Quantifying the Effects of Concept Maps on Student Learning

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Abstract

Concept maps are valuable tools for visualizing relationships between key ideas, improving students' understanding and retention of concepts, particularly in complex fields such as engineering. This study investigates the impact of iterative concept map creation on student learning in mechanical engineering courses over a 15-week semester. Additionally, a survey was conducted to gather student feedback on how the concept map assignment influenced their engagement, ability to connect ideas, and capacity to apply the concepts learned in class. By integrating both quantitative and qualitative data, the analysis combines statistical methods, correlation analysis, and insights derived from natural language processing tools to provide a comprehensive understanding of the pedagogical impact of concept maps. Findings reveal no significant correlation between students' course grades and their concept map scores. However, survey feedback underscores their positive influence, particularly in fostering connections between ideas and improving the application of course knowledge, suggesting that traditional scoring may not fully capture the educational value of concept maps. Overall, this study highlights the potential of concept maps as an effective pedagogical tool in engineering education.

Introduction

A concept map is a visual representation of information that displays the relationships between different ideas and concepts through nodes and links[1,2]. It is structured hierarchically, starting with general concepts and branching out to more specific concepts. The concepts are connected with linking words clarifying the nature of the relationships. Additionally, crosslinks are used to highlight connections between different branches, emphasizing interrelated ideas. Figure 1 shows the general structure and the different components of a concept map. The node "central concept" in Figure 1 represents the main concept and the surrounding nodes represent the related sub-concepts[1].

Concept maps have been shown to be an effective tool in the learning process, allowing students to connect related ideas and increasing student understanding of a topic[3,4]. Concept mapping has been demonstrated to be beneficial in higher education. The use of concept maps to help students understand the structure of a mechanical engineering curriculum and the relationships between sequences of courses has been investigated[5]. This study discussed concept mapping as a tool to improve the effectiveness of lectures and to help students achieve a greater depth of understanding of course material. The use of concept maps has also been shown to be beneficial in illustrating the effects of problem-based learning (PBL) by examining the patterns of concepts and differences in the knowledge structures of students taught with and without a PBL approach[6]. This study showed that concept relationships, hierarchy levels, and cross linkages in the concept maps were significantly greater in the PBL group; however, examples of concept maps did not differ significantly between the two groups. Concept maps have also been used to assess entrepreneurial-minded learning in students, particularly their ability to make connections.[7,8]. Most studies on concept maps involve evaluating the maps by scoring the accuracy, depth, and organization of the concepts to assess students' understanding and learning progress. This scoring often focuses on how well students can represent and connect key ideas, as well as their ability to structure relationships logically. The process helps educators gauge the extent to which students grasp the material, identify gaps in their knowledge, and track their cognitive development over time. However, scoring the maps alone does not provide a full picture of the learning experience. It is also important to study students' perspectives on concept maps as a learning tool[9], as this can provide valuable insights into their perceptions and the overall effectiveness of concept maps.

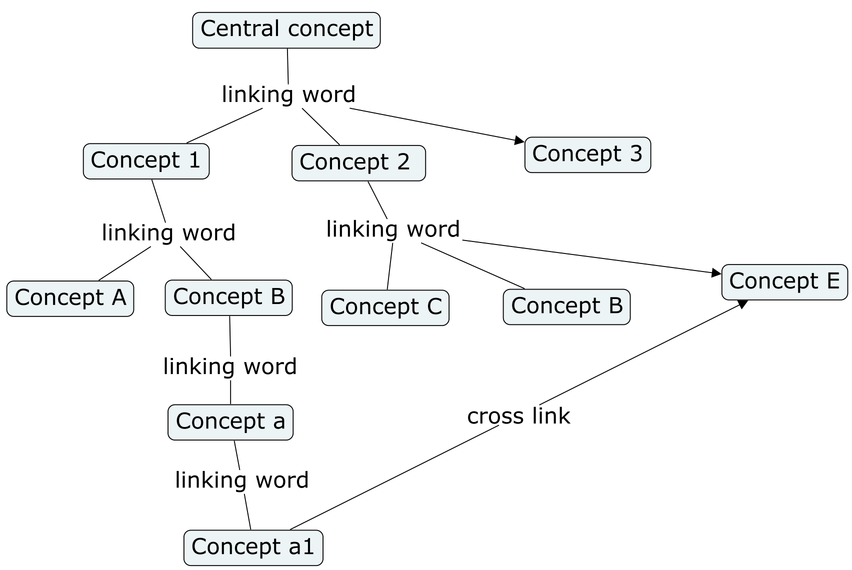


Figure 1: General structure of a concept map showing concepts, hierarchy, and links.

In this study, we examine how concept maps can be used to assess students' learning. We analyze the evolution of knowledge through concept maps generated by students throughout the semester, collected at different intervals for both undergraduate and graduate-level courses. We explore the benefits and limitations of using concept maps as a tool for measuring students' understanding, including insights from student surveys on the effectiveness of concept maps in connecting course content to other courses and applications. Additionally, we investigate the influence of course level—undergraduate versus graduate—on students' ability to demonstrate connections. The study was conducted across three different courses in a mechanical engineering curriculum.

Methods

This section discusses the procedures for data collection, concept map scoring, and data analysis used to assess students' learning through concept maps and their perceptions of concept maps as a learning tool.

Data collection

Data for this study was collected through a multi-part assignment on concept maps. The maps were generated by students at different intervals throughout the 15-week semester for three courses. For the two undergraduate level courses, concept maps were collected at two points - midway through the semester and at the end of the semester. For the cross-level undergraduate and graduate course, concept maps were collected three times - after the first week of instruction, midway through the semester, and at the end of the semester. Data from 31 students across the three courses in the Mechanical Engineering department at Rowan University is used in this study. The concept maps were used as a tool to track the evolution of students' learning and ability to connect the course content. In addition to the concept maps, surveys were administered to gather insights into the students' perceptions of the concept mapping process and its effectiveness as a learning tool.

The concept map assignment was designed as a low-stakes task. The assignment prompt asked students to create a concept map with the course title as the central node. Students were required to include key technical concepts related to the topic while also considering real-world applications of the topic in engineering. Additionally, they were encouraged to think beyond just the technical aspects by incorporating social, ethical, and personal implications. Students were prompted to explore how these concepts intersect with their career aspirations, societal impact, and everyday life. The concept map had to be created digitally and clearly structured, showing different levels of hierarchy and connections.

The survey employed a Likert scale[10] to measure students' perceptions of the assignment's impact. Specifically, it assessed whether the assignment helped students understand how the course connected to other topics, with response options ranging from *Strongly agree* (5) to *Strongly disagree* (1). The scale was also used to evaluate whether the assignment facilitated the application of course learning to other areas, using the same response options. Additionally, the survey included a question asking students if they liked the concept map assignment, with a *Yes* or *No* response option, followed by an open-ended question inviting students to elaborate on what they liked or disliked about the assignment. This combination of structured and open-ended questions aimed to provide both quantitative and qualitative insights into students' experiences and perceptions of the concept map assignment.

Concept map scoring

Two popular methods for scoring concept maps are holistic scoring and traditional scoring[8]. Holistic scoring evaluates concept maps based on three key criteria - comprehensiveness, organization, and correctness. Each criterion is assessed using a distinct set of evaluation guidelines. After individual scores for each category were assigned and agreed upon, the total score was calculated by summing the scores across all three categories. On the other hand, traditional scoring of concept maps evaluates a student's understanding based on structural components such as the number of concepts, hierarchy levels, and cross-links[1]. While the scoring method emphasized validating the correctness of connections and hierarchical relationships, this step is often omitted to save time and ensure efficient, reproducible assessments. Key metrics include (i) knowledge breadth, measured by the number of concepts (NC), (ii) knowledge depth, reflected by the highest level of hierarchy (HH), and (iii) knowledge connectedness, indicated by the number of cross-links (NCL). Using this method, the total score (TS) of the concept map is calculated as follows:

$$TS = NC + HH \times 5 + NCL \times 10 \tag{1}$$

Using Eq. 1, the total score for the concept map illustrated in Fig. 1 is calculated to be 40, where $NC = 10$, $HH = 4$, and $NCL = 1$. In this study, we employ the traditional scoring method to evaluate the concept maps.

Data Analysis

The data collected from the concept maps and survey were analyzed using the following methods:

Concept Map Iteration Analysis
The concept map scores were systematically examined to assess their evolution over multiple iterations throughout the semester. The changes in the scores were analyzed to determine how students' understanding and ability to connect course material changed over time. In addition to the total score, the individual components of the concept maps (i.e., number of concepts, hierarchical levels, and crosslinks) were tracked to observe how students' maps developed in terms of complexity and organization as the course progressed.

Correlation Analysis
The relationship between the concept map scores and students' final course grades was explored through correlation analysis[11]. This allowed for an examination of whether the quality of the concept maps reflected overall academic performance in the course. By comparing the concept map scores with final grades, the analysis aimed to determine if the concept maps could serve as a reliable indicator of student achievement and learning progress.

Linkert Scale Data Analysis
The Likert scale responses from the student survey were analyzed to evaluate perceptions of the concept map assignment. Responses on how well the assignment helped students make connections between course content and other topics, as well as its role in applying the knowledge, were analyzed to understand the trends in student sentiment and assess the overall perception of the assignment.

Text Analysis
Open-ended survey responses were analyzed using AzureChatOpenAI, leveraging the LangChain framework powered by a large language model (LLM) and integrated with the Microsoft Azure platform. GPT-4 models were deployed to perform sentiment analysis[12], providing deeper insights into students' feedback. This analysis identified recurring themes such as likes, dislikes, and suggestions for improving the assignment.

Results and Discussion

The evolution of the students' concept maps is shown in Figure 2. The data from the two undergraduate level courses (Figure 2a) and one cross-level undergraduate and graduate course (Figure 2b) were analyzed separately. As expected, both the breadth and depth of the concept maps expanded, as evidenced by the increase in the mean of the number of concepts (NC) and the hierarchical structure (HH). Additionally, the connections between concepts grew, reflected in the rise in the number of crosslinks (NCL).

Correlation between the total score of the concept map generated at the end of the semester and the final grades of the students in the course is shown in Figure 3. No correlation between the map score and final grade is observed. This is further quantified using correlation relation analysis.

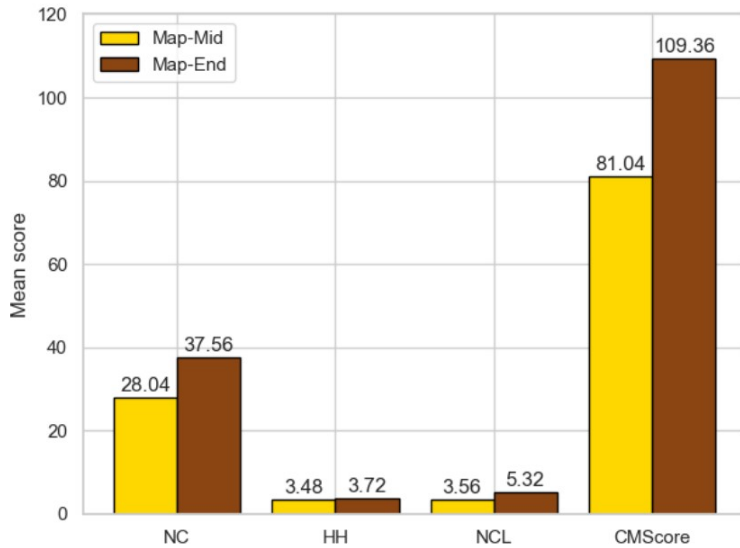
The Pearson correlation coefficients[11] for the total scores of the map, the number of concepts, highest hierarchy and number of cross links with the final numerical grade of the course is low for both the undergraduate courses (Figure 4a) and the cross level course (Figure 4b). As expected, a stronger correlation is observed between the number of crosslinks (NCL) and the total score of the map, owing to the higher weight assigned in Eq. 1. The correlation analysis results reaffirms the conclusions for Figure 3. Upon further analysis of the concept maps from the top-performing students, it was noted that some students concentrated more on refining the maps by revising the concepts and linking words. However, the concept map score does not reflect the learning progress necessary to make such modifications to the map. Thus, the traditional scoring method for concept maps may not be a good indicator of student learning.

The survey data was analyzed next. Students in both the undergraduate level and cross-level courses liked the assignment on concept maps, with 95% and 100% positive response. Students also provided positive feedback on the impact of concept maps in helping to establish connections between the course topics and other areas as seen in Figure 5. The students in the cross-level course (Figure 5b) had no neutral or below responses, whereas approximately 4% of the undergraduate students disagreed with the concept map as a tool for making connections between the learned topics.

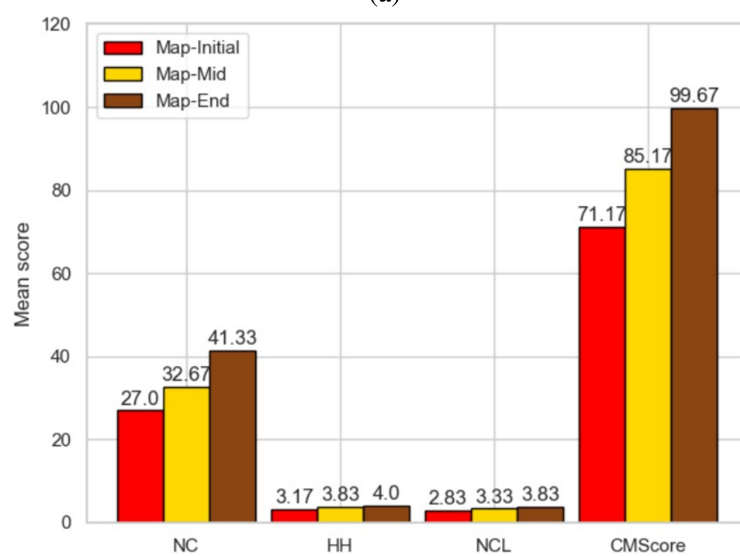
The students' perception on the use of concept map as a tool to aid in the application of knowledge is shown in Figure 6. Approximately 33% of students in the cross-level course were neutral, while 67% agreed on the usefulness of concept maps for applying knowledge (Figure 6b). In the undergraduate-level course, around 4% students disagreed with the usefulness of concept maps for knowledge application (Figure 6a). Figures 5 & 6 indicate that students have a more favorable impression of concept maps as a tool for making connections than for knowledge application across the levels of courses.

Finally, the text data from the survey were analyzed using the GPT-4 model. The student comments were predominantly positive, which was also reflected in the quantitative responses from the survey discussed earlier. The GPT model was utilized to generate suggestions for improving the assignment based on the open-ended comments from the students. The suggestions included the following:

- Introducing concept maps as in-class, group activity to help students better understand the



(a)



(b)

Figure 2: Progression of the students' concept maps throughout the semester. (a) Undergraduate level courses (b) Cross-level undergraduate and graduate course. CMap score denotes the total score of the map based on its components - concepts, links, and hierarchical structure.

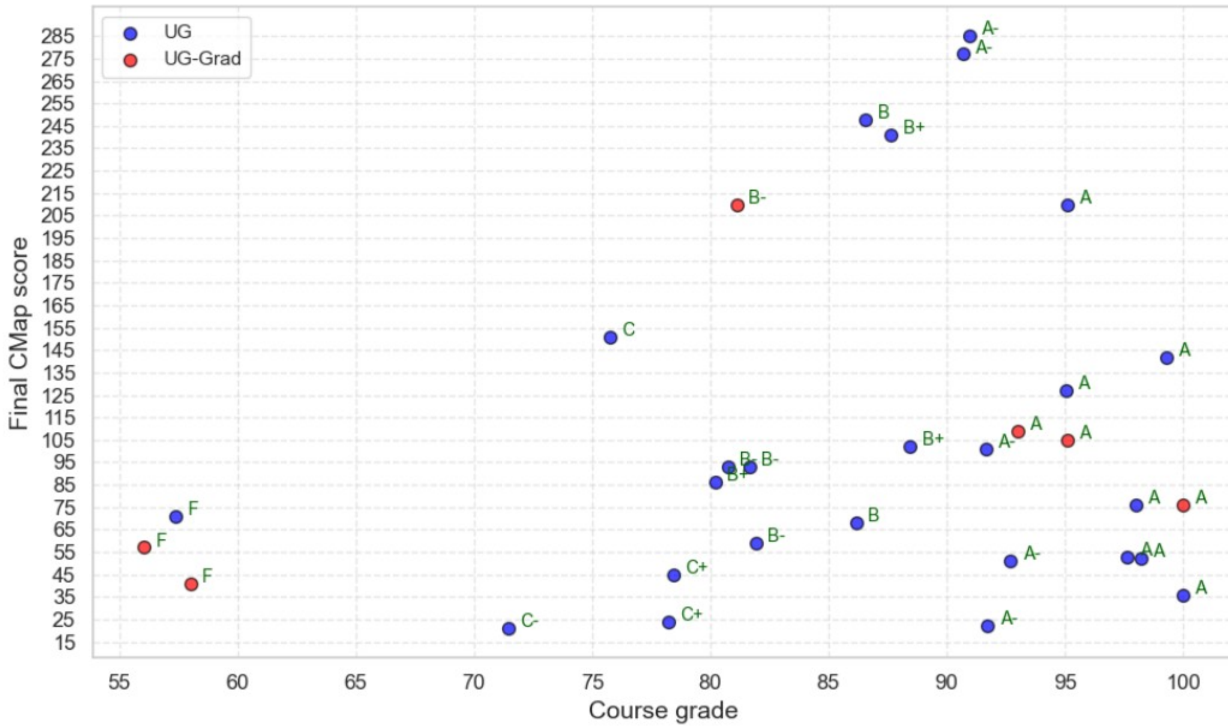
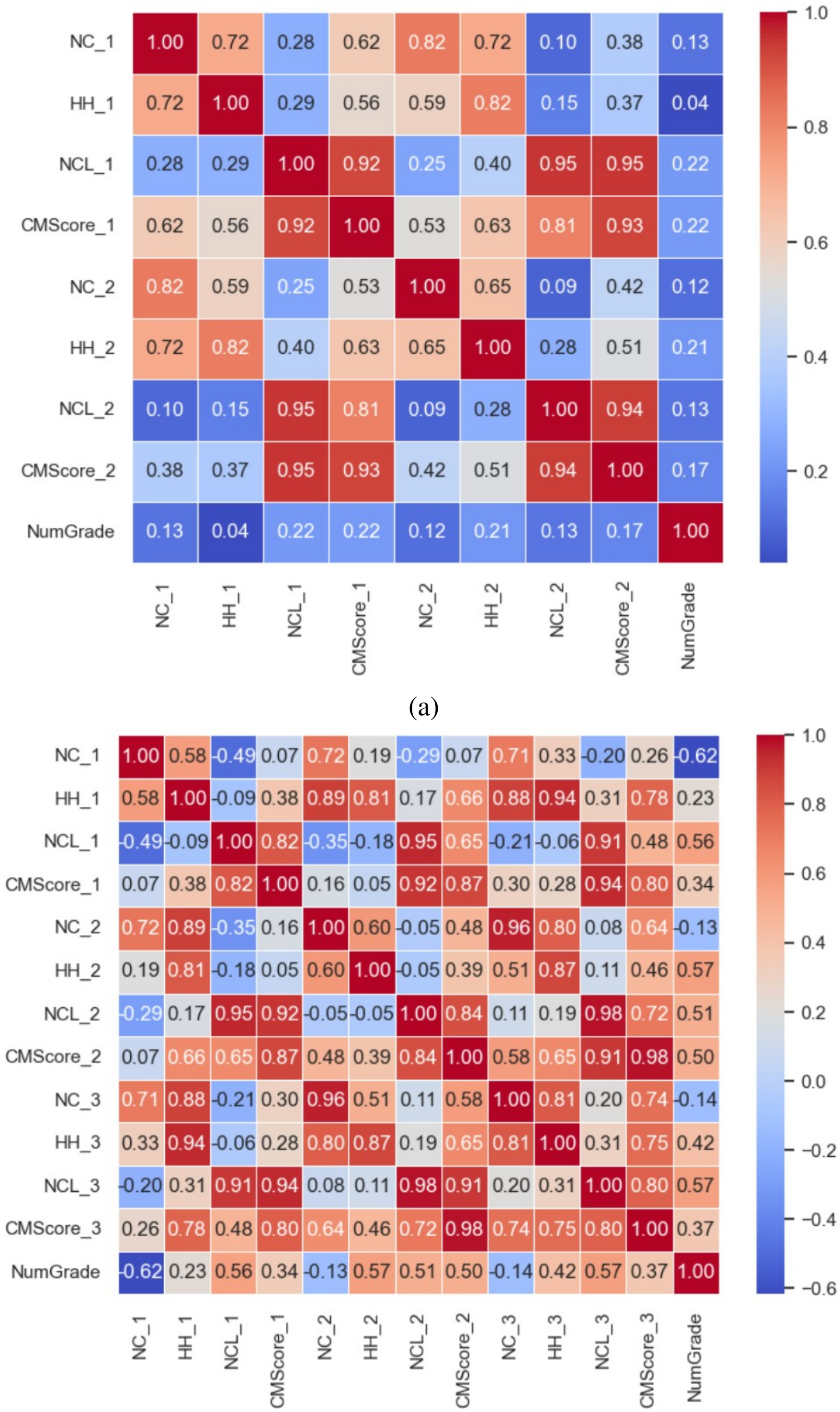


Figure 3: Relationship between course grades and concept map scores. Letter grades assigned to the students are labeled.

expectations and methodology before they attempt them individually.

- Moving away from redoing the same map by having students create separate maps for each course segment, which are then integrated into a final concept map, can keep the task engaging and foster continuous interaction with the material.
- Providing clearer guidelines while still maintaining the open-ended nature of the assignment to encourage creativity
- Encouraging students to update their concept maps regularly after each class or module to reinforce learning
- Incorporating peer reviews to allow students to share their maps and gain valuable feedback from classmates
- Integrating digital tools specific for concept map creation to make the process more accessible and engaging

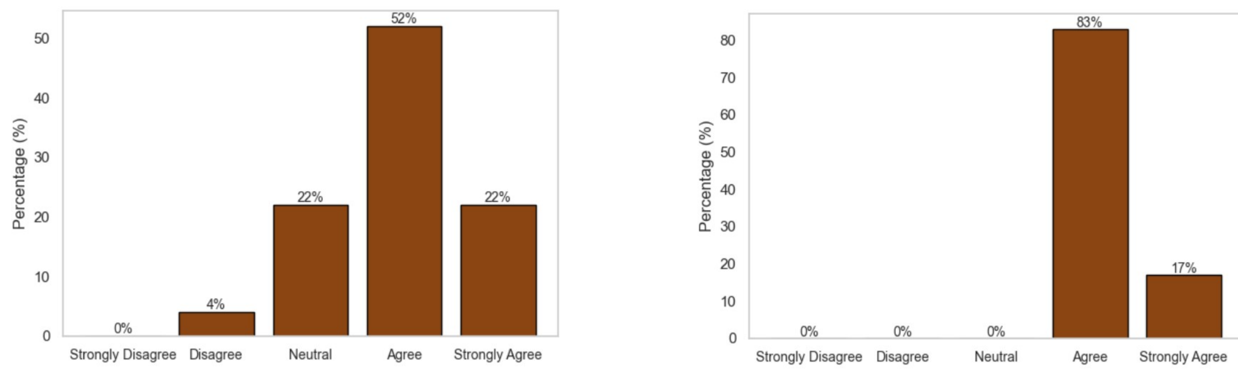
The suggestions derived from students' feedback provide valuable insights for refining future iterations of the concept map assignment. Implementing these recommendations can improve the assignment by aligning it more closely with the course's learning objectives and making it more effective in reinforcing course content and connections.



(a)

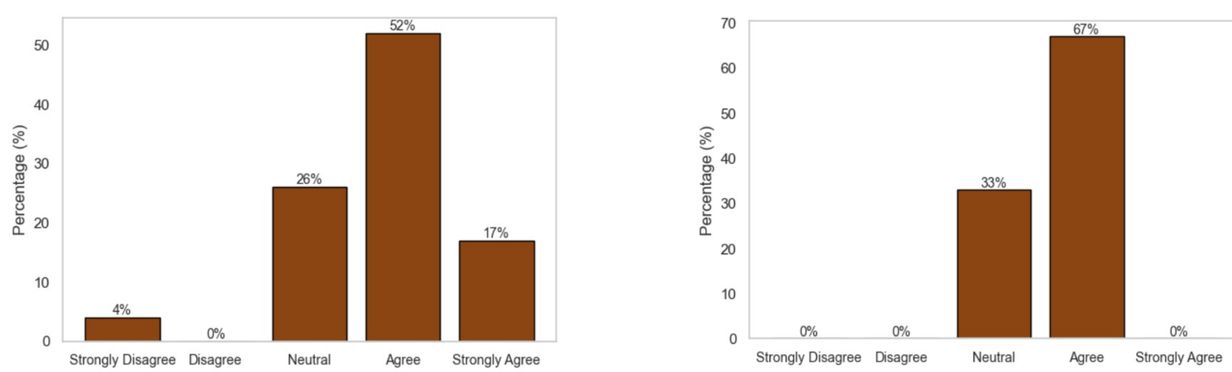
(b)

Figure 4: Correlation analysis between the concept map score, its components and the course grade



(a) (b)

Figure 5: Student perceptions of concept maps as a tool for making connections between topics. (a) Undergraduate level courses (b) Cross-level undergraduate and graduate course.



(a) (b)

Figure 6: Student perceptions of concept maps as a tool for knowledge application. (a) Undergraduate level courses (b) Cross-level undergraduate and graduate course.

Conclusion

This work integrates both quantitative and qualitative data to provide a comprehensive understanding of the impact of concept maps on student learning, engagement, and satisfaction. The findings reveal that while no correlation was observed between students' course grades and their concept map scores, survey feedback highlighted the positive influence of concept maps on learning, particularly in fostering connections between ideas and improving the application of knowledge. This suggests that concept maps can serve as an effective tool for improving higher-order thinking skills, though traditional scoring methods may not fully capture their educational impact.

A primary limitation of this study was the small sample size of 31 students, which restricts the generalization of the findings. Additionally, the GPT model used for analysis was not trained on domain-specific data, potentially limiting the depth of insights derived from qualitative analysis. Future research should explore alternative methods for assessing the educational impact of concept maps, moving beyond traditional scoring approach to more nuanced techniques that better capture their benefits. Expanding the sample size to include a more diverse and representative student population will improve the reliability of findings. Furthermore, integrating domain-specific training for GPT models or other analysis tools could provide deeper insights into how concept maps influence learning. Finally, iterative refinements to the concept map assignment, guided by student feedback, will help ensure alignment with course objectives and maximize their potential to improve student learning outcomes.

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