formulated to foster STEM achievement for all students. In conclusion, this shift towards a comprehensive and fair educational environment cultivates a forthcoming cohort of proficient and enthusiastic electrical engineers prepared to propel technical progress and make meaningful contributions to a more promising future.

6. Conclusions and Recommendations

The vital role of mathematics in engineering is not under dispute; many studies have shown that the engineering sciences depend on mathematical tools for problem-solving and design. However, in this study, the relationship between mathematics and electrical engineering was under consideration in terms of the alignment of mathematical concepts and engineering tools and the relationship between student attainment in mathematics and electrical engineering modules. This study showed a complex and possibly undesirable relationship between the two modules, with many potential causes. The study drew on LCT to explain the complex relationship between mathematics and engineering modules using the principles of abstraction and application. LCT provided a way of understanding the relationship between mathematics and engineering as one in which abstraction and application must be woven together through curricular and pedagogical arrangements to provide students with the appropriate mathematical tools for solving engineering problems. The contribution to knowledge that this study offers is a deeper understanding of the relationship between the two modules and how this might become a more productive one with better curricular and pedagogical alignment.

The research presents a number of practical recommendations for the South African education system. We recommend that early childhood education learning and development for students be strengthened, especially for STEM modules, regardless of their diverse backgrounds. Evidence-based pedagogical practices tailored to students' needs can to be implemented by creating an active, supportive, and engaging learning environment. There is a direct need for STEM lecturers to work more closely to understand students' needs and how the mathematics and engineering curricula could be better aligned. A study of curricular documents, syllabus outlines, and other relevant documents would enable mathematics and engineering lectures to pinpoint more precisely the topics that need improved alignment. The study also raised issues of pedagogy, in particular the need to explore pedagogies in support of retention, offering suggestions for the academic development of mathematics lecturers. The study raised many additional questions that require research; for example, in-depth interviews with students would reveal additional explanations of the relationship between mathematics and engineering from students' perspectives. Also, strengthening the mathematics foundation and integrating real-world electrical engineering applications into mathematics courses for practical application by demonstrating the relevance of mathematical concepts to the electrical field enhances critical thinking, problem-solving, and communication skills in preparation for the 21st-century workforce. Doing this can significantly improve mathematics education and promote equitable access to quality mathematics learning for all South African students. Encouraging collaborative and active learning, regular assessment and evaluation, and partnership with industry enables students to develop the necessary knowledge and skills.

By implementing these recommendations, South African diploma programs can foster a stronger connection between mathematics and electrical engineering attainment, enabling students to develop the necessary knowledge and skills to succeed in their chosen field. This, in turn, will contribute to the advancement of the electrical engineering industry and the overall economic development of South Africa.

7. References

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