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Conceptual Modeling Enables Systems Thinking in Sustainable Chemistry and Chemical Engineering

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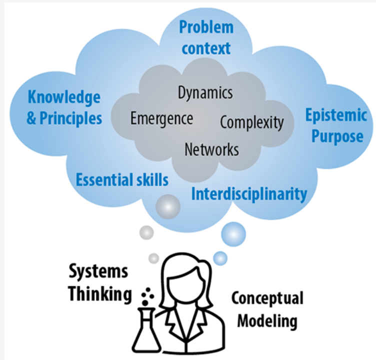
ABSTRACT: This study aims to equip students with conceptual modeling skills to address compelling 21st-century challenges in chemistry and chemical engineering education. System-based concept mapping is a critical competence for analyzing global, often complex, problems. We examined how conceptual modeling could scaffold practical experimental design, transitioning from problem identification to testable hypotheses. We set up a project in which first-year undergraduates in chemical engineering work in groups of 5–6 students. Their task was to develop concrete hypotheses for assignments that center on finding sustainable solutions for polluted environments. A set of educational roles (i.e., lecturers, tutors, learning assistants, educational specialist, and project coordinator) were implemented to ensure that students could accomplish their main learning outcome; that is, to become familiar with the academic way of thinking and apply critical thinking skills as a team. Interviews were conducted after the project was finished and revealed that, while conceptual modeling helped students to structure their ideas (i.e., to learn how to design research questions, incorporate interventions, and test models), developing hypotheses remains a challenging task. Our findings brought us to the recommendations for teaching conceptual modeling in the curriculum rather than at the project level, allowing students to progressively transition from understanding and applying concept mapping in their first year into creating solutions within the context of solving complex real-world problems in the final year of their bachelor's degree. The collaborative learning environment and project format employed in this work could spark new ways to teach science that facilitates systems thinking in chemistry.



KEYWORDS: *Introductory Chemistry, Chemical Engineering, First-Year Undergraduate/General, Conceptual Modeling, Systems Thinking, Systems Chemistry*

1. INTRODUCTION

1.1. Complexity of Global Problems Requires New Ways to Teach Chemistry

Education of grand challenges of the 21st Century (e.g., the ambitious targets in sustainability outlined by the United Nations) requires skills in investigating and understanding interactions between a system and its environment, including the human components therein.[1,2] Addressing these global issues such as ecosystems, diverse life forms, urban areas, and climate dynamics demands a focus on complex systems.[3] Chemistry offers great potential for tackling these global, often complex, problems,[4] as it is a discipline that facilitates a range of methods, varying from organic (e.g., the synthesis of relevant molecular structures) to analytical (e.g., the development of experimental methods) to physical chemistry (e.g., the design and elaboration of mechanisms that govern the systems' dynamics).[5] Advances in the past two decades, particularly in systems chemistry,[6] demonstrate that this "flexibility" has enabled important findings in the domain of autonomous molecular materials,[7,8] out-of-equilibrium chemistry,[9−12] and more generally understanding natural phenomena with an apparent complexity.[13,14]

Complex systems consist of various interacting parts, where the collective behavior of those parts together is more than the sum of their individual behaviors,[15] which cannot be solved using the traditional reductionist approach.[16] However, our current teaching methods for students in higher education (bachelor, master, and Ph.D. level alike) remain grounded in the 19th century, teacher-centered, style of instructing.[17] We need innovative and student-centered approaches to teach chemists to think in terms of systems, leveraging the interdisciplinary nature of chemistry as a "central science" to address real-world environmental challenges.[4]

This paper is targeted at chemistry teachers, as their curriculum involves conceptualizing phenomena that are derived from many different directions (including but not limited to engineering, physics, and biology). Organizational

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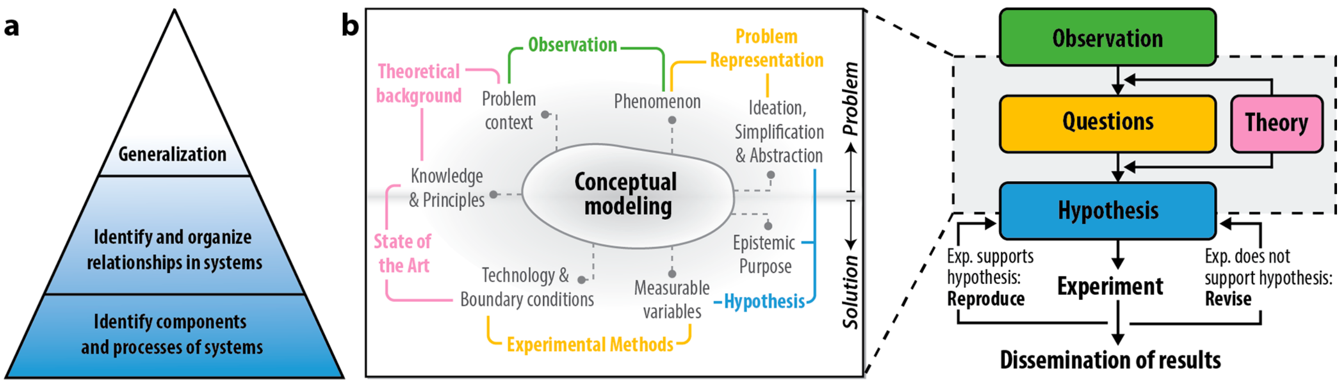

Figure 1. A conceptual model integrates the systems thinking (ST) model with the classical hypothesis-deductive model. (a) A simplified model for systems thinking with a focus on identifying components and their relationships in order to understand (or generalize) a system from a holistic viewpoint (Adapted from ref 19, Copyright 2019 American Chemical Society). (b) The conceptual model[25] as an interconnected approach with a focus on synthesizing questions required for transitioning from an observation of a phenomenon to a hypothesis which can be placed in the standard scientific process scheme.[35]

frameworks have been developed for learning concepts in so-called systems thinking (ST) (Figure 1a).[18,19] Such a framework promises a teaching perspective to increase the reasoning ability of chemistry and chemical-engineering students and impacts what students focus on in learning, their way of conducting research, and their understanding of scientific concepts that are difficult to disentangle otherwise.[20] Chemistry-relevant applications of ST skills involve:[21] (i) examining the behavior of a system as a whole, as opposed to the behaviors of the parts of a system, and (ii) considering the ways in which two system-relevant variables affect each other (as in closed loops), as opposed to how one variable affects the other (as in linear chains). Crucially, however, empirical studies on the implementation of ST in chemistry education are lacking.[22]

1.2. Conceptual Modeling in Chemical Sciences Education

To guide and scaffold ST in chemistry education, we looked for methods that promote concept-related thinking.[23] Conceptual modeling (CM)[24,25] is one such method that focuses on the reasoning ability of scientists. Akin to other established methods that focus on essential critical thinking skills[26] and project intensification,[27] it can be used for the purpose of collaborative problem solving.[1] Through iterations, a conceptual model becomes a hub in which aspects can be brought together to represent the scientific concept, i.e., the problem and its solution (Figure 1b). Importantly, this method entails the construction of models that represent a system and its components, allowing students to understand the interrelationships among various system components and how they work together.

Recent developments in educational research suggest that systems thinking abilities can be developed through concept mapping,[28,29] provided that students are guided to focus and reflect on specific systems thinking skills.[30] The action of mapping in the perspective of CM involves essential characteristics in the "way of reasoning", taking into account the relationship between systems and other approaches in chemistry,[29] which is an important academic skill that we wish to promote in our education.[31] For context, our Chemical Science & Engineering (CSE) bachelor program at the University of Twente (Enschede, The Netherlands) comprises in total 12 "modules", spread over three years. Each module has its own topic and focuses on the development of a specific set of knowledge, skills, and learning attitude according to competence areas required for a research-university grade in chemistry. In this frame, project-based learning is regularly applied[32] and organized according to the five phases of an inquiry cycle:[33] (i) orientation, (ii) conceptualization, (iii) investigation, (iv) conclusion, and (v) discussion. Acknowledging the potential complexity of systems thinking that first-year bachelor students may encounter, we prioritize providing prior instruction in conceptual modeling theories to establish a solid theoretical foundation for the students before they embark on their projects. Further, we facilitate a stimulating learning environment by training and employing learning assistants (LAs, i.e., trained, senior CSE students) who can guide junior students in the project. The LAs play a pivotal role in making sure that students remain motivated throughout the project by actively coaching students in their group work. We experienced that students (unintentionally) skip an important phase in the inquiry cycle: conceptualization. As a consequence, they iterate similar solutions whereas radical new solutions are required to address the grand challenges.

Specifically for the context of CSE, CM can be used as a methodology to focus on scientific reasoning for the purpose of designing experiments. In this view, CM was first introduced at the end of the first year in 2021, integrated with courses in electrochemistry.[34] Students were given the task to propose and carry out experiments to understand how an electrochemical cell works in a project lab assignment. Students and teaching staff, however, both expressed concerns that the introduction of CM (requiring the students to develop a hypothesis for experiments) and a practical course (requiring the students to execute the designed experiments) simultaneously led to a reduced understanding of the learning outcomes for both objectives. Given this challenge, we now question: *How can we leverage conceptual modeling to enhance the existing CSE curriculum to effectively teach systems thinking?*

1.3. Approach

We introduced CM as part of a project assignment in the first module.[36] The general learning outcome for this project is to allow students to become familiar with the academic way of thinking and apply critical thinking skills as a team. The project focuses on how students can critically assess information, discuss reasoning, identify criteria, and formulate a research question in order to create an accurate representation of a relevant societal problem and, in the end, to propose (a direction for) a solution.

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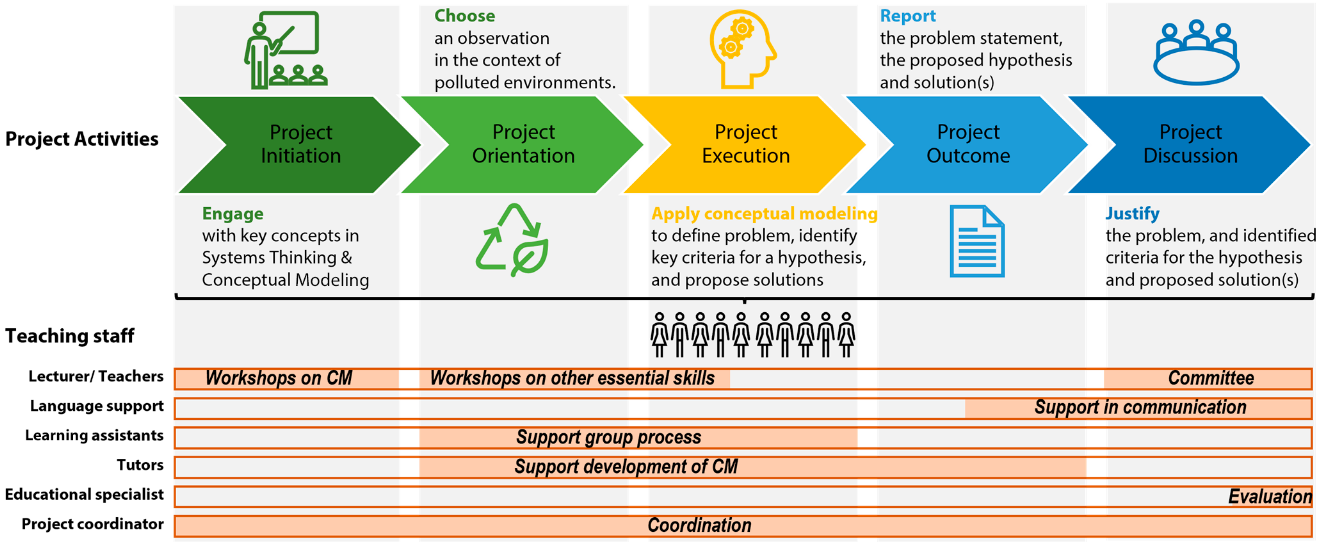

Figure 2. General project activities and learning objectives in the project. Project activities are divided in five general milestones, and the teaching staff involved in each milestone is indicated below in the bar chart. Details of the timeline and assessments are provided in Figure S1.

The assessment in this project is, thus, based on the concrete products of conceptual modeling.

To setup this project, our approach starts from identifying the crucial requirements in the ST model (Figure 1a) and use CM to integrate it with the classical deductive reasoning[37] (Figure 1b). CM from the original, philosophical standpoint emphasizes "key aspects" (indicated in gray): the process of ideation, formulation of the so-called epistemic purpose, sketch of the problem context, and definition of what can be accounted for as relevant knowledge, among others.[25] We clustered these aspects into well-established and widely used terms: observation, theoretical background, experimental method, state of the art, problem representation(s), and hypothesis. This intervention aims to ensure students apply CM according to its principles: an effective framework for constructing models that allows students to learn how to design interferences and develop hypotheses in a systematic manner.

In greater detail, the CM is developed by a project called "Systems thinking in sustainable chemistry". The project centers around a mandatory group assignment and aims to find sustainable solutions for polluted environments. We assembled a teaching staff to guide the project activities as well as organized workshops to develop the students' essential skills (Figure 2). The teaching staff includes a project coordinator (or a preceptor) who oversees the process from conceptualization to preparation to evaluation (see Methods and Protocols), an educational consultant who evaluates the application of CM, lecturers in essential skills, and finally tutors (experienced researchers with a Ph.D. degree in chemistry and a permanent position at our university) and the learning assistants (LAs, senior students with extensive didactical training and experience in CSE projects) who guide the execution of the project. The activities of the project are organized as follows:

- **Project initiation.** The project started with a workshop on conceptual modeling, wherein the project assignment was first introduced by a lecturer. The learning objectives of the introductory workshop are to understand the context of conceptual modeling and to become acquainted with chemistry-related problem examples in society and possible routes for developing a hypothesis. In addition, to mimic the conditions expected during the execution of the project, the workshop provided the first setting for the students to work in groups. They practiced how to conceptualize a problem and develop a solution (see Methods and Protocols). At the end of the workshop on conceptual modeling, three project themes were introduced, namely. find solutions to (i) perfluoroalkyl chemicals (PFAS) in the environment, (ii) heavy metals in water, and (iii) methane emissions from waste dumps.
- **Project orientation.** The students were given two working days to choose their project topic. We reasoned that the topics (given in project initiation) involve general chemical processes with a large environmental impact[38,39] and that because of their topicality (i.e., all topics had been in the news in the months before the start of the term) these themes would appeal to the students. In addition, the scope of the project themes was broad, providing sufficient room for students to identify different problems. Alongside the orientation, workshops on effective meetings (focusing on teamwork), information skills (focusing on assessing and referring to literature), academic English (focusing on written communication), and presentation skills (focusing on oral communication) were organized to gradually develop the students' essential skills required for this project (and, more generally, for ST). Thus, students started with all options open, not thinking about practicalities yet thinking creatively in many directions. Upon their first tutor meeting, the scaffolding would start.
- **Project execution**. In this phase, the students learned to plan project-based work, meet effectively, work in a team in order to identify a problem, and propose solutions for a chosen sustainability topic. For the execution of the assignment, we divided the population of 48 students into collaborative project groups (comprising 5−6 students), with each group supported by two trained learning assistants (LAs) and one tutor. The tutors are tasked to discuss the propositions of the working groups and to help in creating further iterations of their conceptual models. The LAs are tasked to support the group process during the project of 10 weeks (for a list of specific tasks, see

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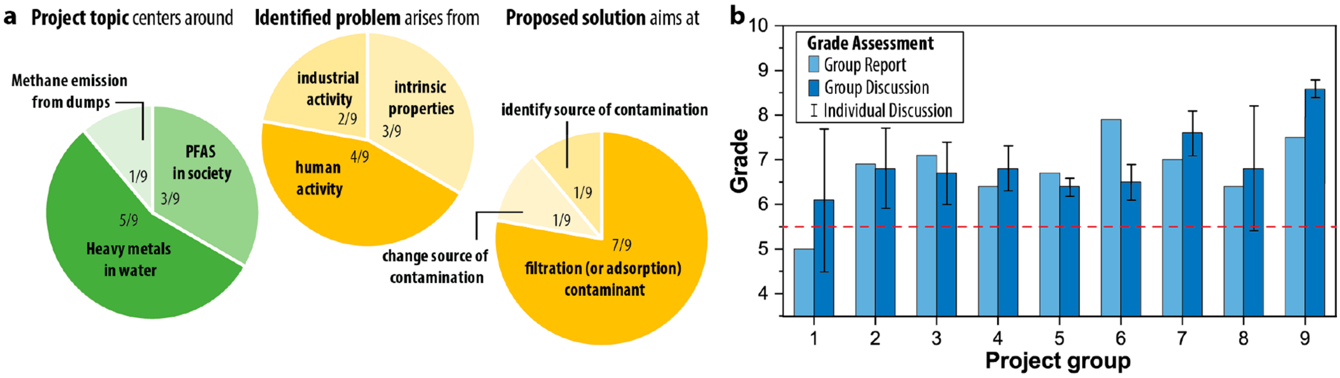

Figure 3. Project results. (a) Project observations. Summary of the problems and solutions in the project assignments, with the distributions in the topics, problems, and solutions based on student responses from 9 project groups (for details, see Table S5). (b) Project assessment. Summary of project grades, determined based on the assessment of the report and the additional discussion (for details, see Section S3.5). Grades are based on the Dutch grading system and range from a distinct fail (<3.5), fail (3.5−4.4), almost pass (4.5−5.4), pass (5.5−6.4), distinct pass (6.5−7.4), good (7.5−8.4), very good (8.5−9.4), and excellent (9.5−10). Red dashed line indicates the cutoff grade, 5.5. Deviation in the grades for discussion represents the distribution among students in a project group.

Table S1). In addition, the information specialist (one of the teachers) guided all project groups in searching literature (including documenting search activities, assessing quality of information, recognizing scientific papers, referencing, and avoiding plagiarism).

- **Project outcome.** The project is concluded with a group report, wherein we expect students to be able to
  - Write a report according to the general scientific method (Figure 1b), making use of their project journal. That is, the reports summarize the assignment, problem statement, proposed solution(s), and the resulting hypothesis (see Table S3).
  - Write a project journal, showing their first steps in CM, as a group. That is, the project journal (i.e., the appendix of the report) demonstrates how the problem statement as well as the solution evolved through the application of CM. Students are encouraged to make visual representations (drawings, mind maps, process schemes) to show their lines of thought and to use as starting points for their conceptual model.
  - Recognize and read scientific literature and discuss its validity (in written form) with respect to the research questions relevant to the chosen sustainability subject.
  - Be familiar with available sources, rules concerning plagiarism, and source acknowledgment and adopt a critical attitude toward literature.
- **Project discussion.** The inquiry cycle is completed with a discussion session, wherein students discussed their results with a committee comprising "external teachers" (teachers that were not involved as tutors). The committee assessed the ability of students (see Methods and Protocols) to
  - Demonstrate their results in an individual presentation, including the use of academic English.
  - Discuss the validity of chosen literature with respect to the research questions relevant to the chosen sustainability subject.
  - Justify the conception of their CM, their assumptions required for the hypothesis, and their solutions.
  - Apply theoretical knowledge to investigate a research question and supplement missing knowledge independently.
  - Show the ability to distinguish between results, discussion, and conclusions.

2. RESULTS AND DISCUSSION

2.1. Project Assessment

We asked nine groups of students to select a topic from three options. Only limited information was provided on the origin of the problem and possible hypothesis. Throughout the course of the project, the groups have worked on defining the problem, coming up with a solution, and developing a hypothesis for the possible experiments that one could design to test their ideas (Table S4). The majority of the groups (seven out of nine) accepted that pollution is part of our society and proposed to develop methods to filter harmful components, independent from the project topic (Figure 3). Only one group wished to investigate the nature of the problem and aimed to develop methods to map the extent and heterogeneity of polluted water. Another group focused on the conditions from which the problem originated and aimed to develop novel materials that are more environmentally friendly than those currently available. The observation that most groups aimed at similar types of solutions is most probably caused by the fact that the project topics revolved around pollution. This project assignment revealed that students can identify widespread problems in given settings or topics but arrive at only a limited number of types of solutions.

The tutors, the LAs, and the information specialist carried out an assessment of the reports as described in the assessment matrix (Table S2). We clustered the various criteria into three essential elements of a report:

- Information skills, i.e., the ability of students to search the relevant literature.
- Process, i.e., the ability of students to communicate and cooperate effectively with their group.
- Product, i.e., the ability of students to report a problem statement and the proposed solution(s).

Combined, these elements determine the average grade for the report (Figure 3b). In contrast to assessing the ability of

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students to search the relevant literature or communicate effectively with their group, we found that the product could not be adequately assessed according to our initial matrix (Table S6). Instead, rather than focusing on the detailed assessment criteria developed for this project, we organized an additional meeting wherein all tutors were present and collectively ranked the project groups with the criteria for the product taken in consideration. This intervention made it possible to identify the strengths and weaknesses of the project groups relative to each other and assign grades accordingly.

We then invited each group for a discussion with a committee comprising external (noninvolved) teachers to validate the ranking among the project groups. This validation includes an assessment of the individual contributions in each group. That is, the committee assessed the ability to justify the project outcome, by directing questions to a specific student and subsequently giving other students of the group the opportunity to add to or comment on the given answer. This discussion method allowed us to obtain an insight into students' understanding of the project based on the content of the topic, the level of justification, and knowledge of the identified criteria that led to the proposed hypothesis and solutions, as well as their communication skills. For instance, the report of one group was graded as an "almost pass", but the discussion showed a significant improvement for this group. As it turned out, there were two students in the group of five that performed insufficiently (which is represented by a grade below 5.4), resulting in a large deviation in the group. The discussion session thus allowed us to refine the grade of the project as well as determine individual deviations from the group performances and to provide grades for each student. The individual grades are presented in Table S7. The project was successfully finalized with 94% (45/48) of students passing with a final grade above the cutoff grade (5.5 or higher). We note that the project only accounts for a small portion for the entire first-year curriculum (specifically, 1.7 European Credits, 3% of the total credits required for the first year). Particularly for those who did not pass, the outcome of this project is meant to create awareness among the new generation of students that a different attitude is desired for an academic way of thinking (and acting). Not attaining a passing grade is intended as an essential moment for reflection, serving to motivate students to strive for improvement as they progress to the next phase in their bachelor program.

The average grade of the report and the discussion, 6.9 (Table S8), shows that students can successfully complete the intended learning outcomes of this project. As anticipated, some of the students required more time, experience, and support to fully grasp the essentials of CM. In greater detail, five among nine groups applied conceptual modeling according to its principles (Figure 4). These groups first acquired background information to understand the relevance of the topic and, subsequently, to organize their final conceptual model, they used intermediate steps to specify their search, find correlations between the phenomenon and different variables, and look for existing methods that one could use. The details are reported in Section S3.4, and with the exception of one group, they (thus, 4 out of 5 groups) successfully defined their hypothesis. Other project groups interpreted CM as a mind map for collecting information from their brainstorming sessions, indicating that they were less strong in critical thinking. While the mind-map interpretation could be equally useful for finding and discussing literature, as well as for sketching the problem context and formulating a research question, we found that the groups who used this mind-map approach experienced difficulties in establishing their hypothesis based on identifiable criteria. They, however, benefited from engaging with the committee in the project discussion.

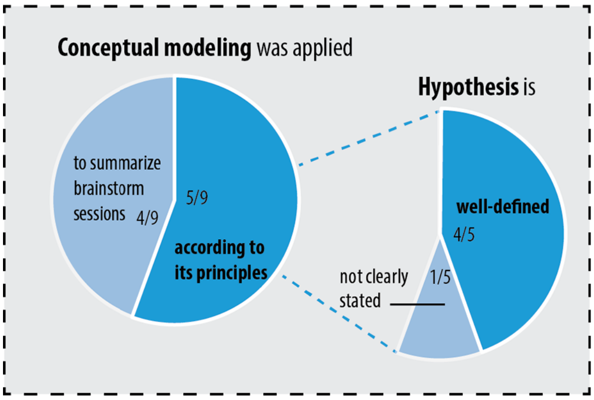

Figure 4. Application of conceptual modeling in the project. Summary of the CM applied and hypothesis developed with the distributions based on student responses from 9 project groups (for details, see Table S4).

2.2. Value of CM

To gain a deeper understanding of how conceptual modeling helped students develop their solutions in this project, we conducted semistructured interviews with a sample of students (n = 20) using an interview protocol described in Methods and Protocols. Before the interview, all students signed a consent form acknowledging their voluntary participation. Most of the students that were interviewed held a positive view of the incorporation of the conceptual-modeling approach to develop systems thinking in the first module of their bachelor program. They perceived that this approach provided them with a scientific method for "structuring ideas", "opening their minds", and avoiding premature commitment to solutions without considering other alternatives. They commented that the initial workshop and the opportunity to work on projects, specifically, aided them most in developing a concept-mapping approach.

Surprisingly, all of the interviewed students emphasized the value of collaborating with their peers in the mandatory group project. According to the students, their engagement in the group projects increased their motivation and openness to diverse perspectives, as they need to openly exchange ideas, actively discuss different opinions, and collaboratively reach a consensus. The students perceived the importance of this process in developing their systems thinking skills. They, however, also pointed out that CM could be perceived as somewhat abstract. They suggested that additional tutoring sessions, where they could receive more specific feedback, would be beneficial and have improved the applicability of the approach. As first-year undergraduates, they were more familiar with receiving direct help from teachers rather than being skilled in independent research and problem solving. In response, we evaluated our project with the LAs and our teaching staff on two occasions (during and after the project was finalized). Overall, tutors facilitated and supported students in finding the answers themselves, instead of providing (immediate) answers. We recognize the challenges faced by students and emphasize the importance of LAs and tutors having a sound knowledge of

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environmental chemistry concepts and conceptual modeling skills to effectively facilitate this advanced pedagogical approach.

2.3. Discussion

Our findings indicate that conceptual-modeling skills can be developed at the start of the first year in a university curriculum. While the students appreciated the concept-mapping approach and the associated learning activities to develop systems thinking, the students and teaching staff pointed out a few aspects which need to be taken into consideration for a successful implementation of CM in chemistry and chemical engineering education:

- The development of conceptual-modeling skills requires students' learning autonomy, which necessitates that bachelor-level students take on responsibility for their own learning. Fostering student autonomy in learning is crucial in helping students to engage in the process of analyzing complex and abstract situations. This may suggest that additional training and support in self-regulated learning are recommended to facilitate and empower students. On the other hand, teachers also need to shift their mindset from "sage on the stage" to "guide by the side" to facilitate students' autonomy.[40] We show that by creating a supportive environment with teachers' scaffolding and guidance, one could create the necessary conditions for those that are new to an academic environment to establish systems thinking, which transcends the classification of problems and design of solutions. The introduction of intermediate expert feedback sessions would further improve the possibilities to address the difficult step(s) in defining criteria required for the development of meaningful hypotheses and avoiding premature solutions.
- The results of this study suggest that conceptual modeling skills are difficult and somewhat abstract for bachelor's students to develop through a single course alone. The project format with various educational roles can assist students in analyzing the system as a whole, but students need first to familiarize themselves with an academic way of thinking and apply critical thinking skills as a team. Hence, it is recommended to ensure that students will have the opportunity to develop their skills in conceptual modeling, progressively from understanding in their first year to applying in their second year to creating in their third year. Alongside this gradual development in their conceptual thinking, CM will lay the foundation for systems thinking as it will:
  - Deepen student learning experiences. The implemented project groups motivated students to actively participate in meetings to achieve deep learning experiences. Notably, the project groups also limit the discrimination of different thinking styles (e.g., reflective, intuitive, or transitional thinkers[41]) as they work together in groups.
  - Alleviate student work load. Learning or teaching assistance professionalization to support students creates a safe and supportive learning environment. Such teaching presence in this supportive environment is generally appreciated by students and, in a broader perspective, can create a sustainable and motivating atmosphere without increasing workload.
  - Improve student−teacher interaction. The support network helped to increase students' scientific thinking, motivation, and learning attitudes. This type of working in teams not only attracted students to the meetings on campus and enhanced learning-by-interaction but also broadened the opportunities of our teaching staff, resulting in high teaching staff satisfaction.
  - We acknowledge the limitations of this study, which was conducted on a single chemical engineering program at a European university. To further strengthen the concept, future work with larger samples of students and/or in different educational settings is recommended. It is essential to recognize that modern chemical students must address complex systems to tackle global challenges. To prepare future chemical engineers, we intend to integrate an interdisciplinary mindset in our teaching.[4] Nevertheless, this study provides valuable empirical input to inform conceptual models in chemical engineering education.

3. CONCLUSIONS

This work describes a conceptual modeling (CM) approach, implemented in the first year of a bachelor's degree in chemistry and chemical engineering at a Dutch research university. We designed a project wherein 48 engineering students were tasked to design solutions to address problems in sustainability (in groups of five or six). The findings of this study indicate that, by employing a CM approach, students can be encouraged to focus on the conceptualization phase in inquiry-based learning, leading to diverse and holistic perspectives of the problem context (key aspects for systems thinking). To help students with CM, it is recommended to create a supportive learning environment that encompasses educational roles such as tutors and learning assistants. This support is necessary to provide students with guidance, motivation, and feedback when facing challenges. Additionally, this study also emphasizes the significance of an interdisciplinary approach that requires students to integrate knowledge in chemistry with essential skills such as collaboration, communication, research, and academic writing. We believe that CM as implemented here could spark new ways to teach science[42] that facilitate systems thinking in chemistry, which allow students to develop critical thinking abilities and apply them toward solving real-world problems. With iteration and reflection and appropriate and informed action, this may evolve into a project format that can be applied to a variety of disciplines, promising a tool that strives for all students to fully develop their potential in becoming academic citizens.

4. METHODS AND PROTOCOLS

4.1. Workshop on CM

To engage students in conceptual modeling, a workshop was developed to introduce the context and application of CM to students. To this end, the workshop was divided into two general learning objectives: (i) understand the context of conceptual modeling and (ii) practice developing a conceptual model. Part I provided examples and poll questions to allow students to determine what is, and what is not, a conceptual model. Part II provided observations, and students were tasked to conceptualize a scientific problem and develop a solution as a group.

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Three project themes were introduced at the end of the workshop, similar to the observations provided during the workshop. A summary of the workshop (*.pptx) can be provided upon request.

4.2. Assessment

To determine how students have applied conceptual modeling in their project, we asked students to write a report, with a template provided in Section S3. The report was 50% of the collective grade, a mark resulting from the combined assessment by the tutors, the information specialist, and the LAs. We developed an assessment scheme (with rubrics for the elements process, product, and information skills) to analyze how the group performed (see Section S4). In addition to the report, a discussion session was organized with a committee (comprising external lecturers) to allow students to justify their reasoning in their report. The discussion was the remaining 50% of their grade.

4.3. Protocol for the Discussion Sessions with Students

All groups were invited to a discussion session (30-to-40 min meeting) to discuss their report and project journal. The committee read the report and was instructed to ask questions to a student from the group and give them time to elaborate their answer. As part of this discussion, teachers from our language center provided individual feedback on oral communication (see project initiation, in Section 1.3) for which each student was required to speak for at least 5 min during this meeting. We therefore organized this meeting very strictly (name tags, speaking time per student, if others want to add something they could only speak when given the floor, etc.). At least 10 min were planned between groups to give tutors and English teachers time for finalizing their notes and for a brief evaluation on the performance of the students. Based on the discussion, the committee determined deviations from the group performances to provide grades for each individual.

4.4. Evaluation

This project was evaluated with our teaching staff on two occasions (during and after the project was finalized). In addition, as this project was newly introduced in our curriculum, we also presented our preliminary results to colleagues in our educational program at our CSE Teacher's lunch (46th ed., November 17th, 2022). Two separate occasions were organized for students to provide feedback: once during a general Quality Assurance meeting and once during a CM-specific interview (see protocol below).

4.5. Protocol for Interview Sessions with Students

Interviews were conducted, and to include each performance group (high, middle, and low; see Figure 3b), we invited four focus groups. The interview sessions were semistructured with an emphasis on conceptual modeling and also allowed participants to freely express their opinions in order to uncover unexpected findings. Before conducting the interview, our study obtained signed consent forms from all the students. Each interview session lasted approximately 1 h. For data analysis, the sessions were recorded and transcribed into text. The questions in the interview are in Section S5.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00337.

Project timeline and activities; general guidelines for writing the project report, a project journal; project assessment (which includes assessment criteria for project, summaries of students' responses, students' interpretation of CM, and project assessment); interview protocol "value of CM" (PDF)

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Author Contributions

A.S.Y.W., P.J., and L.E.K.-H. conceived the project. A.S.Y.W. designed the workshop on conceptual modeling. L.E.K.-H. supervised and planned the project. L.P. developed and executed the CM interview. L.E.K.-H. and P.G.V. developed the assessment. A.S.Y.W., J.M.J.P., and S.L. developed the project topics and acted as tutors and/or assessors for this project. P.J. and L.E.K.-H. acted as committee members for the oral assessment. A.S.Y.W., L.P., and L.E.K.-H. wrote the manuscript. All authors contributed to reviewing the manuscript.

Notes

The authors declare no competing financial interest.

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