Teaching and assessing systems thinking in first-year chemistry

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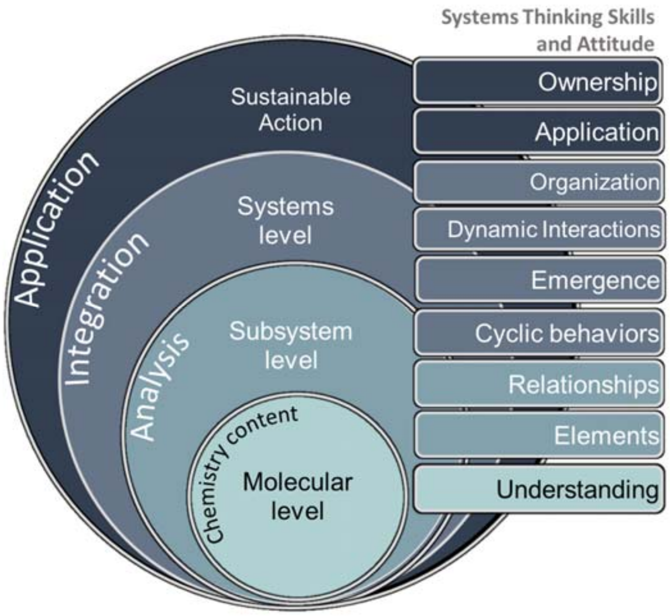
ABSTRACT

Powerful arguments have been made recently to advocate for the introduction of systems thinking in chemistry education to equip graduates to address sustainability challenges. This contribution describes systems thinking activities and an assessment tool that enables meaningful learning in first-year organic chemistry as students engage with the molecular level foundation and real-world implications of the system under consideration. The activity incorporates concept maps and systems-oriented concept mapping extensions (SOCMEs) as visualization tools to scaffold the development of systems thinking skills. A rubric based on the SOLO taxonomy was designed and used to assess evidence of systems thinking skills demonstrated on SOCMEs. The activity was implemented in a small and a large group of 18 and 219 participants respectively, where findings from both groups are presented. The grading of six SOCMEs by three independent raters proved to be inconsistent at higher thinking SOLO levels, where rater experience was flagged as an area for future improvement to ensure raters are proficient in assessing systems thinking. However, meaningful progress was made to assess the quality of learning. The rubric was an effective tool for formative and low-stakes assessment to drive the teaching and learning of systems thinking in Chemistry.

GRAPHICAL ABSTRACT



KEYWORDS

First-year undergraduate, General Chemistry, Organic Chemistry, Collaborative/Cooperative learning, Testing/Assessment, Sustainability, Systems thinking

The infusion of systems thinking (ST) in chemistry education presents a powerful way to link fundamental chemistry knowledge to human-environmental interactions and the sustainability agenda.[1] However, limited ST training, lack of teaching resources and assessment exemplars, and concerns regarding cognitive overload have hampered the implementation of Systems Thinking in Chemistry Education (STICE).[2] Recent IUPAC-funded projects have sought to promote the introduction of STICE,[3] the first of which culminated in a special issue of this journal in 2019 showcasing such initiatives in the field.[4] Attention has predominantly been given to the development of approaches to include ST in general chemistry. However, valid assessments of ST teaching interventions in chemistry have posed a challenge for large first-year classes, which invites exploration to address this gap. We contribute to this endeavor by reporting on the design and implementation of an intervention for first-year organic chemistry which was specifically intended to foster the development of ST skills. Our intervention centers on concept maps and systems-oriented concept map extensions (SOCMEs) and the assessment of demonstrated ST skills as students built onto these maps to reflect their thinking and learning.

CONCEPT MAPPING AND ASSESSMENT

An important impediment to the implementation of most systems thinking activities, apart from their complexity and potential cognitive overload, is the lack of assessment tools. [1] Concept mapping is an effective tool to develop and assess students' ability to organize concepts and identify interrelationships.[5, 6] Concept maps can reveal the knowledge and skills that students gained as their construction promotes the engagement and processing of content.[7, 8] SOCMEs are extensions to concept maps that are used to explore the interconnectedness of subsystems and their boundaries. Formulating SOCMEs encourages the exploration of implications of subsystems and enables the conceptualization of greater complexity.[9] SOCMEs aid in visualizing the complexity of increasing interconnectedness between concepts, which is a key feature of systems thinking.[9] The use of SOCMEs in the assessment of systems thinking has not been reported on yet, however, systems thinking has been directly assessed from concept maps.[2, 6, 10, 11] In the assessment of concept mapping, Novak warned that the "strictly defined quantitative use of concept maps is believed not to do justice to the personal nature of people's understanding".[12] He argued that there is a need to assess the *quality* of learning (how well students demonstrated their knowledge and skills) together with the *quantity* of learning (how much knowledge and skills were demonstrated). Biggs and Collis emphasized that the structural organization of students' thoughts is the clue to quality as it differentiates mature thinking from immature thinking.[13] Mature thinking and deep learning can be inferred from an increase in structural complexity. Biggs and Collis developed a hierarchical model informed by Piaget's stages of development to describe levels of increasing complexity in students' understanding.[13] This taxonomy, called the Structure of the Observed Learning Outcomes (SOLO), provides a structure for judging learning quality from surface learning to deep learning. Five levels of increasing complexity, known as SOLO levels, have been identified. The SOLO levels are pre-structural, unistructural, multistructural, relational and extended abstract. [13]

Stewart used the SOLO taxonomy to assess concept maps in higher education where students learned about complex systems in an Earth Sciences module. He reported that the evaluation tool was effective and that students demonstrated improved connectivity in thinking after engaging with complex systems.[6]

Vogelzang et al.[14] used the SOLO taxonomy in a green chemistry course to assess open-ended responses for critical scientific literacy with the use of a rubric adapted from Stewart [6] and Biggs et al. [13] This study draws on the above use of the SOLO taxonomy to assess the quality of systems thinking from SOCME diagrams.

SYSTEMS THINKING INTERVENTION

Several objectives guided the design of the intervention, i.e. to enable deep and meaningful learning of chemistry, to manage cognitive load through effective scaffolding and cooperative learning activities, and to demonstrate the relevance and real-world implications of chemistry.

Teaching systems thinking with SOCME diagrams

Visualizing the complexity within a system requires the ability to "understand the multi-level structure" of various components and processes.[15] However, the multi-level structure of a system can be viewed on several scales of granularity ranging from a molecular to a macroscopic, local, or global systems level. The molecular level is comprised of submicroscopic components and processes, such as the physical and chemical properties of a molecule, that influence its emerging chemical behavior.[16] The molecular level becomes "hidden" when the level of granularity changes to view the whole system. The chemistry then becomes the "hidden dimension" that still influences the system-level concepts and processes. Focus can only be placed on one level of granularity at a time, and therefore a zoom-in and out strategy is used to reduce cognitive overload as suggested by Pazicni and Flynn.[17] First-year students are likely to find the construction of SOCME diagrams more challenging if they have limited or no prior systems thinking or concept mapping skills. We reduced the cognitive load associated with the difficulty of the task by asking students to extend a provided partial SOCME. Novak suggested that a partial map, which he refers to as a skeleton map or a scaffold, should have 20 concepts to facilitate expansion to 50-60 concepts to enable high cognitive performance.[18]

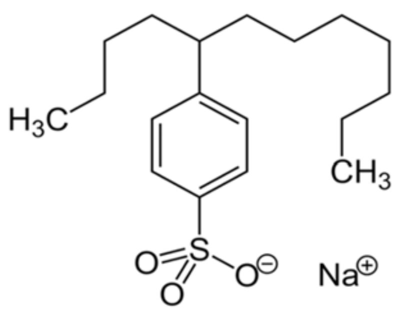
The extension of SOCME diagrams as a means of scaffolding systems thinking skills has not been reported previously, even though several authors suggested teaching activities that involve the construction of SOCMEs that relate to systems thinking learning outcomes.[1, 17]

The first step in the design of our ST activity was to formulate appropriate learning outcomes (LOs). These LOs (Table 1) were based on the Systems Thinking Hierarchical Model (STH) established by Assaraf and Orion[19], and York and Orgill's ChEMIST table of systems thinking characteristics.[20]

Table 1. Learning outcomes for the systems thinking activities

	Systems thinking skills
1	Examine and understand molecular level concepts and processes that influence system-level behavior
2	Identify and illustrate relevant system-level concepts and processes
3	Identify and illustrate the relationships between concepts within subsystems
4	Explain causes of cyclic behavior and examine feedback loops in the system
5	Analyze potential emerging system level behavior in the system
6	Identify and describe interactions within and between subsystems that can change over time
7	Organize system-level concepts in the whole system and identify new subsystem boundaries
8	Predict factors that influence how a system changes over time
9	Consider the role of human activity on current and future system-level behavior

The general and organic chemistry concepts covered in the activities as illustrated in the supporting materials were considered to be prior knowledge. We intended to teach students new chemistry knowledge on the topic of surfactants and new systems knowledge regarding the relevance of surfactants in order to encourage meaningful learning. We chose an anionic surfactant commonly used in laundry detergent, Linear Alkylbenzene Sulfonate (LAS), for this purpose and taught its chemistry as the molecular level foundation of the intervention (Figure 1).



Linear Alkylbenzene Sulfonate (LAS)

Chemistry Knowledge specific to surfactants and LAS
Intermolecular forces and types of mixtures
Ionic salts, acid-base chemistry, and solubility
Skeletal structures, functional groups, and isomers
Hydrocarbons and fractional distillation
Organic reactions
Systems Knowledge specific to LAS (domain of influence)
Industrial manufacture and detergent quality (economy)
Hygiene, cytotoxicity, and our health (society)
Ecotoxicity, foaming, and biodegradation (environment)

Figure 1. Chemistry and systems knowledge taught

Systems knowledge of LAS requires knowledge of its chemical properties because these properties influence its industrial manufacture, solubility, cytotoxicity, ecotoxicity, foaming ability, and biodegradation rate. In turn, systems knowledge of LAS explains the impact of LAS on a macroscopic level, in our society, economy, and environment.

Once the molecular level foundation was taught as the core content of the activity, the development of systems thinking skills was scaffolded hierarchically (Figure 2). Students were tasked with identifying the elements and relationships that make up the subsystems (these skills were labeled *analysis: elements* and *analysis: relationships*). The next step required integration of the components and their relationships to visualize the whole system through studying its organization, dynamic nature, cyclic and emergent behavior (skills labeled *integration: cyclic behavior*, *integration: emergent behavior*, *integration: dynamic interactions, integration: organization*). For students to develop systems thinking they require both analysis and integration skills to visualize the parts and interconnections within the whole and have to return to the molecular level foundation to understand its relevance and real-world implications. The overall application of systems thinking skills and chemistry knowledge in context is what inspires an attitude or disposition of ownership (labeled *application* and *ownership*). An important learning outcome was the development of a sustainable action perspective as it enables students to "critically analyze the complex interactions between human and earth systems and engage in responsible action toward global sustainability".[21] In essence, the activity guided students to "zoom out" from the molecular level to systems level, before prompting them to consider their contribution to sustainable action.

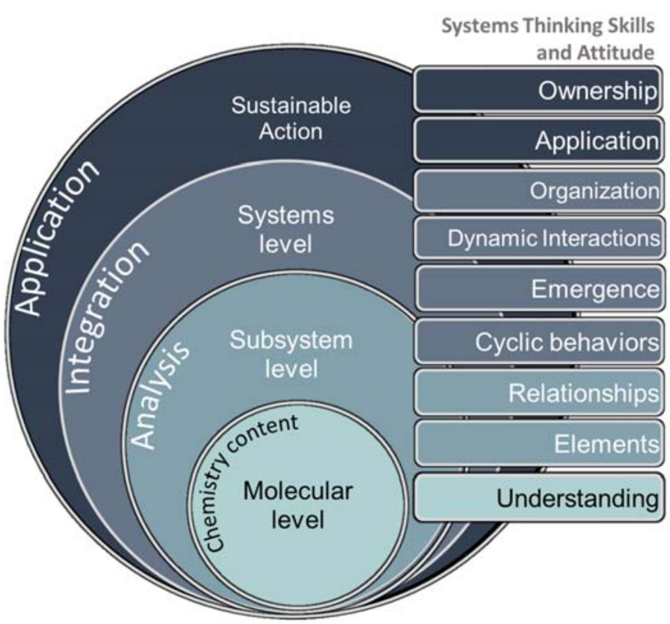


Figure 2. Hierarchical scaffolding of systems thinking skills from a molecular level foundation to sustainable action

Context

The study took place at the University of Pretoria in a first-year general chemistry course that runs in the second semester. The module builds onto the first semester general chemistry module and is divided into two parts where analytical and physical chemistry topics are taught first followed by organic chemistry. The module spans 14 weeks and consists of 56 hours of lectures with an additional 36 contact hours for laboratory and tutorial sessions. Due to the Covid restrictions all lectures and tutorials were offered online, and students conducted practical activities in their own time. The practical component contributes 5% of students' final mark for the module, with midterm exams, class tests, and online homework contributing 45%. The remaining 50% is derived from the final examination. The two general chemistry modules are pre-requisites for all Science undergraduate degrees and therefore attract a large enrolment of approximately 1400 students.

Description of the activities

The systems thinking intervention consisted of four pre-recorded videos, two quizzes, two practical activities, and a self-reflection questionnaire. Students had to watch two videos prior to the activities: video one introduced systems thinking, its importance for future sustainability, concept mapping, and SOCME diagrams. Video two gave instructions for the activities, and introduced the economic, environmental, and societal subsystems, the group roles, and the ice-breaker activities to enhance group dynamics for all subsequent activities of the intervention.

At the start of the intervention, students had to complete a quiz to activate chemistry prior knowledge. This was followed by a video lecture (video 3) on LAS as a surfactant and its system-level behavior in laundry detergents together with its role and real-world implications in society, the economy, and the environment. Students then applied their knowledge to expand concept maps for each subsystem. The second session started with a quiz on new systems knowledge which was followed by a group activity to expand a partial SOCME diagram. The intervention was concluded with the last video about chemistry's contribution to sustainable surfactants and how individuals can take sustainable action and a self-reflection questionnaire. Figure 3 provides a schematic representation of the sequence of events during the two sessions.

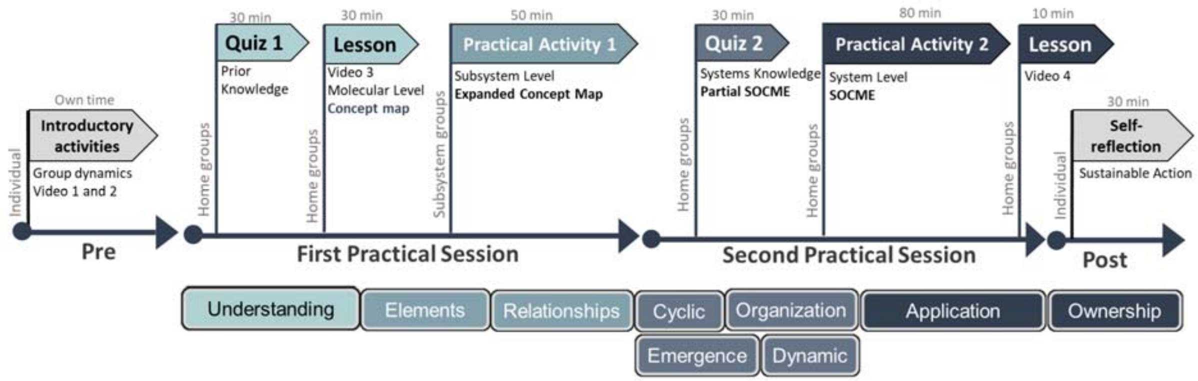


Figure 3. Sequence of activities during the intervention with the ST skills targeted and scaffolded in each activity

Design for cooperative learning

The activity used a jigsaw cooperative learning approach, [22] with home groups and subsystem groups, to encourage collaboration and interdependence to deal with the complexity and cognitive load associated with systems thinking. Each home group had three students and each student had a dedicated role to fulfill during the activities, either as group facilitator, presenter/recorder, or strategy analyst/researcher. In addition, each group member was responsible to contribute expert subsystem knowledge (societal, environmental, or economic), which they co-constructed in specialist subsystem groups with members from other home groups with the same role. This design fostered an inclusive environment where each student had an opportunity to fulfill a group responsibility both in terms of knowledge contribution and group dynamics.

Design of teaching

The molecular level foundation of anionic surfactants, provided in a concept map, was used to build students' systems-level knowledge concerning the relevance of LAS in various subsystems. During the first practical session subsystem groups identified and illustrated elements and relationships in their subsystem on concept maps. In the second practical session, students completed a system-level knowledge quiz, and then applied their integration skills as they engaged with a partial SOCME diagram (Figure 4). Assaraf and Orion[19] and Yoon et al.[23] reported that students generally struggle to identify dynamic interactions, cyclic and emergent behavior due to its non-linearity and complex interconnectedness. Therefore, students' demonstration of these integration skills, including system-level behavior that changes over time, was not expected or assessed but was taught and carefully facilitated throughout the activity. Students were asked to extend the partial SOCME by applying analysis and integration skills, which are fundamental to systems thinking. After the activity, students were required to reflect on their learning to encourage an attitude of taking ownership for their contribution to sustainable development.

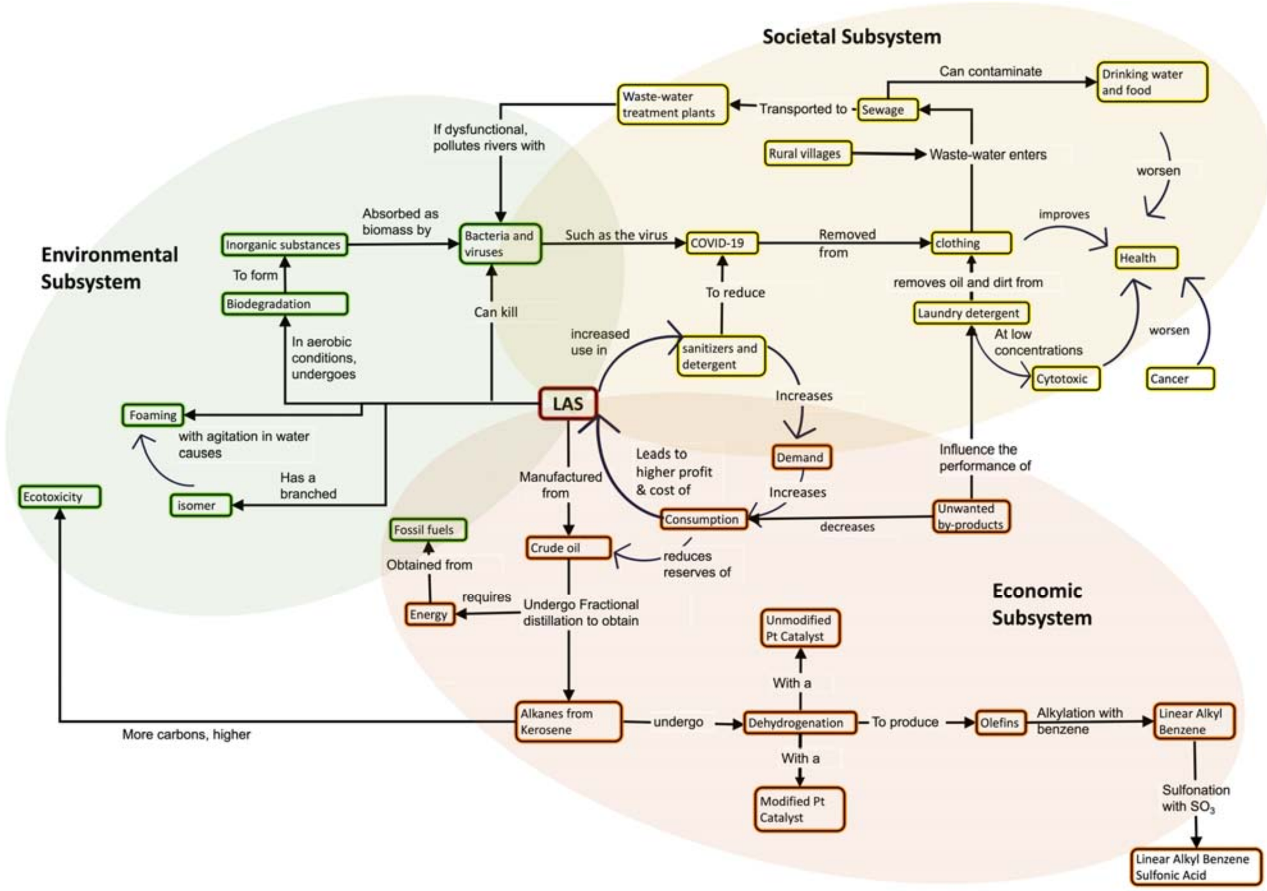


Figure 4. Partial SOCME concerning Linear Alkylbenzene Sulfonate.

Design of SOCME assessment rubric

Rubrics designed for assessing the authenticity of demonstrated skills can be crucial to the learning process as a formative assessment, to drive student learning and improve teaching. Assessing the quality of concepts, linking words and new subsystem boundaries can provide deeper insights into the development of systems thinking skills. However, to counter the subjectivity associated with qualitative evaluation, the SOLO taxonomy which was derived empirically, was used to design a rubric to assess extended partial SOCME diagrams "in an objective, systematic way." [13] The adapted SOLO levels - pre-structural, unistructural, multistructural, relational, and extended abstract - were aligned to systems thinking skills in the learning outcomes (Table 1). A short version of the grading rubric is shown in Table 2. (Refer to the supporting materials for the full rubric.) The levels and scores we assigned to students based on the SOLO taxonomy depended on the number of relevant concepts identified, how these concepts were combined, how they were integrated into the structure, and finally how they were used to make predictions and generalizations. Thus, we used the SOLO taxonomy to assess the hierarchy of levels of increasing abstraction on SOCME diagrams. This allowed us to give a score, which does not judge the success or failure of students, but rather their levels of performance or progress made. [13]

Table 2. A short version of the SOCME grading rubric

SOLO levels	Sublevel	Description	Total Score (/80)	Systems Thinking Skills*
Unistructural	---	At least one new concept added	8	**Learning Outcome 2** Analysis: elements
Multi-structural	Low	2 or 3 concepts without connections	8	
	Medium	More than 3 concepts without connections	8	
	High	More than 3 concepts with connections	8	
Relational	Low	Connections between concepts within one or two subsystems	10	**Learning Outcome 3** Analysis: relationships
	Medium	Connections between concepts within all three subsystems	10	
	High	Connections within AND between subsystems	10	**Learning Outcome 6** Integration: dynamic interactions
Extended abstract		Organize concepts into subsystems and add new subsystems	10	**Learning Outcome 7** Integration: organization
		Apply knowledge holistically to make future predictions	8	**Learning Outcome 8** Application

*Learning Outcomes 1, 4, 5 and 9 are not assessed by the SOCME rubric

The assessment of extended partial SOCME diagrams for the quality of concepts, connections, subsystem boundaries, and predictions demonstrated, was intended to make explicit how well students were able to build on the taught molecular level foundation, to demonstrate analysis and integration skills as well as their understanding of the interactions of LAS within and between various subsystems. Students' chemistry understanding (LO1), assessed by the knowledge quiz 1, was not assessed by the SOCME rubric, as the chemistry is the hidden dimension on the zoomed-out level of granularity of the SOCME. The unistructural and multistructural SOLO levels aligned with the skill *Analysis: elements* (LO2) to assess the new relevant elements added to the system. Relational low and medium aligned with *Analysis: relationships* (LO3*),* the assessment of connections, and linking words added between concepts within subsystems. The skills *integration: cyclic behaviour* (LO4) and *integration: emergence* (LO5) were identified as challenging skills for first-year students to demonstrate on their SOCMEs. They therefore engaged with feedback loops and emerging system behaviours given on the partial SOCME, and were not required to create their own. For this reason, LO4 and 5 were not assessed by the SOCME rubric.

Relational high aligned with *Integration: dynamic interactions* (LO6), the skill to assess the connections made between subsystems. The organization of concepts within subsystem boundaries, the addition of new subsystems, and the application of knowledge to make future predictions aligned with the highest SOLO level, *Extended abstract* (LO7, LO8). The attitude *ownership* was also not assessed by the SOCME rubric, as students reflected on their intentions to take ownership in a self-reflection questionnaire.

Implementation

The activity was implemented for a small group of 18 students that volunteered as research participants in our pilot study, and a large group of 219 students, where 60 students met virtually per timeslot to complete the activities with two facilitators. Students in both groups gave informed consent for use of their data in line with ethical clearance. The activity was a component of formative assessment and was implemented over two synchronous virtual practical sessions that spanned two weeks and that took approximately 4 hours in total to complete. However, students were given an additional week if they wanted to meet with group members to complete their SOCME before the submission deadline. The activity comprised of individual and group work submissions and counted out of 120 marks, where 60% of the score was derived from the SOCME rubric and 40% from quizzes that were computer-graded. This represents one third of the laboratory component of the course, which had a reduced overall contribution to the final grade as students were not gaining laboratory experience during the pandemic. Thus, the activity contributed only about 1% of students' final course grades, but it provided enough incentive for productive engagement. Three independent raters used the designed marking rubric to assess the six submitted SOCMEs from the group of 18 volunteers. From seventy-eight submitted SOCMEs of the large group, six independent raters used the rubric to assess 13 SOCMEs each.

FINDINGS AND DISCUSSION

Assessment of an example SOCME

Students' understanding was made explicit as they added new concepts, interconnections, subsystem boundaries, and predictions to their SOCME diagrams. This encouraged meaningful learning as students applied their multilevel thinking in chemistry and visualized interconnectedness on a systems level. We selected one of the expanded SOCMEs (Figure 5), to present the scores obtained by application of the rubric and discuss the interpretation of the scores for the quality and quantity of learning. This group of students added concepts to the environmental subsystem (in green), the economic subsystem (in brown orange) and they added a new subsystem (in blue). A total of sixteen new concepts were added, with appropriate connections and linking words that placed the SOCME on a multi-structural high level (Table 3). *Analysis: relation*ships was demonstrated as connections were made between concepts within the environmental and societal subsystems, achieving relational low, however, not relational medium as connections between concepts were not made in all three subsystems. Connections were made between subsystems but were limited and therefore the application of *Integration: dynamic interactions* was not fully demonstrated. Concepts were not organized into appropriate subsystems, even though a new subsystem was added revealing that *Integration: organization* was not fully applied, however, extended abstract: application of knowledge was achieved as future predictions were made relating to the environmental subsystem.

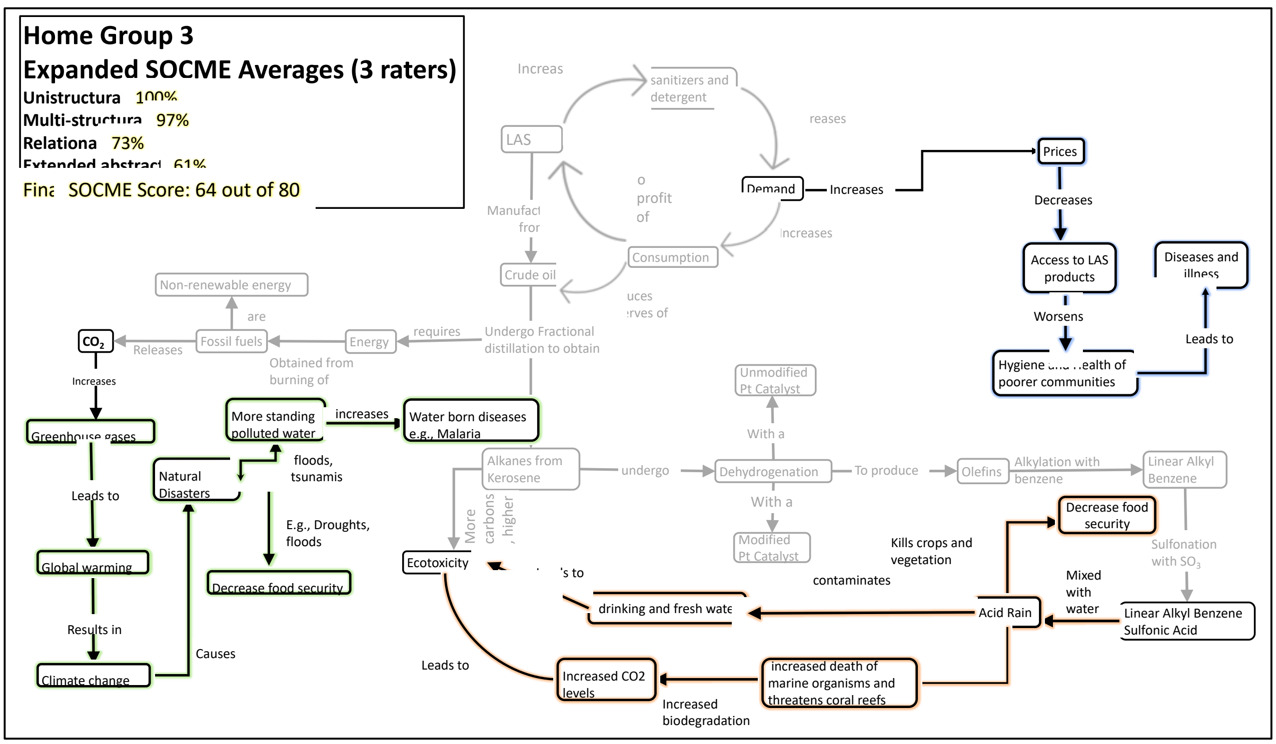


Figure 5. Evidence of an expanded partial SOCME submitted by home group 3. This figure includes a component of the partial concept map that students received as the shaded part (Figure 4)

The average scores assigned to this SOCME by three independent raters are shown in Table 3. Refer to the supporting material for an exposition of how this SOCME was assessed. The scores reveal that this SOCME achieved higher scores for unistructural (100% average) and multi-structural (97% average) and lower scores for relational (73% average) and extended abstract (61% average). Overall, students demonstrated competence in the lowest levels of the SOLO taxonomy, i.e. at the unistructural, multi-structural, and lower relational levels. Concerning systems thinking skills, students demonstrated their ability to analyse elements and the relationships between them on their SOCME diagram.

Table 3. Average scores assigned per SOLO level for the SOCME submitted by home group 3

SOLO levels	Sublevel	Total Score	Average Score	Systems Thinking Skills
Unistructural	---	8	8,0	Analysis: elements
Multi-structural	Low	8	8,0	
	Medium	8	8,0	
	High	8	7,3	
Relational	Low	10	9,0	Analysis: relationships
	Medium	10	7,3	
	High	10	5,7	Integration: dynamic interactions
Extended abstract		10	4,7	Integration: organization
		8	6,3	Application

These scores also aligned with informal feedback from raters who commented that "good concepts were added", but that "implementation and connection" were lacking with poor quality and "inappropriate linking words" that "were also not arranged well in the SOCME" even though a "future prediction with good linking words" was given. Therefore, the qualitative assessment of the SOCMEs through content analysis and rater feedback confirmed the quantitative scores and pinpointed areas that require attention during the teaching of systems thinking. The other submitted SOCME diagrams from the pilot study revealed similar findings with higher scores for lower SOLO levels and lower scores for higher SOLO levels. First-year students were able to identify concepts and connections (*analysis: elements* and *analysis: relationships*) even though the quality of linking words and connections required improvement. Students found demonstrating *integration: dynamic interactions*, *integration: application,* and *integration: organization* skills on the SOCME more challenging. These scores, therefore, reveal the progress that students have made to develop systems thinking skills through what they were able to apply and demonstrate on their extended SOCME diagrams.

The assessment of SOCME diagrams from the large group in a reasonable time frame, demonstrated that the rubric can be used on a large scale to evaluate the progress made in developing systems thinking. Raters scored SOCME diagrams after initial familiarization in approximately five to ten minutes and only assessed one SOCME per three students, thereby reducing the workload and scoring time by two-thirds.

Reliability of SOCME grades

İlhan and Gezer investigated the reliability of the most widely used taxonomies, the SOLO taxonomy and Bloom's revised taxonomy, for the assessment of cognitive assessment questions in science and technology and social science textbooks.[24] They reported that agreement amongst experts was higher for the SOLO taxonomy. This finding aligned with teachers' views of the SOLO based rubric as clear, intelligible, and objective for the assessment of open-ended questions.[24] For the SOLO taxonomy the inter-rater reliability is the most important measure to understand the consistency of grading amongst raters.[13] A high inter-rater reliability is possible if one rater gave consistently low scores and another gave consistently high scores. The inter-rater reliability can be evaluated with the intraclass correlation coefficient (ICC) to understand the consistency of grading. The intraclass correlation coefficient (with a two-way mixed model and a mean rating ($k=3$)) was used to investigate the consistency amongst three independent raters for grading the SOLO levels of the six SOCME diagrams produced by the pilot sample in this study. The ICC (3,3) was calculated as 0.74 with a 95% confidence interval of (-0.098;0.960) indicating a moderate consistency between raters, however, the large confidence interval and the small sample size made it difficult to conclude whether grading with the rubric was reliable. To determine where the inconsistency was located, we constructed a scatterplot (Figure 6) of the SOCME grades for each SOLO level as assessed by the raters. The plot revealed consistent marking in lower SOLO levels as shown by the small variation from unistructural to relational low. However less consistent marking was seen from the increased variation in scores for the higher SOLO levels, from relational high to extended abstract. An increase in variance at higher SOLO levels was strongly positively correlated and found to be statistically significant ($r=0.62$, $t=2.08$, $df=7$, $p=0.04$), therefore rejecting the null hypothesis stating that there is no positive correlation between variation and SOLO levels.

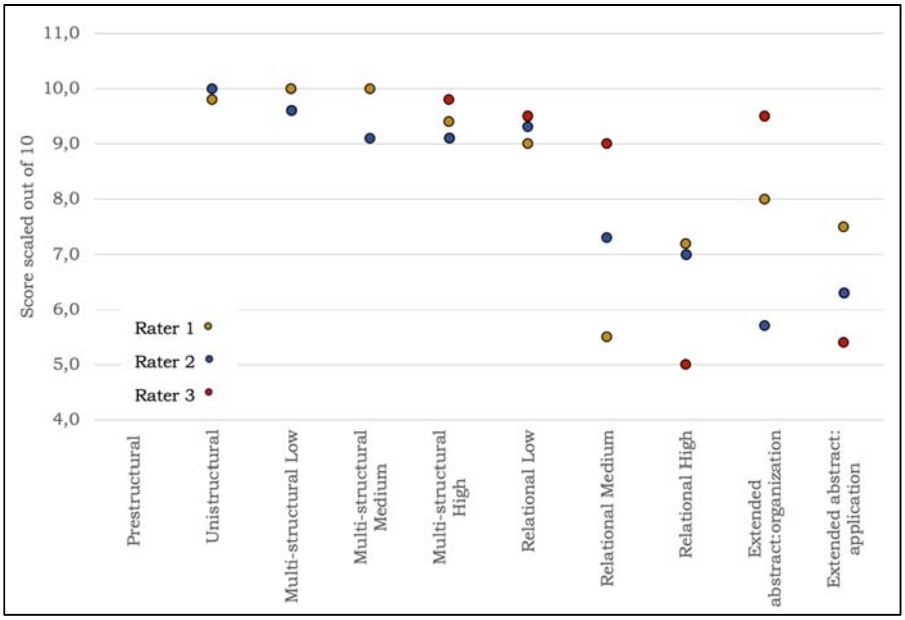


Figure 6. Average SOLO level scores from six SOCME diagrams assessed by three independent raters

The sources of variability in grading could be due to the high complexity associated with the systems thinking task. Therefore, if students struggled to demonstrate the skill, then raters will also find it more challenging to assess it. In tasks of high complexity, subjectivity is in some instances unavoidable as raters have to make judgments at the edge of their competency levels.[25] Teachers' unfamiliarity with SOLO based rubrics can result in lower inter-rater reliability.[26, 27] This could be addressed by making the rubric more explicit and by providing better systems thinking training to the raters to ensure they are better equipped to judge systems thinking using the SOLO based rubrics in future assessments. However, despite these shortcomings, we are convinced that the rubric was useful to drive the learning of systems thinking, enable the formative assessment of SOCME diagrams, and identify areas that require future attention in the teaching and assessment of systems thinking.

IMPLICATIONS FOR PRACTICE

The use of partial SOCMEs as a teaching strategy allowed students to engage with systems thinking on a molecular and macroscopic, local and global systems level. Using SOCME diagrams in the classroom enables students to recognize the relevance and real-world implications that stem from a molecular-level understanding of chemistry, which can make the teaching and learning of chemistry meaningful. However, concept mapping skills are a prerequisite for students to achieve measurable learning gains during an intervention of such limited scope. The initial construction of a partial SOCME requires effort and time, but it is well rewarded. We found the intervention design to be effective to deepen chemistry learning and foster commitment towards sustainable action, but we simplified the rubric and some of the tasks for future implementation based on this study.

Progress was made to assess the quality and structural complexity demonstrated on extended partial SOCME diagrams with the use of a rubric based on the SOLO taxonomy. A finding of inconsistent grading at higher SOLO levels flagged rubric reliability and rater training as areas for future improvements. The formative assessment confirmed that students developed analysis skills more than integration skills, which is expected due to their unfamiliarity with systems thinking and the cognitive complexity associated with behaviors that emerge or change over time. Assessment rewards the application of systems thinking skills as students demonstrate systems concepts on the diagram. We demonstrated that SOCME diagrams are a useful tool for teaching systems thinking, and can be assessed with rubrics on a large scale in a reasonable time frame to evaluate the quality of skills development.

LIMITATIONS AND RECOMMENDATIONS

Since the systems thinking activity was implemented online in a small and large group of first-year students enrolled in a general chemistry module at the University of Pretoria, extrapolation to other contexts must be done with care. It is recommended that the implementation of the systems thinking activity occurs in an in-person setting, to avoid challenges associated with online group work. Teaching and assessing systems thinking in one intervention limits the time students have for the gradual development of STs skills, however, it demonstrated the relevance of chemistry and made the case for sustainable action. The rubric was not designed to measure the achievement of skills and is therefore limited to use in formative assessments to promote systems thinking skills development. Students might experience the extension of a partial SOCME diagram to be challenging due to their lack of concept mapping skills. SOCMEs are also limited in showcasing the full range of systems thinking skills, as some skills are too challenging to demonstrate. Similarly, an attitude of taking ownership cannot be demonstrated in a graphical representation. The level of granularity of a SOCME, which in this case was on a systems level, has limited students' ability to show interconnections between core chemistry concepts, even though it helped students to look at the core chemistry concepts from a more holistic perspective. We recommend adjusting partial SOCME diagrams to scaffold the development of systems thinking skills based on students' prior knowledge and to allow space for creativity on the SOCME diagrams so that students can express their perspectives and ideas to link chemistry to the system under consideration.

ASSOCIATED CONTENT

Supporting Information

- Rater Training Manual and SOCME Assessment Rubric (.docx)

Systems Thinking Activities

- Prior Knowledge Quiz 1(.docx)
- Practical Activity 1-Economic Subsystem(.docx)
- Practical Activity 1-Environmental Subsystem(.docx)
- Practical Activity 1-Societal Subsystem(.docx)
- Systems Knowledge Quiz 2(.docx)
- Practical Activity 2(.docx)
- Self-reflection Questionnaire (.docx)

Activity Resources Available on Request from the Authors

Videos

- Introduction to Systems Thinking-Video 1(.mov)
- Instructions to Systems Thinking Activities-Video 2 (.mov)
- Surfactant Lesson-Video 3 (.mov)
- Take Home Message-Video 4 (.mp4)

Presentations

- Introduction to Systems Thinking- Video 1(.pptx)
- Instructions to Systems Thinking Activities-Video 2 (pptx)
- Surfactant Lesson-Video 3 (.pptx)
- Take Home Message-Video 4 (.pptx)

Additional Resources

- Example SOCME diagrams (.docx)
- Journal Article Abstracts and Media Reports (.docx)

Concept maps and SOCME diagrams

- Core Chemistry Concept Map (.pptx)
- Expanded Concept Maps (.pptx)
- Partial SOCME (.pptx)
- Practical Activity 2 Expansion of SOCME(.pptx)

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