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Feedback on implementing a structured approach to solving electrical circuits problems

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Abstract

Engineering education necessitates more than mere technical competence; it demands adaptability, creativity, and advanced problem-solving abilities to address the multifaceted challenges of the modern-day engineering workplace. However, traditional curricula frequently encourage students to prioritize attaining correct answers rather than spending time developing and refining effective learning processes. This approach may constrain students' adaptability and hinder the development of self-regulated learning skills that are essential for a professional engineer.

To address this, a structured metacognitive framework was introduced to strengthen engineering students' learning strategies within the context of electrical circuit problem-solving. The framework comprises three sequential stages: Planning, Monitoring, and Evaluating. In the Planning stage, students a develop a plan and anticipate the difficulties and concepts associated with each problem. During Monitoring, they execute their plan and adjust strategies where necessary. Finally, through Evaluating, students reflect on their approaches and outcomes, given an example solution. This systematic process helps learners assess their own thinking, identify areas for improvement, and develop effective habits for managing complex tasks. Ultimately, the framework aims to cultivate independent, reflective learners prepared for the dynamic expectations of modern engineering practice.

The framework was implemented in a series of third-year electrical circuits classes where students documented their perceived, experienced, and retrospective views of problem difficulty and conceptual understanding as part of the three stages. Analysis of student reflections revealed several patterns: some students articulated their problem-solving strategies with clarity and considered outcomes thoughtfully; others approached problems without a clear plan; some solved problems correctly but did not see value in reflection; and several expressed surprise at their own learning outcomes. Transitions among these groups occurred as students grew more accustomed to the framework's structured nature.

Initially, many students equated achieving incorrect answers solely with numerical errors, overlooking deeper conceptual or strategic causes. However, as familiarity with the process improved, such surface explanations decreased. Student feedback was varied and largely centered on their unfamiliarity with taking a structured approach. Some students requested more time to complete the problem-solving, while others preferred traditional, teacher-led sessions covering a greater volume of problems. This feedback demonstrates both the challenge and promise of integrating structured metacognitive approaches into engineering curricula and suggests that a more integrated approach across multiple courses is needed in order to more deeply influence student learning behavior.

Introduction

Engineering education must prepare graduates not only with strong technical expertise but also with the flexibility, innovative problem-solving capabilities, and professional competencies needed to address the increasingly complex and ambiguous challenges of modern engineering practice. Phenomenographic research among engineering faculty has shown that academics highly value attributes such as adaptability, critical thinking, and the ability to manage ill-defined problems, viewing these as vital for equipping students to thrive amid globalization, disruptive technologies, and socially intricate issues [1]. As technological progress accelerates, engineers routinely confront poorly structured problems that necessitate ongoing learning, creative adaptation, and the skill to operate effectively in uncertain conditions [2, 3]. Central to developing these capabilities is metacognition, often described as "thinking about thinking" [4], which enables individuals to actively monitor, control, and refine their cognitive activities, leading to more efficient and adaptable problem-solving [5]. In engineering contexts, where tasks frequently involve iterative refinement and bridging knowledge deficiencies, metacognition supports practitioners in crafting robust solutions and transferring skills across varied scenarios [6].

Metacognition is broadly divided into two components: metacognitive *knowledge* and metacognitive *regulation*. Metacognitive knowledge encompasses declarative aspects (awareness of personal strengths, limitations, and domain content, for example, understanding key principles like Ohm's law in circuits or stress-strain relationships in materials), procedural aspects (knowing how to implement techniques, such as applying mesh analysis to resolve circuit currents or using moment distribution for indeterminate structures), and conditional aspects (knowing under what circumstances certain methods are most appropriate, like preferring superposition in linear circuits with multiple sources or selecting finite element methods for nonlinear structural analysis) [7, 8]. Metacognitive regulation, in turn, involves planning (establishing objectives and choosing approaches before beginning, for example defining solution steps for a feedback control system design), monitoring (observing ongoing progress and making adjustments, such as checking intermediate calculations during transient analysis or validating assumptions in fluid flow simulations), and evaluating (reviewing results and methods afterward, for instance, assessing the validity of a power system load flow study or examining the efficiency of a chosen algorithm in signal processing) [9]. These processes are integral to self-regulated learning models that underscore metacognition's role in building effective learners capable of sustained academic and career achievement [10] [6].

Nevertheless, conventional engineering instruction and evaluation methods, which are often centered on high-stakes exams that reward final answers rather than thoughtful processes, consequently tend to undervalue reflection, leaving many students unaware of their own thinking patterns and thus less prepared for real-world ambiguity [11, 12]. This was apparent in the course considered in this paper, where students were often unable to clearly articulate the reasoning behind their approaches to circuit-solving, especially when becoming stuck or obtaining incorrect answers.

An approach that attempts to tackle that shortfall embeds structured metacognitive activities, centered on planning, monitoring, and evaluating, within problem-solving sessions in a core third-year electrical circuits course [13, 14]. While this approach has provided some encouraging quantitative results, this paper extends the research in providing a qualitative analysis of the students' reflections and some of their overall feedback. The intent is to further build our understanding of students' thought processes in solving circuit problems. The paper concludes by offering recommendations, based on the lessons learned over several iterations, for engineering educators who are interested in adopting a similar approach, either in teaching electrical circuits or adapting it to other disciplines.

Background and Context

The electrical circuits course that is the subject of this paper is at the third-year of an undergraduate mechatronics degree and covered concepts from both analog and digital electronics. The course consisted of three one-hour lectures and one two-hour workshop class per week over a 12-week semester. The workshop classes alternated between laboratory sessions and problem-solving classes, with the latter occurring in Weeks 3, 5, and 8. In the initial problem-solving workshop class in Week 3, students received a brief 10-minute overview of metacognition and the adapted cyclical self-regulation framework from Zimmerman [9], emphasizing its three phases: planning, execution/monitoring, and self-reflection/evaluation. Each workshop involved tackling a series of analog circuit analysis problems through this consistent three-stage process, shown in Figure 1 and summarized below.

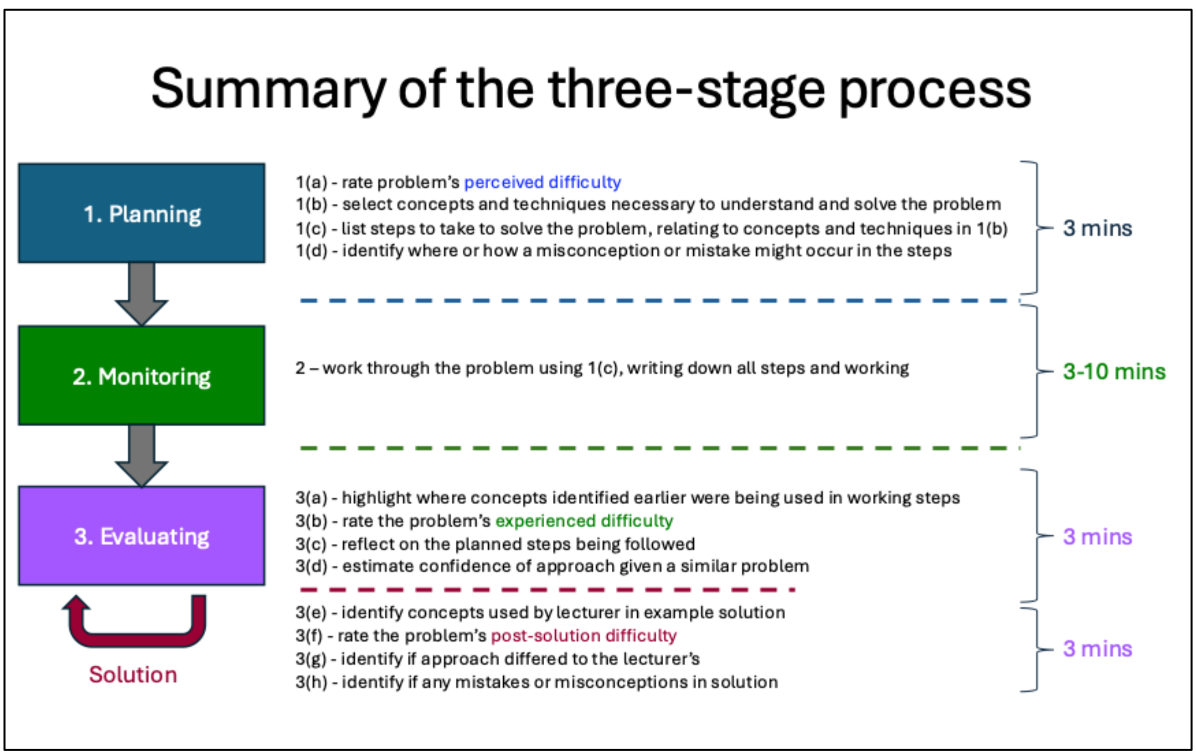

Figure 1: Planning, Monitoring, Evaluating process

The **Planning** stage required students, after reviewing the problem, to (a) rate its perceived difficulty on a 1-10 scale (1 = extremely simple, 10 = extremely difficult), (b) choose relevant concepts and solution techniques needed to solve the problem from a provided list derived from the subject outline, prerequisite outcomes, and a circuits concept inventory [15], (c) sketch a brief step-by-step plan based on those selections, and (d) anticipate possible misconceptions or errors in execution of the plan. A strict three-minute limit applied to this stage, regardless of perceived difficulty, so that students could not begin problem-solving until they had adequately prepared a plan, aligning with pre-task strategies for heightened task awareness as described by Palincsar and Brown [6].

In the **Monitoring** stage, students solved the problem individually within a 3-10 minute window (adjusted per problem based on the lecturer's estimate of reasonable completion time), documenting all workings while tracking adherence to and progress against their initial plan, mirroring real-time strategy adjustment in Zimmerman's performance phase.

The **Evaluating** stage involved two reflective components, each allocated three minutes. First, students assessed their own solution by considering (a) which planned concepts/techniques were actually applied and why any were omitted, (b) the difficulty experienced during solving (1-10 scale), (c) how closely they followed their plan, and (d) their confidence (0-100%) in applying the approach to a similar future problem. After viewing the lecturer's worked solution, they then (e) identified concepts and techniques used in that example from the list, (f) rated the problem's retrospective/reflected difficulty (1-10), (g) compared their method to the lecturer's, and (h) noted any errors or misconceptions in their attempt, drawing on post-task reflection to calibrate metacognitive judgments as emphasized by Dunlosky and Metcalfe [5].

Subsequent problems in the session followed the same three-stage process. All students recorded their responses on structured template worksheets, collected at the end of the session, which included student identifiers to enable longitudinal tracking of individuals over the remaining problem-solving sessions in the semester.

Prior research performed a quantitative analysis of concept and solving-circuit technique selections for the three Week 3 problems and showed that students systematically overestimated the number of concepts and methods required during Planning, however the gap between the selections made during the Planning and Evaluating phases decreased across the three problems [14]. This suggested that students were improving their ability to judge what was needed to solve a particular circuits problem in a given topic area. However, the quality or influence of their plan were not analyzed.

For two of the three Week 3 problems, the students' experienced difficulty exceeded their perceived difficulty with statistical significance, while their reflected difficulty ratings (after viewing the worked solutions) were on average lower than both their perceived and experienced difficulty for all three questions [14]. This implies a possible calibrating effect of structured reflection, however it was not investigated any further through the qualitative student reflections that were gathered.

Across the three problem-solving classes, mean differences between perceived and reflected difficulty diminished, and the pattern shifted from experienced difficulty being greater than perceived difficulty to being less than or equal to perceived difficulty [14]. This is consistent with students developing more accurate expectations of problem difficulty and smoother solution processes.

While these quantitative data are encouraging and suggest that a simple, repeatable metacognitive framework can build students' awareness of concepts, strategies, and perception of difficulty in circuit problem solving, the reflective, qualitative data gathered as part of the three stages were not previously analyzed. The following sections will perform an analysis of these data to better understand these prior results. Due to the vast volume of student data to process, and to ensure the conciseness of this paper, we will constrain a more detailed analysis to the three problems presented in Week 3 and highlight where any observed trends were maintained over the three sessions.

Methodology

A rubric was constructed to assess students' plans formed during the Planning stage. Four components were assessed, each on a four-point scale, shown in Table 1. The simplicity of the rubric allowed large numbers of student submissions to marked relatively easily.

Table 1: Rubric for assessing student plans

Criterion	Good (3)	Fair (2)	Poor (1)	No credit / missing (0)
Selection of Appropriate Techniques	Selects and justifies the most effective techniques (e.g., node analysis, mesh currents) that align with the problem's requirements.	Selects suitable techniques, but with incomplete justification or minor mismatches.	Selects irrelevant or incorrect techniques.	No techniques selected, or only completely inappropriate / random approaches mentioned.
Logical Sequence of Steps	Outlines a clear, step-by-step plan that logically progresses from setup to solution, ensuring feasibility.	Provides a mostly logical sequence, but with some gaps or disjointed elements.	Lacks a coherent sequence; steps are random or largely missing.	No sequence of steps provided, or plan is entirely incoherent / absent.
Clarity and Conciseness	Plan is concise, well-organized, and easy to follow, using precise language and diagrams if needed.	Plan is understandable but somewhat wordy, vague, or disorganized.	Plan is confusing, overly verbose, or lacks structure.	Plan is illegible, incomprehensible, or no meaningful written plan is submitted.
Accuracy and Completeness	Plan is fully accurate, covers all aspects of the problem, and anticipates potential issues.	Mostly accurate and complete, with noticeable errors or omissions that may affect solvability.	Inaccurate, incomplete, or fundamentally flawed.	Plan contains no accurate content, is entirely incomplete, or shows no understanding of the problem.

In addition to the marks for the student plans, the following qualitative response items on the student submissions were analyzed:

- Planning phase 1(d): anticipate possible misconceptions or errors in execution of the plan;
- Evaluating phase 3(c): reflect on whether students followed their plan or not, and if not, why not.

Student responses to these items were categorized by two assessors via an iterative process. The assessors collaboratively developed a set of category definitions, decision rules and examples based on their experience and initial observations of a small batch of responses. They then independently coded another subset of responses (approximately 20% of all responses). Inter-rater agreement between the two on this subset was very high (Cohen's kappa = 0.87, $p < 0.01$), and any disagreements were jointly discussed and resolved. As reliability was deemed as 'almost perfect' [16], the full dataset was coded independently by one of the assessors. This research was approved under Human Ethics Protocol 29248.

Results – analysis for a single problem

The distribution of marks for the plans for Problem 1 in Week 3 using the rubric in Table 1 are shown in Figure 2. Some students were able to achieve full marks, a cohort of students constructed reasonable plans (from 8-11 marks), and another, more spread cohort formulated plans that are deficient in several areas (below 8 marks).

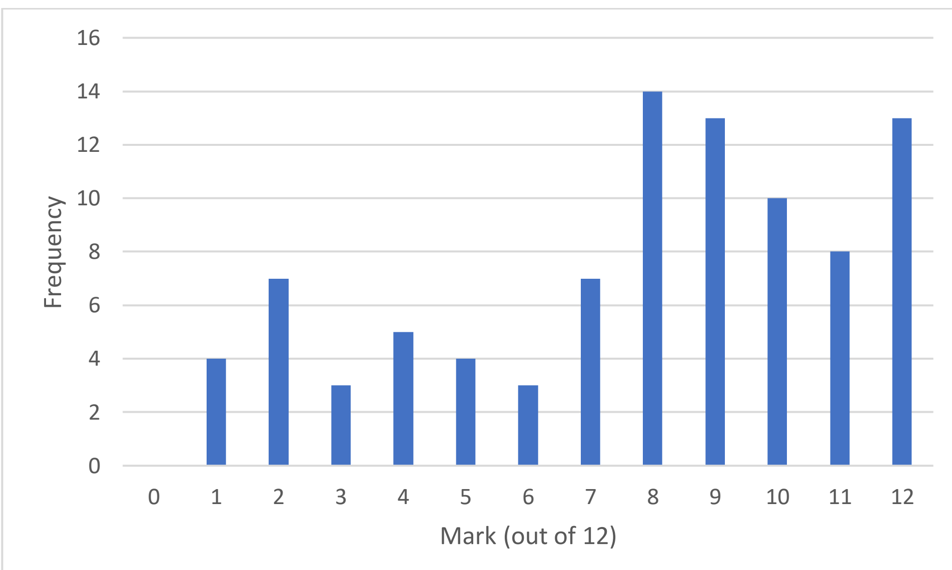

Figure 2: Distribution of student plan marks for Problem 1, Week 3 (91 responses)

As part (d) of the Planning phase, students were requested to list any anticipated misconceptions they might have or errors that could occur in the execution of their plan. For Problem 1 in Week

3, 61 students provided a response, with another 30 either listing ‘none’, or not providing a response. Table 2 shows the categorized responses from the students who provided a response. Note that the sum of the frequencies exceeds 61 as several students listed multiple items.

Table 2: Frequencies of potential misconceptions or errors in plan execution for Problem 1, Week 3 (61 responses)

Potential misconception or error in execution of plan	**Frequency**
Mathematical errors	9
Calculation error	22
Applying circuit solving methods	26
Planning issue	3
Misinterpret question	4

When categorizing student responses, students who explicitly mentioned calculation errors, e.g. numerical errors in their working, were differentiated from those mentioning broader ‘mathematical’ errors, such as manipulating algebraic equations, by placing them in the ‘calculation’ category. Most students identified either calculation errors or the misapplication of circuit solving methods as the primary causes for not being able to obtain a correct answer, overlooking deeper conceptual (misinterpreting the question) or strategic causes (poor planning). The latter is surprising, given the broad tail of the distribution of marks for the plan shown in Figure 2, which might represent that some students were unaware of how poor their plans actually were. Note that no feedback was given to students on their plans while they were performing the exercises due to the time constraints of the class.

As part (c) of the Evaluating stage, students were asked to reflect on whether they followed their plan for Problem 1 in Week 3, and if not, why not. All 91 students provided a response, with 25 students claiming they followed their plan precisely, while 66 students indicated that they did not. The reasons given by these 66 students are categorized in Table 3.

Table 3: Reasons for not following the plan devised in the Planning stage for Problem 1, Week 3 (66 responses)

Reason for not following the plan	**Frequency**
Forgot circuit solving method	13
Misread circuit	4
Ran out of time	18
Became stuck on a step	13
Followed same steps but in different order	9
Significantly modified plan	9
Plan not detailed enough to follow	14
Incorrect working	5

A clear issue that emerged was students not having enough time to enact their plan to solve the problem (18 students). Students were given a set time to execute their plan during the Monitoring phase (between 3 and 10 minutes) that was determined by the lecturer and based on their perceived difficulty of the problem. It is likely that these times will need to be adjusted in the future based on these data.

Fourteen students reported that their plan was not detailed enough to follow, which reflects some of the observations made when the plans were marked. On further investigation, the vast majority of these students (12) scored below 8 marks out of 12 for their plans. Thirteen students each either became stuck on a step or reported that they forgot how to apply a particular circuit solving technique. This is somewhat surprising as all students have completed a pre-requisite foundational course and should be familiar with the course material; however, a long summer break of approximately 12 weeks occurs after the conclusion of the foundational course and the commencement of the course under study here. This might cause a lack of retention of the foundational knowledge and add to time pressures.

If the data shown in Table 3 are read alongside those in Table 2, it shows that students encountered quite different issues to what they originally envisaged during the Planning phase. Only 5 students explicitly mentioned that incorrect working (i.e. calculation and mathematical errors) prevented them from following their plan in Table 3, compared to a combined 31 students in Table 2, who predicted that either mathematical or calculation errors would occur.

Results – analysis across multiple problems

We turn our attention to the subsequent two problems in Week 3 and compare results to the first problem to see how students were responding to applying the framework. To this end, a comparative plot of the distribution of plan marks for all three problems is given in Figure 3.

The distribution of marks appears to improve slightly, with more students at the higher end of the distribution. Means for the plans over the entire cohort for the three problems were 7.70, 8.03 and 8.12 respectively. This improvement is encouraging, given that students were not given any direct feedback on their plan in class due to no time being available between the problems to have them marked on the spot. However, the students may have begun to intuitively realize, through reflection after solving the problems, that their plans needed more careful consideration or detail in order to solve the problems more efficiently.

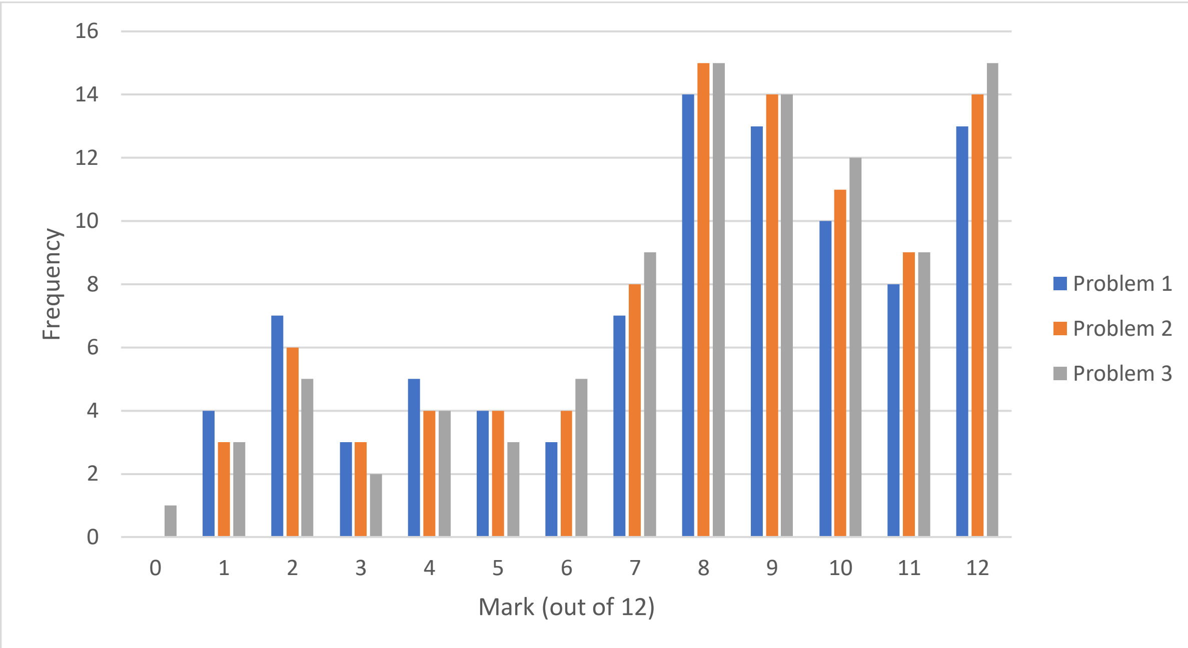

Figure 3: Distribution of student plan marks for Problems 1-3, Week 3 (91 responses)

Table 4 compares the frequencies of potential misconceptions or errors in plan execution for all three problems in Week 3 and reveals an emerging shift in students' thinking.

Table 4: Frequencies of potential misconceptions or errors in plan execution for Problems 1-3, Week 3

Potential misconception or error in execution of plan	Problem 1 Frequency (61 responses)	Problem 2 Frequency (64 responses)	Problem 3 Frequency (59 responses)
Mathematical errors	9	7	5
Calculation error	22	18	14
Applying circuit solving methods	26	24	20
Planning issue	3	12	15
Misinterpret question	4	9	8

Students appear to be recognizing that planning plays a more pivotal role in solving problems than originally expected, with both planning issues and misinterpreting the question showing an overall increase, while mathematical and calculation errors decreasing over time.

Results – trends across problem solving sessions

While the shift in recognizing the importance that planning plays in problem-solving is quite pronounced over the problems in the first workshop class, the trend continued over subsequent problem-solving sessions in Weeks 5 and 8. Table 5 gives the average of percentages over all problems and student responses for the three sessions, which shows that the shift observed over the three problems in Week 3 appears to have persisted throughout the rest of the semester.

Table 5: Distributions of potential misconceptions or errors in plan execution for problems across Weeks 3, 5 and 8

Potential misconception or error in execution of plan	Week 3 average	Week 5 average	Week 8 average
Mathematical errors	11%	13%	9%
Calculation error	28%	20%	21%
Applying circuit solving methods	36%	34%	34%
Planning issue	15%	21%	24%
Misinterpret question	11%	12%	12%

Discussion

The qualitative analysis in this study helps to further explain and reinforces the improvement trends seen in the quantitative data from [14], while also revealing some limits and conditions for those gains. Together, the two studies show that a structured Planning, Monitoring and Evaluating framework both sharpens students' quantitative judgments about circuit problems and gradually shifts their underlying metacognitive thinking. The earlier work demonstrated that, across multiple problem-solving sessions, students became more accurate in selecting the concepts and techniques needed for each question and in rating problem difficulty at different stages of the task. Over time, the gap between what they anticipate and what is actually required narrowed, and perceived difficulty became better aligned with experienced and retrospective difficulty, indicating more calibrated expectations and smoother solution processes. The qualitative investigation of plans and reflections presented in this paper provides possible mechanisms for these numerical patterns. Rubric-based marking of plans for the sequence of Week-3 problems shows a move from a broad spread of weak plans to a slightly higher concentration of more coherent, detailed plans, despite students not receiving explicit feedback on those plans. This implies that repeated use of the framework, coupled with reflection, moved many students toward clearer sequencing of steps, better choice of techniques, and more complete anticipation of what a solution would involve.

Student comments about anticipated and actual errors expose an important metacognitive shift. Early on, many students predicted that failure would be due mainly to arithmetic or general mathematical mistakes, while largely overlooking poor planning, misreading of the question, or misapplication of circuit methods. In practice, when reflecting on why they did not follow their plans, students frequently cited running out of time, plans that were not detailed enough to execute, forgetting specific analysis techniques, or getting stuck mid-solution, with relatively few attributing breakdowns to simple calculation errors. This divergence suggests that the improved calibration of difficulty ratings and concept selections in the quantitative data from [14] reflects a growing awareness of deeper strategic and conceptual factors rather than mere accuracy in performing calculations.

It should be noted that a significant amount, in some cases up to a third, of participants, did not list any potential misconceptions during the Planning phase of the problems. Several reasons could account for this: a resistance to the activity, spending most of the Planning stage time on listing the steps required to solve the problem, a failure to understand that they have any misconceptions, or a genuine belief that they did not have misconceptions. Future work will need to investigate further in order to discover the underlying reason(s) for this.

There are several limitations to the analysis of student data which could constrain the generalizability of its qualitative findings on the metacognitive framework. Due to the large volume of qualitative data collected as part of this study, and to ensure conciseness for a conference paper format, results in this paper largely focus on the analysis of the three circuit problems in Week 3. However, some broader trends that were observed over subsequent sessions were highlighted, where possible, but there is scope for further analysis. Additionally, students received no direct feedback on the quality of their plan during the activities, yet plan marks still improved slightly across the three problems. This could raise questions about whether self-reflection alone drove gains, as some students seemed unaware of their plans' deficiencies. Finally, strict time limits for the stages were applied uniformly, leading to frequent complaints of insufficient time to execute plans or complete work, which could have affected how students responded to the various tasks.

Feedback collected on end-of-semester surveys was varied, revealing resistance emerging from a lack of familiarity with the structured approach, which some students believed consumed too much valuable class time, and a preference for traditional teacher-led sessions covering more problems. Many students questioned the value of spending time on planning and reflection when this reduced the number of worked examples seen in class and when a high-stakes end of semester exam, which retained the previous style and format, dominated their learning priorities. If the assessment was more aligned, for example the final exam also assessed students' ability to plan and evaluate their problem-solving methods, this concern could be reduced and potentially better support metacognitive adoption during semester.

Complaints about insufficient time in the Monitoring phase were also prevalent, however this should be easily addressed through adjustment in timing for future iterations. This does show that gains in metacognitive abilities are emerging alongside, and sometimes in spite of, perceived workload pressure and misalignment with a traditional, exam-focused assessment culture.

For engineering educators adopting this approach in circuits, or other disciplines, some recommendations are:

1. providing timely feedback on student plans to accelerate metacognitive growth;
2. adjusting time allocations for problems based on problem complexity and student feedback to mitigate frustration;
3. introducing metacognition early in curricula to build familiarity;

4. integrating the framework across multiple courses for sustained impact, rather than isolated sessions; and
5. aligning assessments with reflective practices to counter exam-driven priorities.

Conclusion

This study examined the use of a structured metacognitive framework, consisting of Planning, Monitoring, and Evaluating stages, to support third-year engineering students in solving electrical circuit problems. The qualitative analysis showed that repeated engagement with the framework encouraged students to move beyond superficial explanations of failure, such as calculation mistakes, and toward a more accurate recognition of strategic and conceptual difficulties. Over time, students produced slightly stronger plans and appeared to demonstrate greater awareness of the demands of the tasks, complementing previously observed quantitative trends that showed improved calibration between students' perceived, experienced, and reflected difficulty of the problems.

The student reflections also revealed important challenges. Many students initially struggled with the unfamiliarity of the approach, and a substantial number reported limited time, incomplete plans, or difficulty sustaining their original strategy during the execution of the plan during the Monitoring phase. Nevertheless, the pattern of responses suggests that the framework helped students develop a more reflective and realistic understanding of how circuit problems are solved, particularly by highlighting the importance of planning before execution and evaluation afterwards.

Overall, these findings suggest that a structured metacognitive approach can improve not only students' problem-solving performance but also their awareness of the processes underlying that performance. The results support broader use of the Planning, Monitoring, and Evaluating framework activities in circuits, and potentially in other engineering, courses especially when paired with sufficient time, early introduction, and alignment with assessment practices.

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