Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025 ASEE
Paper ID #46287

The Development of Concept-Space, a Digital Workspace that Mirrors How the Brain Organizes and Expands Knowledge, Reveals Positive Impacts for Learners, Teamwork and Teachers

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1. Introduction

A tool that facilitates effective communication of knowledge and ideas in a way that mimics how they are generated in the mind is likely to aid in accomplishing three key objectives: 1) enhancing learners' ability to comprehend and construct complex concepts, 2) facilitating the creation of a shared understanding among teams, and 3) aiding teachers in assessing the comprehension of their students and the orientation of their teams. This idea started a research effort in 2010 to develop such a tool [1], which crystallized in 2020 into the principles of Concept-Space, a form of collaborative multi-dimensional mapping of knowledge. In 2022, the web platform relate.space was launched to make these advancements accessible and to further research in this innovative workspace.

This paper presents what Concept-Space is and how it came to be what it is. It then presents the results of two recent case studies in engineering. The first case study uses Concept-Space in the context of engineering capstone projects where Concept-Space provided a collaborative workspace for developing problem understanding, generating design requirements, developing concepts, analyzing them, and converging toward a final design. The second case study uses Concept-Space in a multidisciplinary entrepreneurial course that included engineering and business students. Concept-Space functioned both as a detailed portfolio to document individual work processes (graded) and as a team workspace for developing an innovative technological product for a valuable market. Before diving into these case studies, we will first examine Concept-Space itself and how its design draws from multiple properties of mental structures.

2. Description and Foundations of Concept-Space

Concept-Space was developed through a design process. It started with a comprehensive exploration of available data from various domains and a synthesis of this information into a framework that was used to define a set of design requirements. This phase was followed by four iterations of design, prototype, pilot study (with engineering students), analysis, communications and redesign [2]. Through these iterations, the work converged in 2020 to a visual system of knowledge organization named Concept-Space. The name is related to concept map [3], but "map" implies a two-dimensional canvas, while "space" is not limited to two dimensions and is used to imply extra dimensions. Figure 1 shows how Concept-Space represents concepts as expandable named boxes and relations between concepts by one of three visual means: a) by arrows with linking phrases, like in concept maps; b) by making a concept be contained inside the space of a parent concept, and c) by attaching concept on the border of a concept. The following section explains how concepts of Concept-Space are designed to represent

manipulable units of thought, how each relation representation is used to convey specific types of frequent semantic relation, and how collaboration and creation are considered as fundamental building blocks of the system. Design knowledge is often organized in logbooks, communication platforms, or through folders and files. However, these methods can make it difficult to maintain a clear, interconnected view of a complex project. Concept-Space addresses this challenge by providing a hierarchical structure that interconnects thousands of pieces of information while maintaining a continuous, high-level overview. It combines the flexibility of a digital logbook with a structured visual organization that enhances comprehension, ensuring that users can navigate and understand the full scope of their knowledge at all times.

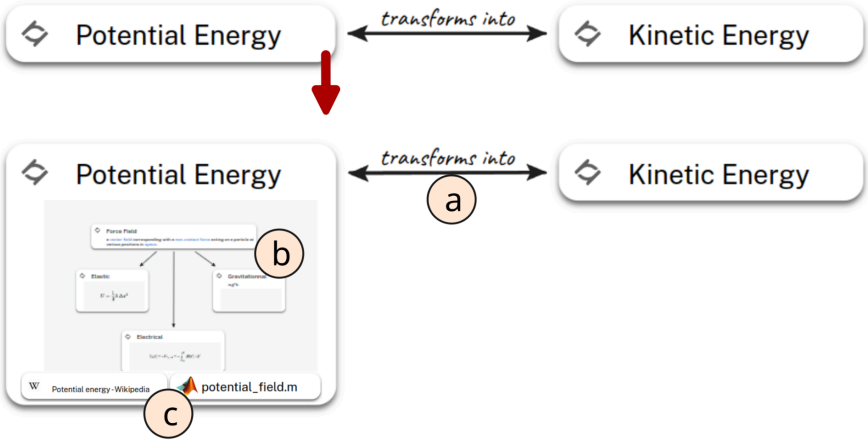

Figure 1: three constituents of Concept-Space

2.1 Concept as a reusable unit of thought

A concept is a reusable abstraction that our brain manipulates to process information. Its details are accessed as needed during mental processes. Concept-Space supports these critical properties with two key mechanisms:

Concept expansion. This is the most distinctive feature of Concept-Space. As illustrated in Figure 1 by the red arrow, any concept can be expanded by dragging its lower-left corner, opening a space to elaborate a more specific Concept-Space. This creates a hierarchical and recursive structure, naturally organizing information from generic to specific. Navigation through these layers is achieved by zooming in, similar to Google Maps. When zooming in, you enter a new level of abstraction, unlocking an infinite Concept-Space specific to that level. The levels traversed are tracked in a breadcrumb trail. This ability to maintain a high-level understanding before diving into details is a key distinction between expert and novice knowledge structures [4]. Moreover, this structure aligns with the natural way humans categorize information into levels of abstraction.

Instantiation of concepts. This is the mechanism that allows the reuse of concepts in various contexts and keeps all its more specific content synchronized. This mechanism turns a concept into a manipulable chunk of information that can be connected in different ways and used in different contexts. In knowledge construction, instantiation allows prior learning to connect seamlessly with new learning by reusing it within the new learning space. Moreover, the learner can view all contexts where a concept is used.

2.2 Relations Representations

Knowledge is built on the relationships between concepts. While concept maps typically use linking phrases, Concept-Space incorporates these and other forms of relational representation. Fauconnier and Turner's [5] vital relations—frequently used relations to connect concepts and form knowledge—are represented in Concept-Space through diverse visual mechanisms, minimizing reliance on arrows. The parenthood of a concept, a concept being inside another concept, expresses the relations of "part-whole" or "categories". The "role" relation is represented by the avatar of a person attached to the side of a concept. The "temporal" relations are available in a timeline representation. "Identity" relation is expressed by using an instance in multiple places. "Similarity" relations can use spatial proximity and grouping. Finally, other relations, such as causality or other less general relations use arrows with linking phrases.

2.3 Collaborative Space for Shared Understanding

An important aspect of knowledge construction and design is the place of the community in the process. This is an essential aspect of Vigotsky's activity theory [6], which is the framework found to best synthesize theories and models from the variety of fields that informed the design of Concept-Space. Concept-Space serves as a collaborative environment where shared understanding can flourish. It supports teamwork, teacher feedback, and assessment—essential components of learning and design. Collaboration is represented as a role relation, granting contributors or viewers access to the shared space. To foster social engagement and ensure up-to-date information, the platform uses real time updates.

2.4 Place for Working and Creating

Concept-Space was designed to support a wide range of work artifacts, aiming to serve as a comprehensive workspace for capturing the knowledge generated throughout a project. It offers an efficient alternative to the traditional engineering logbook [2] and for a form of e-portfolio. The platform accommodates various artifacts, including images, sketches, text editors, documents, videos, and web links. Additionally, it provides access to documents in OneDrive and GoogleDrive, making Concept-Space a central hub for constructing and interrelating all aspects of projects and knowledge.

3. Methodology

The objectives of this study are: (1) to validate the effectiveness of Concept-Space in supporting engineering design activities, (2) to analyze how students and instructors utilize Concept-Space for design processes and feedback mechanisms, and (3) to identify areas for enhancement of the platform. To address these objectives, two case studies were conducted, employing a mixed-methods research approach. The rationale for using a mixed-methods design stems from the need to capture both the breadth (quantitative data) and depth (qualitative insights) of users' experiences with the platform. The quantitative data from surveys provide measurable outcomes, while the qualitative data from interviews and focus groups allow for a deeper understanding of the students' and instructors' lived experiences and perceptions.

3.1 Study 1: Capstone Design Projects

The first case study was conducted within the context of capstone design projects at a Canadian engineering institution. These projects span the final three semesters of the undergraduate engineering curriculum, where teams of 5–8 students address a self-selected engineering problem through a structured design process. During the first semester, teams focus on generating design requirements, planning the project, developing and analyzing concepts, and prototyping initial solutions. Subsequent semesters emphasize detailed design, product realization, and validation through testing. Teams culminate their work with a public presentation. The projects are multidisciplinary, involving students from mechanical, electrical, robotics, and software engineering programs.

For this study, five teams used Concept-Space as their primary tool for managing the technical aspects of their projects, while the remaining teams utilized Microsoft OneNote. Faculty members, serving as coaches, provided weekly feedback and evaluation.

3.1.1 Data Collection

A mixed-method approach was used to collect both quantitative and qualitative data:

Student Questionnaires: Students completed a survey assessing their perceptions of Concept-Space's utility in enhancing three core graduate attributes as defined by the Canadian Engineering Accreditation Board (CEAB) [7], which is comparable to the USA's ABET: (a) design, (b) individual and teamwork, and (c) communication skills. Responses were recorded using a 5-point Likert scale. The survey instrument is detailed in Appendix 1.

Focus Groups: Semi-structured focus group discussions were conducted with each team following the survey. These sessions, lasting approximately 30 minutes, explored participants' experiences with Concept-Space, including strengths and areas for improvement.

Instructor Questionnaires and Interviews: Faculty mentors completed a questionnaire assessing Concept-Space's utility in supporting their instructional roles, including coaching (imparting technical and professional knowledge), protecting (minimizing student failure risks), and providing exposure (facilitating iterative feedback). These roles are derived from a functional taxonomy of design teaching [8]. Individual interviews, lasting approximately 20 minutes, provided additional qualitative insights. The survey instrument is detailed in Appendix 2.

3.1.2 Data Analysis

Quantitative survey data were analyzed descriptively, with Likert-scale responses summarized to identify trends in student and instructor perceptions. Qualitative data from focus groups and interviews were analyzed using thematic analysis. An initial coding framework was informed by the survey instruments, but the analysis also employed inductive methods to capture latent themes and emergent insights.

3.2 Study 2: Innovative Product Development Course

The second case study examined Concept-Space's application in a multidisciplinary course on innovative product development. This six-credit course emphasizes high-impact practices (HIPs), requiring students to work collaboratively in teams to identify real-world problems, engage with stakeholders, and develop technological solutions with market potential. The course concludes with a pitch competition judged by industry experts.

In 2022, one voluntary team of 12 students (10 engineering students and 2 business students) utilized Concept-Space as their primary tool for project documentation and collaboration. This replaced the standard OneNote system used by other teams. The team was tasked with maintaining detailed logs of their work, including stakeholder interviews, concept development, and prototyping. The primary goal of this study was to evaluate the platform’s effectiveness and readiness in supporting dynamic, multidisciplinary, and collaborative activities.

Subsequent to the 2022 study, Concept-Space was adopted for the entire course in 2023 and 2024, involving approximately 200 students each year. However, ethics approval was not obtained for these later iterations, so only general outcomes are reported for these years.

3.2.1 Data Collection

Teaching Assistant Interviews: A teaching assistant responsible for evaluating student work provided qualitative feedback through mid-semester and end-of-semester interviews. These interviews focused on Concept-Space's utility in supporting documentation and assessment.

Student Feedback: Four students from the team conducted peer interviews and provided insights into their experiences with Concept-Space as a collaborative tool.

3.2.2 Data Analysis

Thematic analysis was employed to evaluate qualitative data obtained from teaching assistant and student interviews. The analysis aimed to identify recurring strengths and limitations of the platform, as well as opportunities for improvement. Observational data derived from project evaluations provided additional context to the findings and helped validate themes identified during the analysis.

4. Results

4.1 Results from Students in Capstone Design Projects

Out of the 30 students, 26 completed the anonymous questionnaires and participated in the focus group. The results section is structured into separate sections, each corresponding to the graduate attribute that was the focus of the study.

4.1.1 Design

The perceived usefulness of Concept-Space for aspects of design is shown in figure 2. In general, students acknowledge that Concept-Space has been beneficial in enhancing their design capabilities. Eighty-five percent of students found that working with Concept-Space provided a global and coherent vision of their project, and 95% found that it helped them organize information. Half the students found that it helped in relating stakeholders' needs with requirements. Ninety-five percent also found it to help develop a complete and detailed solution. Sixty percent found that it helped develop solutions in parallel.

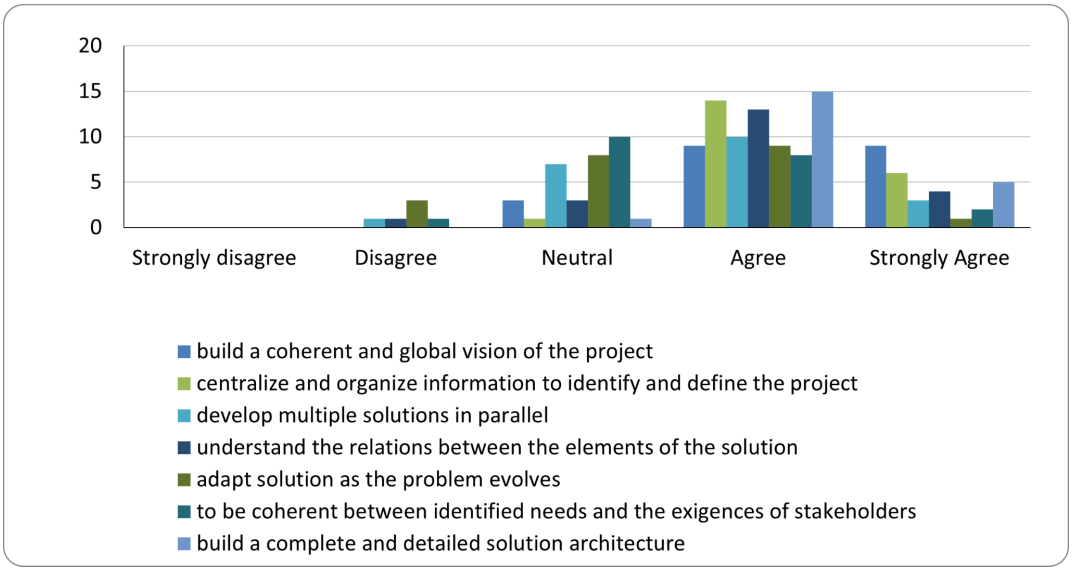

Figure 2: Results of perceived helpfulness of Concept-Space for various aspects of Design

The focus group frequently supported the quality of the visual organization. It was mentioned that as the project grows in size, navigation through the space is not enough to find precise information and search functionality or bookmarks would help. For some, Concept-Space forced them to better organize information, which was an extra effort, mostly at first. Some mentioned that it helped them understand the problems they were trying to resolve. It was also pointed out that the system was flexible, which allowed it to iterate rapidly. Figure 3 shows the Concept-Space of a team working on a CrossKart. More precisely, this view is the Concept-Space after navigating in the concept “Architecture” and provides students and teachers with an overview of all the parts of the CrossKart. Each part can be zoomed in to navigate in the detailed concepts and analysis made for each part.

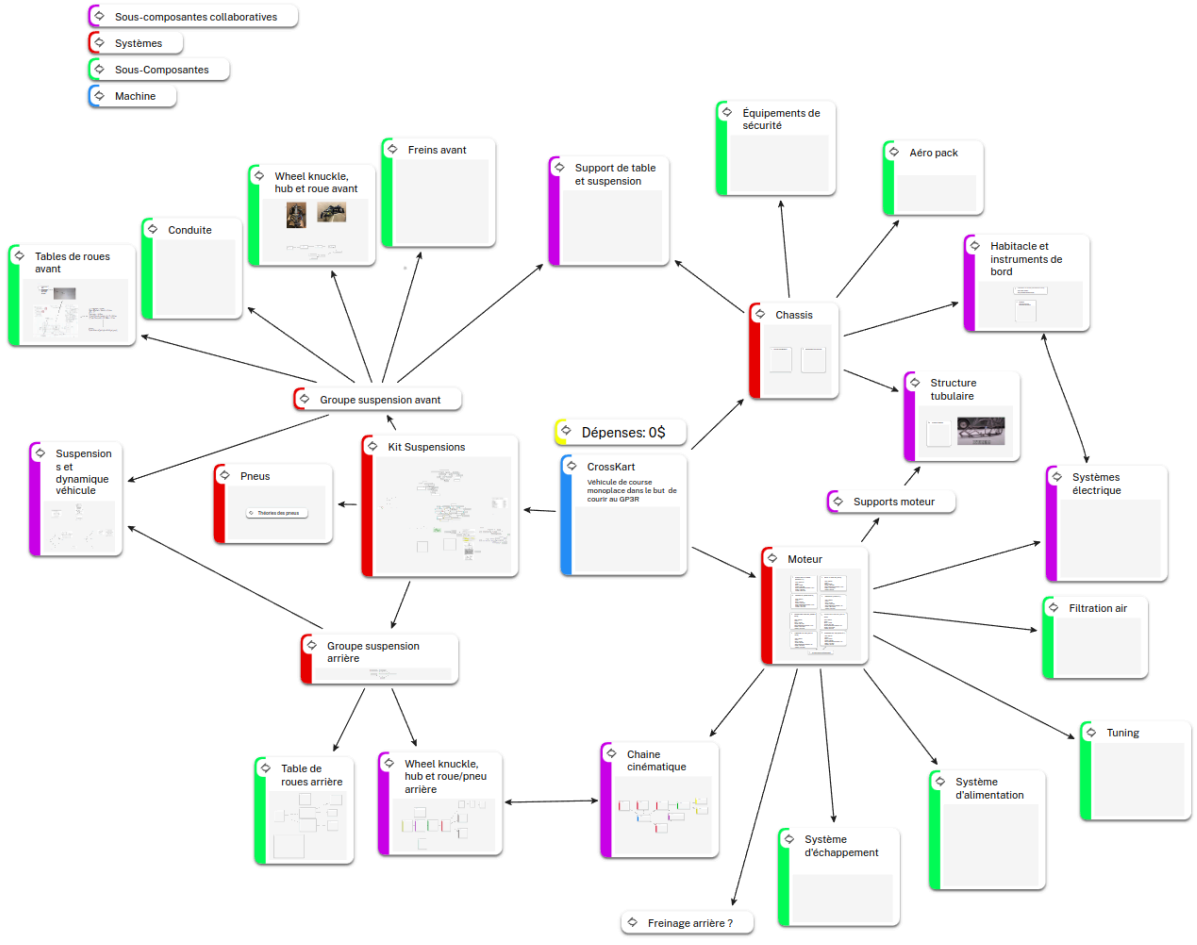

Figure 3: Part of a Concept-Space from a team working on a CrossKart project

4.1.2 Communication

Students generally agree that Concept-Space helps support communication of technical knowledge. The biggest improvement in communication was in sharing a common vision of the

project across the team, with 85% agreeing. Sixty-five percent found Concept-Space to support the transmission of complex engineering concepts. Fifty-three percent of students agreed that Concept-Space led to better feedback from teachers.

The focus group revealed that many used external software for drawing technical schematics. The boxes and lines of Concept-Space were not sufficient. Some proposed that a sketching feature would be a valuable addition to communicating ideas. For some students, the visual quality provided by the platform was not sufficient for use in reports, so it required some extra work to redraw information in a different tool. The visual strength for communicating the whole of a project was highlighted, for example, in sayings like "when [supervisor] arrived in the project, he looked quickly and right away he knew what we were doing", or "in OneNote, you don't see the project, but in Relate you really see the project and the big blocks".

4.1.3 Individual and Team Work

The perceived usefulness of Concept-Space for aspects of Teamwork is shown in figure 4. There is general agreement among students that Concept-Space supported individual and team work. Most significantly, 77% found that it helped them understand the links between domains of expertise, and 77% agreed that it improved the technical documentation of their project. This criterion could be classified under communication skills but was classified here because documentation was used to assess individual and team work. Forty-two percent agreed that the platform helped track the progress of their teammates.

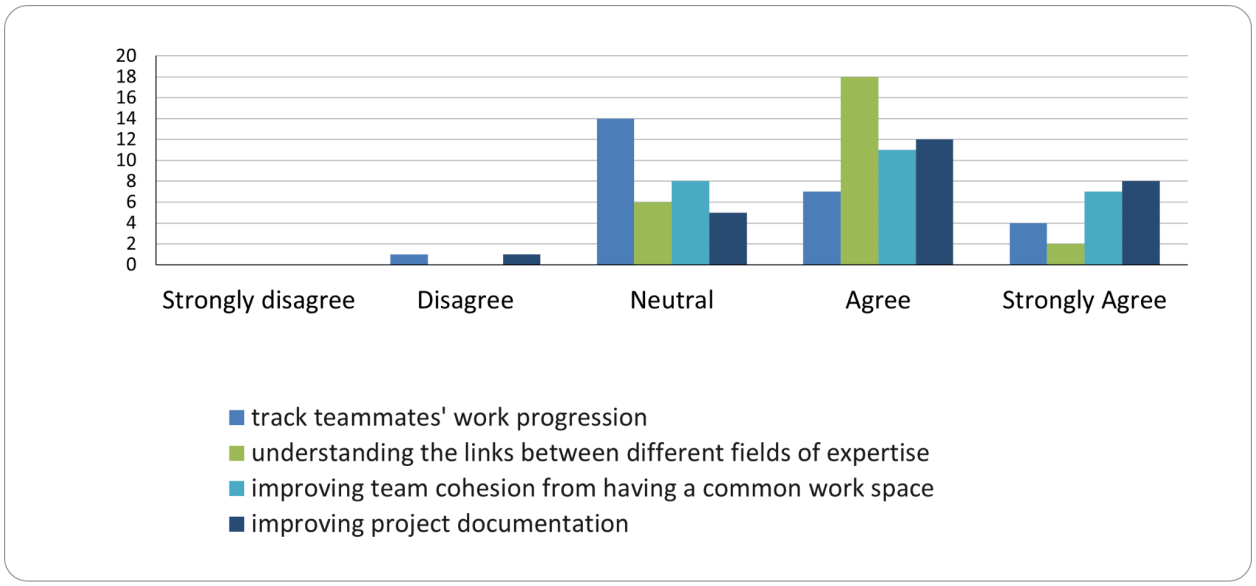

Figure 4: Results of perceived helpfulness of Concept-Space for various aspects of Teamwork

The platform used in this study was expected to provide a feature that would display the author of each piece of information, but the feature was not developed on time. Hence the low agreement about tracking the progress of teammates is unsurprising. Moreover, this feature was

requested multiple times in the interviews. This feature was available in the next case study. Students suggested that templates could offer an initial structure that could help everyone organize information properly from the beginning.

4.2 Results from Teachers in Capstone Design Projects

Six teachers completed the survey and the interview. Figure 5 shows the result of the questionnaire. All teachers agreed that Concept-Space helped obtain a complete portrayal of all parts in every discipline and 71% found that it helped ask the right questions. Seventy-one percent also found that it helped provide students with adequate feedback and guidance. All teachers agreed that the system simplified the access to the design work of teams. On a final question, not provided in the figure, all teachers agreed that Concept-Space is beneficial to teaching engineering capstone projects.

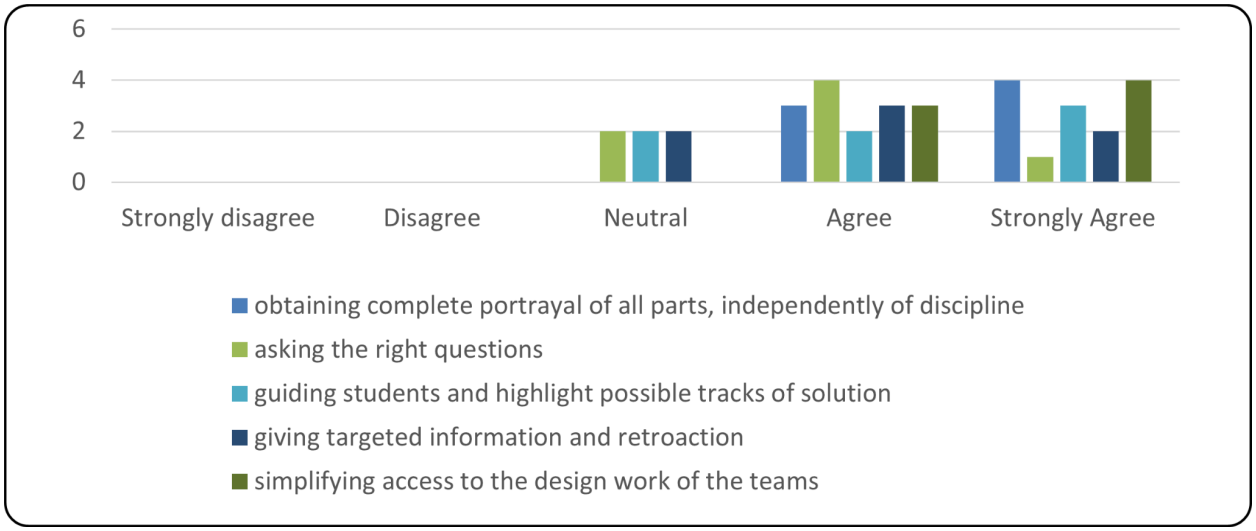

Figure 5: Results of perceived helpfulness of Concept-Space for various aspects of teaching

The interviews confirmed that Concept-Space is efficient to understand the work of students. There was also discussion about reducing the workload of students by removing the need to build PowerPoint presentations and using the platform to present technical work. However, there was also a complaint by one teacher that the look was not quite professional and esthetic enough for such use. Some pointed out that the way teams have used it has an impact on the ease of assessment. Some features were also requested, such as a search feature, a way to visualize what had changed in time, mostly since the last visit, and more technical tools that would be included in the students' space.

4.3 Results from the Innovative product development course

4.3.1 Student Feedback

Students reported a generally positive experience with Concept-Space, particularly highlighting its utility for collaborative work. The platform facilitated team-wide transparency, enabling members to track contributions and understand the progress made by others. One participant noted that Concept-Space reflected their thought process, though they acknowledged it might be less intuitive for individuals who prefer linear workflows. However, a critical issue emerged early in the case study: a software error during concurrent editing of the same text box led to data loss for some students. This significantly impacted user confidence and was frequently mentioned during interviews. Additionally, students suggested several feature enhancements, such as the ability to move multiple concepts simultaneously and the option to protect specific concepts from further edits.

4.3.2 Teaching Assistant Feedback

The teaching assistant responsible for project evaluation found Concept-Space to be more efficient than OneNote for grading. The real-time collaborative features of Concept-Space eliminated the need for document submissions, which mitigated common issues such as late entries and corrupted files. This was identified as a key advantage over traditional tools.

4.3.3 Survey Results

An anonymous survey was conducted to compare student preferences for Concept-Space versus OneNote. Ten out of twelve students preferred Concept-Space, citing its collaborative capabilities and intuitive interface. Based on this feedback, it was decided to implement Concept-Space as the primary platform for subsequent iterations of the course.

4.3.4 Subsequent Improvements and Large-Scale Adoption

Feedback from the 2022 cohort directly informed platform enhancements prior to the 2023 academic year. Key updates included addressing the concurrent editing issue, introducing functionality for bulk concept manipulation, and implementing additional safeguards for concept protection. The first half of the 2023 semester revealed additional areas for refinement, particularly in managing increased platform activity during deadline peaks. These issues were promptly addressed, and the platform's performance in the second half of the semester demonstrated its readiness to support large-scale adoption. In 2023 and 2024, the project expanded to include all 200 students per cohort, with Concept-Space effectively supporting collaboration among students, teachers, and teaching assistants in a highly dynamic environment.

5. Conclusions

Concept-Space is an innovative system designed to facilitate knowledge organization and collaborative work, enhancing the ability to communicate complex ideas and mental constructs effectively. Developed through 12 years of research with a primary focus on engineering design activities, Concept-Space has been implemented as a web platform, Relate, to bring these advancements to a broader audience.

This paper presents findings from recent studies on Concept-Space, including its application in engineering capstone projects and a multidisciplinary entrepreneurship course combining engineering and business students. Results demonstrate that students perceive significant benefits from using Concept-Space in terms of supporting engineering design, fostering effective teamwork, and enabling clear communication. In particular, the platform's ability to organize knowledge hierarchically, its flexibility in developing and connecting ideas, and its high-level visualization tools received strong positive feedback.

Beyond collaborative projects, Concept-Space opens doors to various educational and research opportunities. For example, recent research initiatives explore its use as a personal tool for engineering students to interconnect theoretical and practical learning throughout their academic journey.By introducing Concept-Space in the first year, students gain a structured way to organize and revisit key concepts, reinforcing knowledge retention and deepening their understanding. This system can also support academic assessment by providing a clear, interconnected view of a student’s learning progression. Additionally, the system shows promise in research laboratories for improving knowledge transfer and collaboration and as a tool for building curricula. One project for 2025 will focus on integrating AI to speed up information entry and improve knowledge reuse.

To encourage further research, the Relate.Space platform and accompanying tutorials are freely available to the academic community at https://relate.space

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Appendix 1: Questionnaire for students of study 1

Données démographiques (demographic data)

- Vous êtes dans quel programme? (Which program are you in?)
- Êtes-vous dans une équipe multidisciplinaire? (Are you in a multidisciplinary team?)

The scale used for the rest of the questionnaire is as follows:

- ☐ Totalement en désaccord (Strongly disagree)
- ☐ En désaccord (Disagree)
- ☐ Neutre (Neutral)
- ☐ En accord (Agree)
- ☐ Totalement en accord (Strongly agree)

Section sur la conception (Section on design)

Utiliser les espaces conceptuels m'a aidé à … (Using Concept-Space has helped me to…)

- avoir une vision globale cohérente de mon projet (gain a coherent global vision of my project)
- rassembler et organiser de l'information (fichier, image, texte, liens) afin d'identifier le problème et définir le projet (gather and organize information (files, images, text, links) to identify the problem and define the project)
- faire évoluer plusieurs solutions en parallèle (develop multiple solutions in parallel)
- comprendre les liens entre les différents éléments de la solution (understand the connections between different elements of the solution)
- adapter une solution en réponse à l'évolution du problème (adapt a solution in response to the evolution of the problem)
- être cohérent entre les besoins identifiés et les exigences des parties prenantes (ensure consistency between identified needs and stakeholder requirements)
- faire une définition complète et détaillée de l'architecture de la solution (create a complete and detailed definition of the solution’s architecture)

Section sur la communication (Section on communication)

Utiliser les espaces conceptuels m'a aidé à… (Using Concept-Space has helped me to…)

- avoir une vision claire et commune de notre projet (have a clear and shared vision of our project)

- efficacement représenter et transmettre des concepts d'ingénierie complexes (effectively represent and communicate complex engineering concepts)
- obtenir des rétroactions du corps professoral (receive feedback from faculty)
- ouvrir un accès à des intervenants externes pour voir notre documentation (provide external stakeholders with access to our documentation)

Section sur le travail individuel et en équipe (Section on individual and team work)

Utiliser les espaces conceptuels m'a aidé à… (Using Concept-Space has helped me to…)

- suivre la progression du travail de chacun (track the progress of each team member's work)
- comprendre les liens entre les différents domaines d'expertise (understand the connections between different areas of expertise)
- avoir une meilleure cohésion d'équipe en rassemblant le travail de chacun dans un espace commun (improve team cohesion by bringing everyone's work together in a shared space)
- mieux documenter le projet (better document the project)

Appendix 2: Questionnaire for teachers of study 1

The scale used for the entire questionnaire is as follows:

- ☐ Totalement en désaccord (Strongly disagree)
- ☐ En désaccord (Disagree)
- ☐ Neutre (Neutral)
- ☐ En accord (Agree)
- ☐ Totalement en accord (Strongly agree)

Les espaces conceptuels sont avantageux pour… (Concept-Space is beneficial for…)

- obtenir un portrait clair et complet de tous les éléments du projet, indépendamment des disciplines (obtaining a clear and comprehensive overview of all project elements, regardless of discipline)
- poser les bonnes questions pour aider les étudiants à cheminer (asking the right questions to help students progress)
- guider les étudiants et offrir des pistes de solution (guiding students and providing solution pathways)
- transmettre de l'information et des rétroactions ciblées (conveying information and providing targeted feedback)

- accéder facilement aux travaux de conception des équipes (easily accessing teams’ design work)
- L'utilisation d'espaces conceptuelles est un atout pour l'enseignement dans les projets majeurs de conception (The use of Concept-Space is an asset for teaching in major design projects)