Developing and evaluating systems thinking in first-year organic chemistry

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ABSTRACT

Powerful arguments recently advocate introducing systems thinking in chemistry education to equip graduates to address sustainability challenges. This study focused on developing teaching and assessment materials to foster the development of systems thinking understanding, skills and attitudes in first-year organic chemistry and to evaluate the effectiveness of the intervention to facilitate the development of systems thinking learning. We designed a systems thinking intervention to scaffold the development of systems thinking skills from a molecular-level foundation to sustainable action using concept maps and system-oriented concept mapping extensions (SOCMEs) as visualization tools. In the intervention, 18 students engaged in a jigsaw cooperative learning approach to learn about the chemical principles and real-world implications of the system of Linear Alkylbenzene Sulfonate, an anionic surfactant commonly used in laundry detergents. The research questions that guided this study asked which systems thinking skills students were developing during and after the intervention and what evidence suggested that students were developing a sustainable action perspective. We used a mixed-methods research design to collect and analyse data from students' perceptions, reflections, and demonstrations during and after the learning process. We used a concurrent triangulation design to compare the evidence from multiple perspectives to create a holistic understanding regarding the extent to which the intervention facilitated the development of systems thinking skills and a sustainable action perspective. We found that students were developing the ability to identify the concepts and relationships within the system. However, they needed help integrating the parts of the system to visualize the whole. During focus group interviews, students acknowledged that they were used to thinking about chemistry topics in isolation and were not used to imagining the real-world implications of chemistry. Evidence also suggested that students engaged deeply with the relevant topic of surfactants and gained an understanding of the system. The intervention enabled meaningful learning as students' moved between different levels of granularity to view the system as a whole and not just as a collection of parts. In conclusion, evidence suggested that students made meaningful progress towards developing systems thinking skills and a sustainable action perspective.

PLAGIARISM DECLARATION

I declare that the dissertation which I hereby submit for the degree of MSc Science Education at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at another university. Where secondary material is used, this has been carefully acknowledged and referenced in accordance with university requirements. I am aware of university policy and implications regarding plagiarism.

SIGNATURE: MReynders ……………………………. DATE: 5 DECEMBER 2022

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CHAPTER 1: INTRODUCTION TO THE STUDY

1.1. INTRODUCTION

This chapter begins by outlining the personal motivation of the researcher, followed by the background and context of the study. The problem statement and rationale of this study will then be discussed to outline the significance of the study and the gaps or challenges that the research intends to address. The aims and research questions, which constitute the foundation of this study, will then be presented. The chapter will outline the sequence of this research report and provide a summary in the concluding remarks.

1.2. MOTIVATION FOR THE STUDY

My journey started as a passionate environmental activist and change agent in high school. I started a recycling committee and organised awareness campaigns and river-clean-up projects to contribute towards a more sustainable future. When I began my journey as a first-year student enrolled in BSc Environmental Sciences at the University of Pretoria, I was convinced that this degree would allow me to take sustainable action and contribute to a sustainable future for the planet. During this time, I was always focused on one part of the story, one perspective, and one outcome and never considered both benefits and risks or the whole picture from many different points of view. I then encountered systems thinking, which forced me to take a step back and reconsider the interconnectedness between our society, economy and environment. I was not satisfied with the Environmental Science modules in my degree because they only taught me to consider phenomena on a surface level without engaging with multiple perspectives to gain a deeper understanding. I then changed my degree to BSc Chemistry to be equipped to explore the molecular-level foundation of these real-world challenges.

Studying chemistry enabled me to understand chemistry's sub-microscopic, microscopic and macroscopic properties. Still, unfortunately, at the first-year level, the focus was rarely placed on the real-world implications or relevance of chemistry. This made chemistry seem fragmented, meaningless and disconnected from my everyday experiences. After I graduated, I taught Environmental Sciences and Chemistry at a high school in Johannesburg. I remember one day in the classroom teaching students about the chemical reactions involved in ozone layer depletion, acid rain and smog formation. However, the environmental science learners were unwilling to incorporate a chemistry perspective into these global issues. I experienced the opposite when I taught chemistry learners about these global issues. This was one of the critical moments in my journey that motivated me to pursue further studies to discover how a systems thinking approach can integrate sustainability into chemistry education. Today, all around the world, many students enrolled in first-year university science programs are exposed to fragmented pieces of knowledge.

In chemistry, students rarely get the opportunity to visualise chemistry as a system with all its interconnections and real-world implications. My journey motivated me to embark on this research study to contribute to changing how chemistry is taught to prepare systems thinkers that can deal with complex global sustainability issues. I realised that embarking on this study could significantly equip students with higher-order cognitive skills to solve real-life problems, ask questions, think critically, and make decisions about chemical systems and global sustainability issues.

1.3. BACKGROUND AND CONTEXT

In South Africa, significant changes have been made to secondary-level education to address past inequalities and to prepare learners for a better future in tertiary education. These changes include a revised curriculum, adjusted university admission requirements and standardised National Senior Certificate (NSC) exams to allow equal access to quality tertiary education (Potgieter & Davidowitz, 2010). However, the 'gap' between students' capabilities and their preparedness for higher education remains a challenge, especially in Science, Technology, Engineering and Mathematics (STEM) subjects (Case, Marshall, & Grayson, 2012). In chemistry, many students are not adequately prepared for first-year chemistry courses. Potgieter and Davidowitz (2010) assessed the proficiency and skills of students enrolled in science programmes at two South African universities to determine their preparedness for first-year chemistry. They reported that students lacked relevant skills and were not proficient in most chemistry topics (Potgieter & Davidowitz, 2010). First-year chemistry lecturers are therefore confronted with high failure rates, which they can either address by lowering standards or adapting their teaching practice to provide additional support to unprepared learners (Potgieter & Davidowitz, 2010).

In light of this challenge, many lecturers adopt a reductionist approach to teaching chemistry for the following reasons. Firstly, students experience chemistry as complex due to the required multi-level thinking. Therefore, focusing only on core chemical concepts can support and enhance students' learning of complex topics (Johnstone, 1991; Orgill, York, & MacKellar, 2019). Secondly, this approach allows for more accessible education and assessment in large classes with high enrollment, which has overwhelmed chemistry departments (Abegaz, 2016). Lastly, lecturers save time by teaching chemistry free from its context, as their focus is to work through a full first-year chemistry curriculum. Teaching chemistry as fragments of knowledge without its context has resulted in students' experiences of chemistry being isolated and separated from real-world implications. Learning in chemistry can be made more meaningful by introducing a context-based focus to engage students with the relevance of chemistry and its critical role in future sustainability (Talanquer, 2019).

To deal with the complexity of future sustainability challenges, students require higher-order cognitive skills (HOCS) such as problem-solving, critical thinking, collaboration and systems thinking (Taimur & Sattar, 2019; Wiek, Withycombe, & Redman, 2011; Zoller, 2012). These skills have been identified as key competencies for Education for Sustainable Development. The South African Department of Environmental Affairs drafted the 2019–2029 Environmental Education and Training Strategy and Action Plan to promote sustainable development in South Africa by encouraging a systems thinking approach in environmental education (UNESCO ROSA, 2019). Since chemistry can be regarded as central to all other scientific disciplines, introducing systems thinking in chemistry provides an opportunity to bring about large-scale changes on a university level (Mahaffy, Ho, Haack, & Brush, 2019). A systems thinking approach goes beyond the environmental contexts of chemistry. It involves teaching real-world chemistry that connects to the dynamic character of a system with its societal, environmental and economic consequences (Orgill et al., 2019).

1.4. PROBLEM STATEMENT

The impact of a growing human population on the planet threatens our future existence due to the "great acceleration" (Mahaffy, Matlin, Whalen, & Holme, 2019). However, since chemistry is a central science that makes up the material foundation of society and economy, it can play a critical role in addressing some of these sustainability challenges so that present and future generations can live within the planetary boundaries (Anastas & Zimmerman, 2016; Mahaffy, Ho, et al., 2019). Chemistry has been taught with a reductionist approach to simplify its inherent complexity, reduce the possibility of an overcrowded curriculum and minimise cognitive overload (Constable, Jiménez-González, & Matlin, 2019; Mahaffy, Matlin, Holme, & MacKellar, 2019; Mahaffy, Matlin, et al., 2019b; Pazicni & Flynn, 2019). Unfortunately, this has resulted in a science community with insufficient knowledge and a too narrow field of concern to develop solutions to sustainability challenges (Mahaffy, Matlin, Holme, et al., 2019; Orgill et al., 2019). Systems thinking can be used to integrate the molecular basis of sustainability into undergraduate general chemistry courses (Mahaffy, Matlin,et al., 2019b). However, limited systems thinking teaching and assessment resources and activities have prevented the implementation of this approach. This study intends to address this challenge by developing teaching materials that can be used to introduce a systems thinking approach in first-year organic chemistry.

1.5. RATIONALE OF THE STUDY

As practised at present, chemistry education is inadequate to deliver graduates with the skills required to address sustainability challenges. Wiek and coworkers (2011, 2021) identified systems thinking as one of eight essential skills needed for sustainability professionals and researchers that are currently not well developed in science training programmes (Redman & Wiek, 2021; Wiek et al., 2011). This realisation has led to the drive internationally to re-imagine chemistry education, specifically to introduce systems thinking in chemistry teaching (Matlin, Mehta, Hopf, & Krief, 2015). Incorporating a systems thinking approach in chemistry can equip students with knowledge of real-world systems phenomena and global sustainability challenges and promote ethics- and values-orientated learning that can advance sustainable action (Sabelli, 2006; Sjöström & Talanquer, 2018; Tripto, Assaraf, & Amit, 2013). This study can contribute by developing meaningful teaching and assessment resources to equip students to deal with future sustainability challenges. It can also contribute to implementing the IUPAC project, Systems Thinking in Chemistry for Sustainability: Towards 2030 and Beyond (STCS 2030+). The STCS 2030+ project was established in 2020 to meet the 2030 UN Sustainable Development Goals (UNSDG) and to articulate the essential characteristics of systems thinking in chemistry (IUPAC, 2020).

I want to contribute towards this drive by developing teaching and assessment materials to introduce systems thinking into organic chemistry. There is a need for systems thinking materials that could enable first-year chemistry students to gain a deeper understanding of chemistry's interconnectedness and real-world implications. These materials can adopt an eco-reflexive approach to allow students to consider the benefits and risks of chemical compounds in household products, such as an anionic surfactant used in laundry detergents, and its impact on society, the economy and the environment in a South African context. This study can thereby also contribute to research regarding the knowledge and skills that first-year students gain when participating in learning opportunities specifically designed to foster the development of systems thinking skills.

1.6. AIM OF THE STUDY

To design teaching and assessment materials for developing systems thinking knowledge, skills, and attitude in first-year organic chemistry and to evaluate the effectiveness of the intervention to facilitate the development of systems thinking skills.

1.7. RESEARCH QUESTIONS

The research questions that guided this study are:

1. Which systems thinking skills were developing in first-year chemistry students as they engaged in a systems thinking intervention?
2. What evidence suggests that a sustainable action perspective was developing in first-year chemistry students?

1.8. OVERVIEW OF THE STUDY

This dissertation reports on the effectiveness of a systems thinking intervention implemented for first-year chemistry students enrolled in the second-semester organic chemistry module at the University of Pretoria. Evidence of students’ perceptions and reflections from questionnaire responses, focus group interviews, and demonstrated systems skills will be considered to answer the research questions above.

1.9. SEQUENCE OF THE RESEARCH REPORT

The sequence of this research report is shown in Figure 1.1. The literature review for this study will be presented in Chapter 2. This will be followed by an explanation of the design of the systems thinking intervention discussed from a teaching perspective, Chapter 3. Chapter 4 reports the methodology and research design, Chapters 5 on the findings and Chapter 6 raises a discussion from the researchers' perspective. Finally, this report will end with Chapter 7, where the conclusions and recommendations will be discussed from a teaching perspective and the researchers' perspective.

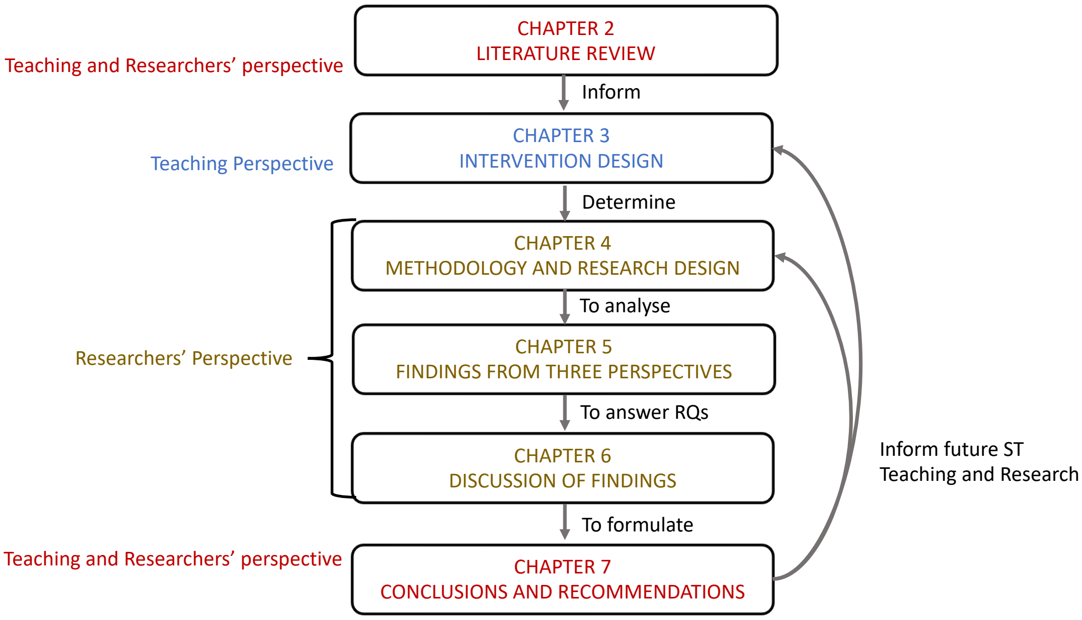


Figure 1.1. Overview of the sequence of the research report

1.10. CONCLUDING REMARKS

The motivation this study, was to contribute to chemistry education as it undergoes a paradigm shift to become a "science for society" and aims to equip students to deal with the uncertainty and complexity of future sustainability challenges. This ties nicely into the problem statement, which highlighted that students are not equipped to deal with sustainability challenges due to a lack of a systems thinking approach in chemistry. Students can be facilitated to develop systems thinking skills and a sustainable action perspective to address this problem. However, the teaching and assessment resources for implementing systems thinking in chemistry are limited. Therefore, this study aims to develop resources to foster systems thinking skills in students, motivate them to learn chemistry more meaningfully and inspire them to take sustainable action. Evidence of students' learning will be analysed to determine the extent to which students developed systems thinking skills and a sustainable action perspective. The findings can potentially inform future systems thinking teaching interventions and research in chemistry education.

CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

This chapter presents an overview of the literature considered relevant for this study. This chapter introduces Education for Sustainable Development (ESD), and the molecular basis of sustainability, where systems thinking (ST) is the common thread in both discussions. After that, these two topics are integrated into a discussion of Systems Thinking In Chemistry Education (STICE). This topic is then embedded into the following two sections: on developing systems thinking in first-year chemistry students and evaluating student learning. In the discussion on developing systems thinking, the skills and attitudes highlighted in the literature will be discussed, together with the visualization tools and the teaching of systems thinking. For the evaluation section, the assessment of systems thinking from a teacher's perspective and the analysis from a researcher's perspective will be shared to provide an overview of how student learning can be evaluated. To conclude this chapter, the discussed literature will be drawn upon to discuss the challenges and gaps of systems thinking in chemistry education research and the aims of this study to contribute to addressing the gaps and challenges as identified in the literature.

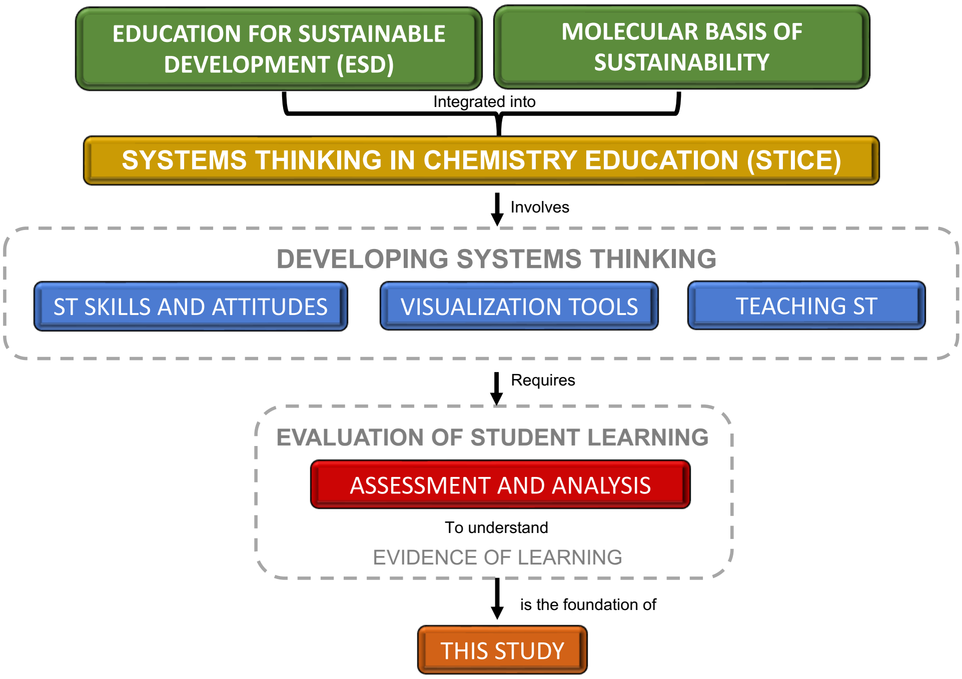


Figure 2.1. Overview of Chapter 2

2.2. EDUCATION FOR SUSTAINABLE DEVELOPMENT

This section will outline how Education for Sustainable Development can equip students with key competencies, such as systems thinking, so that they can deal with the complexity and uncertainty of future sustainability challenges.

EDUCATION FOR SUSTAINABLE DEVELOPMENT (ESD)

Aims to develop the capacity for **critical reflection**, **systemic** and **future thinking** and **motivates action** to promote **sustainable development** (UNECE Expert Group, 2012).

Figure 2.2. Aim of Education for Sustainable Development (UNECE Expert Group, 2012)

Ilya Prigogine (1997), a physical chemist who won the Noble Prize in 1997 for his work on complex physical systems, published a book titled "The End of Certainty" where he describes "we are observing the birth of a science that is no longer limited to idealized and simplified situations but reflects the complexity of the real world, a science that views us and our creativity as part of a fundamental trend present at all levels of nature" (Prigogine & Stengers, 1997). In this book, Ilya refers to an arrow of time that point towards uncertainty, irreversibility, non-linear behaviour and limited predictability. As we explore the sciences that describe the natural world's complexity, we also observe a similar arrow of time in our society threatening our future existence. This arrow of time represents the complex, irreversible and non-linear sustainability challenges passed on to a generation of young minds not equipped to deal with the uncertainty and complexity of our future.

Education oriented towards sustainability can equip students to deal with complex global issues and motivate them to take responsible action. Education for Sustainable Development (ESD) can contribute to preparing students to deal with the complexity and dynamism of global challenges as it aims to prepare critical reflection and systemic and future thinking to promote sustainable development, as shown in Figure 2.2. Introducing ESD can "empower learners to take informed decisions and responsible actions for environmental integrity, economic viability and a just society, for present and future generations, while respecting cultural diversity" (UNESCO, 2014). However, students require vital competencies, including knowledge, skills and attitudes, to deal with real-world sustainability challenges and opportunities (Wiek et al., 2011).

The UNECE Steering Committee on Education for Sustainable Development established an expert group with the mandate to identify a range of core competencies in ESD to facilitate its integration into all educational programs on all levels (UNECE Expert Group, 2012). The expert group recognized that a holistic approach to education is required that incorporates integrative thinking and dealing with complexities to prepare students for future learning. Students' need to be confronted with complex systems that are dynamic, self-organizing and adapting (Tripto et al., 2013). Wiek et al. (2011) identified systems thinking as one of the five key competencies for ESD as it involves "the ability to collectively analyze complex systems across different domains (society, environment, economy, etc.) and different scales (local to global), thereby considering cascading effects, inertia, feedback loops and other systemic features related to sustainability issues and sustainability problem-solving framework" (Redman, Wiek, & Barth, 2021; Wiek et al., 2011).

Systems thinking can be used to examine and address behaviours of a complex system from a more holistic perspective. Complex systems' behaviour cannot be predicted from isolated parts without interrelations between the parts (Hmelo-Silver & Azevedo, 2006; Wilensky & Resnick, 1999). Systems thinking involves visualizing the whole system through the interaction of its parts with its nonlinear and dynamic relationships (Assaraf & Orion, 2005; Hmelo-Silver & Azevedo, 2006). Systems thinking has been characterized by a two-dimensional perspective, which includes structural and procedural systems thinking (Brandstädter, Harms, & Großschedl, 2012; Sommer & Lücken, 2010). Brandstädter et al. (2012) defined structural systems thinking as "the ability to identify the system's relevant elements and interrelationships" which give structure and identity to the system. They defined procedural systems thinking as the "ability to define the dynamic and time-related processes that emerge from the systems' structure" (Brandstädter et al., 2012).

The structural and procedural characteristics of systems thinking align with the skills that students require to analyse the parts of the system that determine its identity and structure and to integrate the parts to create a fuller picture of the system with its complex interconnections. A systems thinking approach can therefore be seen as *"a bridge between a reductionist and holistic vision"* where parts are not isolated but interdependent to compose the identity and character of a whole phenomenon (Barile & Saviano, 2011). Systems thinking is, therefore, a critical competency in ESD as it can enable students to recognize the components and relationships within systems, from a local to a global scale, so that they are better prepared to deal with the complexity and uncertainty of future sustainability challenges.

2.3. THE MOLECULAR BASIS OF SUSTAINABILITY

In this section, the frameworks that connect and place chemistry at the center of sustainability will be discussed together with calls to reform chemistry education and its associated challenges.

MOLECULAR BASIS OF SUSTAINABILITY

*"How the **material basis** of **society** and **economy** underlie considerations of how p**resent and future generations** can live within the limits of the natural world."* (Anastas & Zimmerman, 2016)

Figure 2.3. Molecular basis of sustainability (Anastas & Zimmerman, 2016)

The United Nations Sustainable Development Goals (SDGs) and the Planetary Boundaries Framework were established to create awareness about humanity's role in sustainability and the urgency to respond to the challenges associated with sustainability. The planetary boundaries framework was established to illustrate a safe space in which humanity can operate to thrive

(Rockström et al., 2009; Steffen et al., 2015). The sustainable development goals (SDGs) concerning water (SDG6), climate (SDG13), ocean life (SDG14) and biodiversity (SDG15) explicitly include four of the nine planetary boundaries that connect chemical substances and processes to the environment, society, and economy (Rockström, 2021). Anastas and Zimmerman (2016) argued that chemistry can be considered to be the molecular basis of sustainability because it plays a foundational role in each of these spheres of life, as stated in the quote in Figure 2.3.

Since chemistry plays an essential role in human life and society, calls to reform chemistry education to include societal relevance have been on the rise. Matlin et al. (2016) proposed that chemistry should be re-imagined from “being a science” to “being a science for the benefit of society (Matlin, Mehta, Hopf, & Krief, 2016). Their concept of one-world chemistry was created so that chemistry can play a central role in tackling global challenges and addressing the SDGs to make meaningful contributions to our society (Matlin et al., 2016). Sjöström and Talanquer (2018) proposed that the concept of eco-reflexive *bildung* should be introduced into chemistry education, which involves taking a stance in our modern society to understand the complexity of life, society and their interactions, and assume responsibility towards socio-ecojustice and global sustainability (Sjöström & Talanquer, 2018). Mahaffy also proposed that Johnstone’s chemistry triplet requires a fourth dimension, which includes human context ,so that the interconnection between chemistry and society can be understood (Mahaffy, 2006).

Chemistry is a central science as it is integrated into our everyday lives and makes up the foundation from which all science disciplines branch (Mahaffy, Ho, et al., 2019). Chemistry is also considered to be a central science because it can explain, predict and control the behaviour of matter (Sjöström & Talanquer, 2018). Unfortunately, not enough attention has been given to the societal and environmental implications of the transformation of matter, which is one of the primary activities of chemistry (Mahaffy, Matlin, et al., 2019a). This is demonstrated by the widespread fragmented approach to chemistry education. Traditionally, most educators teach chemistry as isolated topics to simplify the inherent complexity embedded in chemistry and to reduce the possibility of an overcrowded curriculum and cognitive overload (Constable et al., 2019; Mahaffy, Matlin, et al., 2019a, 2019b; Pazicni & Flynn, 2019).

This has contributed to students' lack of understanding about the role and real-world implications of chemistry throughout different spheres of life and has resulted in the lack of knowledge required for addressing sustainability challenges (Mahaffy, Matlin, et al., 2019b). However, chemistry education can contribute to future sustainability. Powerful arguments have been put forward to integrate the molecular basis of sustainability into general chemistry modules with the use of a systems thinking approach (Mahaffy, Krief, Hopf, Mehta, & Matlin, 2018; Mahaffy, Matlin, et al., 2019a, 2019b; Orgill et al., 2019)

2.4. SYSTEMS THINKING IN CHEMISTRY EDUCATION

In this section, the literature discussed above concerning ESD and chemistry as the molecular basis of sustainability will now be integrated into a discussion about Systems Thinking In Chemistry Education (STICE). This discussion will outline the importance, components, and challenges of STICE.

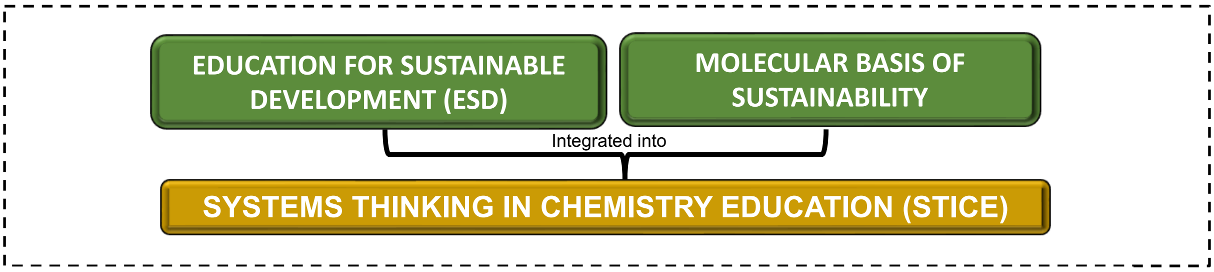


Figure 2.4. ESD and the molecular basis of sustainability are key considerations in STICE

Integrating a systems thinking approach in chemistry education can contribute to shaping a generation of systems thinkers who can relate their fundamental chemistry knowledge to human-environmental interactions and the sustainability agenda (Mahaffy, Matlin, et al., 2019b). Talanquer (2019) proposed that systems thinking in chemistry will consist of three components: mechanistic reasoning, a context-based focus, and a sustainable action perspective (Talanquer, 2019). Mechanistic reasoning in chemistry is required so that students can consider the processes that contribute to cause-and-effect interactions and the relationship between concepts and their organization based on their properties (Talanquer, 2019; Weinberg, 2018). A Context-based focus is required to foster meaningful understanding as students engage with real-world challenges and the role of chemistry (Talanquer, 2019). Lastly, students must adopt a sustainable action perspective to solve sustainability problems after critically evaluating the impacts and interrelationships between humans and the environment (Talanquer, 2019).

A systems thinking approach has been advocated in the chemistry education community to contribute towards guiding human action towards sustainability. However, some challenges have prevented its realisation in chemistry classrooms. Some of these challenges include limited systems thinking training and time to learn systems thinking, limited teaching resources and assessments, the lack of an operational definition for the practical implementation of STICE, time and curriculum coverage limitations and concerns regarding cognitive overload(Jackson & Hurst, 2021; Szozda, Bruyere, Lee, Mahaffy, & Flynn, 2022; York, Lavi, Dori, & Orgill, 2019)

The recent IUPAC project on STICE established global momentum by addressing some of these challenges, as published in a special issue of JCE in 2019 titled *“Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry”* (Holme & Mahaffy, 2019; Mahaffy, Brush, Haack, & Ho, 2019). The follow-up project that is also supported and funded by IUPAC, Systems Thinking in Chemistry for Sustainability: Towards 2030 and Beyond (STCS

2030+), aims to use a systems thinking approach in Chemistry to meet the 2030 UN Sustainable Development Goals (SDGs), to articulate the essential characteristics of systems thinking and to incorporate it into the chemical industry (IUPAC, 2020). The STCS 2030+ project proposed operational definitions to ensure consistency in the implementation of systems thinking in chemistry education (IUPAC, 2020).

These projects brought together a group of thought leaders in chemistry education to articulate strategies and develop exemplars to infuse systems thinking into chemistry education with a focus on general chemistry or first-year students (Mahaffy, Matlin, et al., 2019b). Pazicni and Flynn (2019) proposed that students' ability to develop systems thinking skills and demonstrate systems thinking knowledge are the essential learning outcomes that emerge from chemistry and systems thinking. Holme and Hutchison (2018) proposed introducing a central learning outcome (CLO) that can be used in STICE to stimulate students to consider both the benefits and risks of chemistry (Holme & Hutchison, 2018).

2.5. DEVELOPING SYSTEMS THINKING IN CHEMISTRY

In this section the focus will be placed on developing systems thinking skills and attitudes in first-year chemistry students, the visualization tools that can be incorporated with a systems thinking approach and how this approach can be implemented.

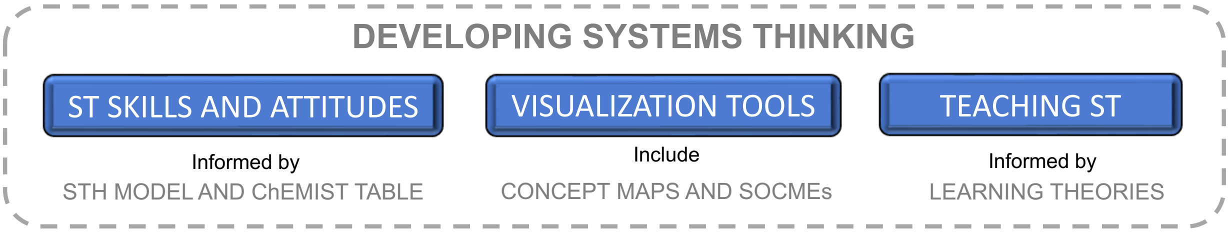


Figure 2.5. Outline of the section on developing systems thinking

2.5.1. SYSTEMS THINKING SKILLS AND ATTITUDES

Many systems researchers have contributed to identifying the characteristics of systems thinkers. Richmond managed to identify seven systems thinker skills: dynamic thinking, system-as-cause thinking, forest thinking, operational thinking, closed-loop thinking, quantitative thinking and scientific thinking (Richmond, 1993, 1997). Assaraf and Orion empirically derived eight systems thinking skills that developed hierarchically in a high school Earth sciences intervention, known as the Systems Thinking Hierarchical Model (STH Model) (Assaraf & Orion, 2005, 2010). The STH model is shown in Figure 2.6. It consists of three sequential levels, namely analysis, synthesis and implementation, with skills that are the “touchstones” that students acquire as they develop systems thinking skills.

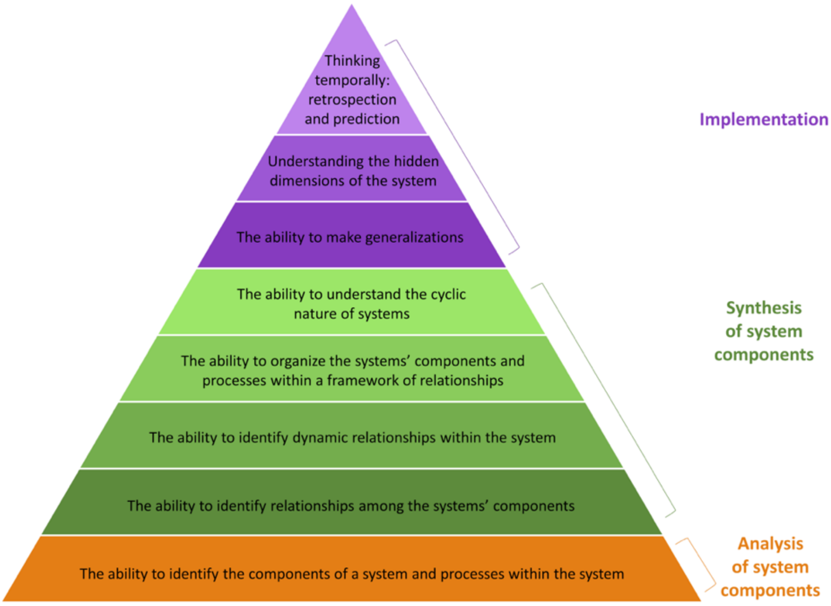


Figure 2.6. The STH model proposed by Assaraf and Orion (2005) adapted by York and Orgill (2019)

The STH model is hierarchical, and as students' progress along these stepping stones from analysis to synthesis and implementation, the skills become more challenging. The systems thinking skills include students' ability to identify components and processes within the system and the relationships in the system and dynamic relationships between these components. They then acquire the ability to organise the concepts and relationships within a boundary or framework of relationships, understand the cyclic behaviour of a system, make generalizations, identify the hidden dimensions and think temporarily, which includes retrospection and prediction (Assaraf & Orion, 2005; Orgill et al., 2019). Even though Assaraf and Orion (2005) recognized that the skills in the STH model aligned with higher-order abilities, they agreed with Resnick that thinking should not be limited to advanced levels of development, as elementary levels might be an integral part of learning (Resnick, 1987).

Orgill et al. (2019) proposed chemistry-relevant applications of the systems thinking skills reported by Richmond and the STH model (Orgill et al., 2019). More recently, York and Orgill (2020) developed a set of essential systems thinking characteristics for chemistry education and presented these characteristics as the ChEMIST table (**Ch**aracteristics **E**ssential for designing or **M**odifying **I**nstruction for a **S**ystems **T**hinking approach). The ChEMIST Table organised five general characteristics on an analytical-holistic continuum. These five essential characteristics are shown in Figure 2.7. below.

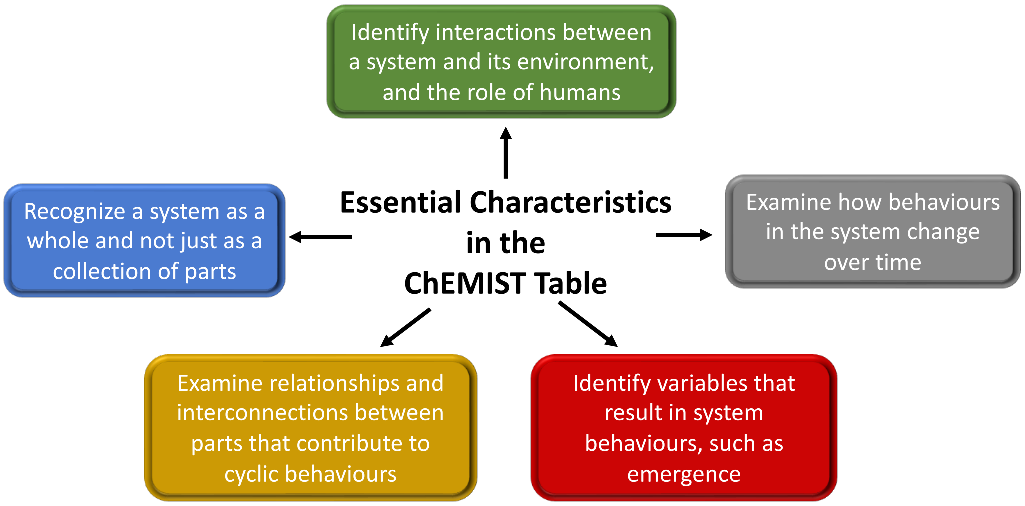


Figure 2.7. The five essential characteristics as outlined in the ChEMIST table (York & Orgill, 2020).

The ChEMIST table is a tool that can be used to design or modify systems thinking instructions, interventions, activities and resources to support chemistry teaching and learning with a systems thinking approach (York & Orgill, 2020). In chemistry, students should be encouraged to recognize a system as a whole and not just as a collection of parts, examine the relationships between the parts and possible cyclic behaviours, identify variables that cause system behaviours, such as emergent properties, examine the dynamic nature of the system and the interactions between a system and its environment, which include the role of humans (York & Orgill, 2020). In their paper, York and Orgill (2020) demonstrated how the characteristics outlined in the ChEMIST table align with the three components of chemical systems thinking proposed by Talanquer (2019), which include mechanistic reasoning, context-based reasoning, and a sustainable action perspective.

The systems thinking skills considered for this study are derived from the STH model shown in Figure 2.5 and the essential characteristics from the ChEMIST table shown in Figure 2.7. The skills and characteristics were combined into nine systems thinking skills and attitudes. These skills will be embedded into the learning outcomes of this study, which will be discussed further in Chapter 3.A systems thinker can visualize a system as a whole with all its interconnectedness and interacting parts. An *understanding* of the chemistry involved is considered to be the starting point for developing all systems thinking skills. *Elements* and *relationships* are considered part of analysis skills identified in the STH model. *Emergent properties*, *cyclic behaviours* and *dynamic interactions* align with the synthesis skills in the STH model. However, seeing that the term "synthesis" has a particular meaning in chemistry, we chose to refer to these skills as *integration* skills to avoid confusion in chemistry. *Application* and *ownership* are considered to be implementation skills as in the STH model. These skills are unpacked below to provide the context of these systems thinking skills in chemistry education

UNDERSTANDING

Students’ chemistry understanding in this study is concerned with their knowledge of the hidden dimensions in the system. Assaraf and Orion (2005) describe the hidden dimensions of the system as patterns and interrelationships that are not visible on the surface, but that can be exposed by expanding the systems’ borders. Orgill et al. (2019) acknowledged that these “invisible” elements could contribute to the behaviour of a system. The hidden dimensions are the submicroscopic and microscopic properties in chemistry that contribute to the macroscopic behaviour of the system. This structure-property relationship aligns with the central dogma of chemistry (Defever, Bruce, & Bhattacharyya, 2015). Defever et al. (2015) claim that the ability to understand the structures of molecules and interactions between molecules is a fundamental outcome of chemistry. It aids in understanding the chemical behaviour, observable characteristics, and macroscopic effects of substances. Orgill et al. (2019) explained with an example that the gas molecules in the NO system could be considered as the hidden dimensions that contribute to photochemical smog as a macroscopic system-level behaviour. Therefore the hidden dimensions that make up the structure of a system are the chemical and physical properties associated with the chemistry system under study. Students' ability to reason about the physical and chemical properties with supported explanations to understand phenomena with mechanistic reasoning has been proposed as a core component of STICE (Talanquer, 2019).

ELEMENTS

When studying the system, an analytical approach is required to describe the components and processes that make up a system's structure. The structural analysis of the system must be distinguished from its emerging system-level behaviour of (Barile & Saviano, 2011). It requires zooming in to identify the parts of the system and the components and processes involved. The analysis of components can be used to describe and predict the nature of a system because it results from cause-and-effect relationships between the parts (Orgill et al., 2019). In a chemistry system where photochemical smog is considered, the concepts, elements, or reactions that affect the amount of NO_2 should be identified, including the amount of NO or sunlight that influences smog formation (Orgill et al., 2019). Not only does analysis involve breaking the system into its constituent parts, but it also requires detecting how these parts relate to one another and the overall structure or purpose of the system (Gogus, 2012). Therefore, defining or describing relationships between concepts is also key to analysing the system.

RELATIONSHIPS

York and Orgill (2020) state that the relationships in a system are concerned with how components are connected. From a structural or analytical perspective, relationships require a point of reference, such as the system's elements, that do not emerge from the relation itself (Barile &

Saviano, 2011). Orgill et al. (2019) exemplified that the characteristics of the reactions involving NO can contribute to the system of smog formation. Assaraf and Orion (2005) stated that the connections could be related to potential effects on the system. Sommer and Lucken (2010) stated that the elements and relationships within a system contribute to its structure and function. Therefore, meaningful connections and interactions between the system components contribute to the overall purpose. Therefore, students' ability to recognize the interconnections between the parts of a system can enable them to visualize the whole system. Systems thinking is a school of thought that deals with the recognition of patterns and interrelationships together with structuring it into efficient ways of thinking about the system (Harris, 1990). Integration of these relationships at a system's level contributes to dynamic interactions, cyclic behaviours, and emergent properties that all require structuring or organizational skills to comprehend the bigger picture. These skills are described below.

ORGANIZATION

Students' ability to organise the components and processes of a system into a framework of relationships is a crucial skill associated with systems thinking. Each system has boundaries within which the relevant elements contributing to the system-level behaviour are included (York & Orgill, 2020). Boundaries allow the system to be distinguished from its surroundings, and it allows us to describe what is included and excluded from the area of focus. The boundaries enable thinking about how the system is influenced by its environment, how it is connected to other systems and how it connects to a more extensive system (York & Orgill, 2020). Ho (2019) asserted that system boundaries could have layers of systems and subsystems, and there are no definitive ways of drawing them, which reveals the range of purposes and depth of knowledge involved in the discipline of chemistry (Ho, 2019). Therefore, systems with large boundaries can have smaller subsystem boundaries, which can contribute to a better understanding of the whole system. However, Pazicni and Flynn (2019) warned that narrow system boundaries diminishes the true nature of a system as it limits the connections amongst chemistry elements. But also, if system boundaries are too broad it can contribute to cognitive overload. Therefore, the organization of these parts can be the foundation for understanding the system as a whole (York & Orgill, 2020). In the photochemical smog system, the rates of NO_2 production and decomposition in production and decomposition subsystems can be considered together to understand how these processes might affect the concentration of NO_2 (Orgill et al., 2019).

DYNAMIC RELATIONSHIPS

The construct of dynamic interactions focuses on the relationships between components in a system and how they affect each other over time (York & Orgill, 2020). In the context of a dynamic system, the interactions between elements and relationships are "*subject to constant evolution*" (Barile & Saviano, 2011). Barile and Saviano (2011) better described these relationships as interactions as they have a dynamic nature and depend on what is observed from the observer's specific perspective of the investigation of reality. Changes in a system's stability can result from feedback loops or changing behaviours over time. Booth-Sweeney and Sterman (2007) asserted that these feedback loops and dynamic relationships, must be recognized to understand complex systems (Sweeney & Sterman, 2007). Yoon et al. (2008) stated that in educational systems, studying dynamic interactions can contribute to an enhanced understanding of a global phenomenon (Yoon, 2008). Assaraf and Orion (2005) also agree that identifying system dynamics provides a way to understand the relationships between elements and their contribution to the whole system.

CYCLIC BEHAVIOURS

Students' ability to understand the cyclic behaviours of systems has to do with their ability to identify the repeating patterns in a system and the causes of these patterns (Orgill et al., 2019). System behaviours can have cyclic patterns that result from interacting feedback loops that students can visualize with closed-looped thinking (York & Orgill, 2020). Closed-loop thinking requires thinking about non-linear relationships in complex systems and how variables influence each other, whether through feedback loops or time delays (York & Orgill, 2020). Assaraf and Orion (2005) explained the idea of cyclic systems from the viewpoint that "we live in a cycling world", and systems can potentially consist of several smaller cycles. Orgill et al. (2019) demonstrated this concept in the NO system, where concentrations can change during the day, influencing photochemical smog formation.

EMERGENT PROPERTIES

From a scientist's perspective, emergence is a core characteristic of a system. Yoon et al. (2018) explained that emergence is a dynamic process in the system that arises from the interactions between the parts of the system, which contribute to system characteristics (Yoon, Goh, & Park, 2018). Emergence is a process of forming new collective entities established by the coherent behaviour of interacting elements, which cannot be predicted based on the properties of parts alone (Barile & Saviano, 2011; Orgill et al., 2019). Emergence is fundamental to chemistry as components at a sub-microscopic or microscopic level can contribute to macro-level patterns with entirely different characteristics than the individual components in the system. Luisi (2002) emphasized that "emergence is a basic characteristic of the molecular sciences" (Luisi, 2002). Students' ability to understand the emergent behaviour of chemical components and processes is key to their future understanding of chemistry (Talanquer, 2015). The ability to identify emergent properties was not empirically derived in the STH model; however, it is presented in the ChEMIST table as one of the essential characteristics of systems thinking in chemistry (York & Orgill, 2020).

PREDICTIONS AND GENERALIZATIONS

A student's ability to make predictions and generalizations is a critical skill in systems thinking. Students can study the patterns of system-level behaviour over time under one set of conditions and make predictions under another set of conditions (York & Orgill, 2020). This skill enables students to recognize yet again the non-linearity of a system, whereby dynamic thinking underpins students' ability to make predictions about future behaviour. Making predictions requires applying other skills, such as recognizing the dynamic relationships and cyclic and emergent behaviour of a system, to understand how changing one component or process can result in a complete change in the pattern and behaviour of the system. Assaraf & Orion (2005) stated that generalizations in a system could be expressed by understanding the cyclic and dynamic nature of the system, which can influence predictions and thinking forward, for example, on preventing environmental threats in the system. In chemistry, predictions are made based on the changing patterns within one system that can provide information about other systems (Orgill et al., 2019). For example, in the photochemical smog system, the concentrations of atmospheric gasses could be altered in the presence of NO_2 (Orgill et al., 2019). Therefore, making predictions in a chemistry system could involve recognizing patterns and predicting future behaviour when variables are altered.

OWNERSHIP

The ability to consider the role of human actions on current and future system-level behaviour is one of the essential characteristics of STICE (York & Orgill, 2020). In a chemistry system, students can predict human actions' influence on increasing or reducing NO_2, which can influence future air quality in the photochemical smog system (Orgill et al., 2019). Students' ability to apply these skills to consider their role in future sustainability can foster a sustainable action perspective (Talanquer, 2019). If students develop a sustainable action perspective, it could, over time, build a new generation of knowledgeable citizens willing and able to change the planet's future through their actions (Orgill et al., 2019; Talanquer, 2019). Ownership is about taking the initiative to address a problem. Ownership results from changing one's thinking and could lead to opportunities for taking responsible action and making informed decisions towards sustainability. To take ownership, temporal thinking is required, which includes thinking about the past, recognizing the problem, and thinking about the future. Thinking temporally has been associated with understanding how past actions have influenced the current system's behaviour, and how present actions can influence the system's future behaviour (Orgill et al., 2019). Assaraf and Orion (2005) fostered the growth of temporal thinking by getting students to think about the present system and predict how changes can occur due to human influences (Assaraf & Orion, 2005).This skill was identified as the most challenging in the STH model, requiring analysis, integration and implementation skills.

2.5.2. SYSTEMS THINKING VISUALIZATION TOOLS

Systems thinking involves visualizing a system as *"a whole through the interaction of its parts"* (Assaraf & Orion, 2005). However, the ability to visualize the system's interconnectedness is inherently complex as a system cannot be predicted by studying isolated parts without the interrelations between the parts (Hmelo-Silver & Azevedo, 2006; Wilensky & Resnick, 1999). Several visualization tools have been reported and implemented to reduce the complexity associated with visualizing the systems' interconnections (Aubrecht et al., 2019; Mahaffy, Matlin, et al., 2019b). These visualization tools include concept maps, System-Oriented Concept Map Extensions (SOCMEs), systemigrams, Object Process Methodology tools, behaviour over time graphs, causal loop and stock and flow diagrams (Aubrecht et al., 2019). These tools can illustrate positive and negative system behaviours, represent boundaries to group system components and aid in visualizing causal relationships and impacts of variables on systems. Visualization tools can aid students in connecting the parts within the system to create an understanding of the holistic nature of the chemistry system under study. In this study, concept maps and SOCMEs will be used as the knowledge frameworks onto which students organize and depict their prior and newly acquired knowledge of the chemistry of surfactants and their role in various subsystems. These visualization tools can also facilitate the development of systems thinking skills as students explore the complex interconnections, the non-linearity of relationships, and subsystem boundaries of a system to grasp the overall complexity of a system (Aubrecht et al., 2019). The use of concept maps and SOCMEs as visualization tools in systems thinking will be discussed below.

CONCEPT MAPS

Concept maps are representations of mental models that contain concepts and relationships that are used to build cognitive propositions that represent ideas (Brandstädter et al., 2012; Yin, Vanides, Ruiz-Primo, Ayala, & Shavelson, 2004). Novak and Cañas (2008) reported that concept mapping is a powerful tool that can facilitate meaningful learning as it can act as a scaffold to help organize and structure knowledge (Novak & Cañas, 2008). Concept maps contribute to knowledge transfer through acquisition, communication, application, acceptance, and assimilation (Šket, Aleksij Glažar, & Vogrinc, 2015). Hierarchical concept maps are considered traditional and allow for a clear arrangement of concepts, reducing cognitive overload and enhancing learning capability (Paas, 1992). Concept maps can be highly directed, where concepts and linking words are given, or they could be nondirected, where concepts and linking words are withheld (Brandstädter et al., 2012). Brandstädter (2012) reported that computer-based and highly directed concept mapping positively influenced student performance in an intervention implemented in a biology class. If concept maps are highly directed, they can act as skeleton maps that can be expanded as part of scaffolded learning (Novak & Cañas, 2008).

Concept maps have been identified as a reliable method to engage students in systems thinking as cognitive mapping and systems thinking share structure, dynamism and hierarchy (Tripto et al., 2013). Stewart (2012) used concept mapping to develop complex system learning in undergraduate students and reported that most students improved their connectivity in thinking (Stewart, 2012). In Chemistry, concept maps have been identified as a helpful tool that can improve students' understanding of chemical concepts (Francisco, Nakhleh, Nurrenbern, & Miller, 2002; Nicoll, 2001). Nicoll (2001) and Cullen (1990) reported that concept maps have great potential to help students make connections in chemistry and can help them "learn how to learn" chemistry (Cullen, 1990; Nicoll, 2001). Šket (2015) used concept maps to facilitate interrelation in the topic of organic reactions and reported that it contributed to effective problem solving (Šket et al., 2015).

Concept maps have also been used to facilitate the development of systems thinking skills in chemistry. Vachiolotis (2014) incorporated concept mapping techniques to elicit systems thinking skills in chemistry and reported a significant link between students' systems thinking level and meaningful understanding (Vachliotis, Salta, & Tzougraki, 2014). Most recently, Szozda et al. (2022) implemented a systems thinking intervention in chemistry to investigate the systems thinking skills that were elicited on concept maps in a topic related to climate change (Szozda, Mahaffy, & Flynn, 2022).

SOCME DIAGRAMS

System-Oriented Concept Map extensions (SOCMEs) are extensions to concept maps devised to explore the interconnectedness of subsystems and their boundaries. SOCME diagrams have been reported as practical visualization tools in science education to integrate complex ideas with boundaries and interconnections (Aubrecht et al., 2019; Mahaffy, Ho, et al., 2019; Mahaffy et al., 2018; Mahaffy, Matlin,et al., 2019a). This visualization tool encourages students to explore the implications of complex phenomena and will aid in students' ability to conceptualize complexity within science disciplines (Aubrecht et al., 2019; Rousseau, Billingham, & Calvo-Amodio, 2018). In Chemistry, SOCMEs can be used to understand the molecular basis of sustainability and the impact of chemistry on various social, economic, and environmental subsystems (Mahaffy, Matlin, et al., 2019b). Multiple authors have suggested systems thinking teaching activities that involve the construction of SOCMEs related to systems thinking learning outcomes in chemistry (Mahaffy, Matlin, et al., 2019b; Pazicni & Flynn, 2019). Only a few SOCME diagrams have been reported in the literature up until now. Mahaffy et al. (2019) constructed a SOCME diagram of Ammonia, with all its subsystems and intended and unintended consequences (Mahaffy, Matlin, et al., 2019b). Another SOCME was constructed to illustrate the interconnections of various subsystems involved in the production of anthropogenic CO_2 and its role in the global carbon cycle (Mahaffy, Matlin, et al., 2019a). Jackson and Hurst (2021) reported a SOCME for the production of polystyrene. Holme (2020) implemented an enrichment activity for postgraduate students involving the construction of a SOCME about the chemistry of pharmaceuticals, see Figure 2.8. below, and reported that his systems thinking intervention holds significant promise to develop systems thinking skills in chemistry students (Holme, 2020).

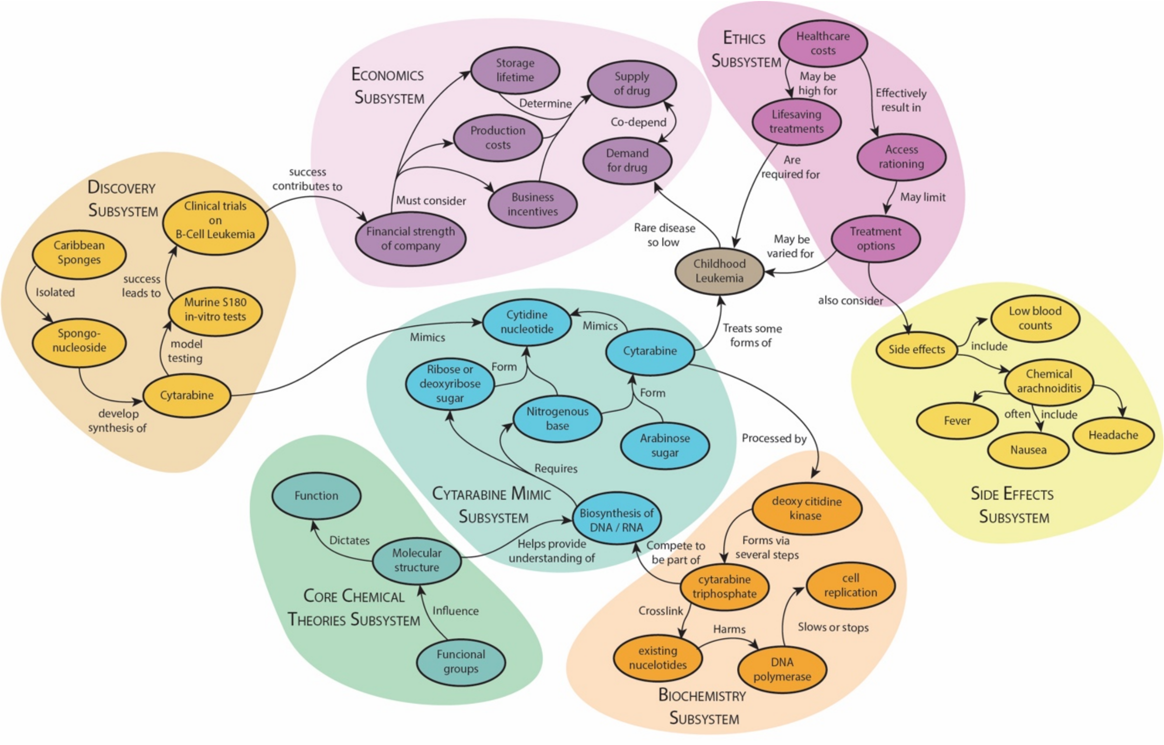


Figure 2.8. SOCME diagram of the drug cytarabine and its influence on various subsystems (Holme, 2020).

VISUALIZING SYSTEMS THINKING IN CHEMISTRY

Visualization tools, such as concept maps and SOCMEs, aid in exploring the complex interconnectedness, non-linearity and subsystem boundaries of a system (Aubrecht et al., 2019). Visualizing the dynamic and nonlinear relationships requires the ability to *"understand the multi-level structure"* of various components and processes (Hmelo-Silver & Azevedo, 2006). However, a system's multi-level structure depends on the granularity at which the system is viewed. The system can be viewed from a molecular level, a subsystem or a systems level. Meaningful understanding is encouraged as students create relationships, draw conclusions and make future predictions about chemical phenomena (Vachliotis et al., 2014). In chemistry, multi-level thinking is required to conceptualize the complexity between submicroscopic, macroscopic and chemical phenomena from representational, explanatory, and phenomenological perspectives (Pazicni & Flynn, 2019; Taber, 2013). Understanding the structure and interactions between molecules within the system is a fundamental outcome of chemistry (Defever et al., 2015). As the level of granularity changes to view the whole system, the molecular level foundation becomes "hidden" but still influences the interacting components within boundaries on a systems level. Incorporating concept maps and SOCMEs to develop systems thinking requires careful consideration to facilitate meaningful learning in chemistry and reduce possible cognitive overload. These teaching considerations are outlined in the following section.

2.5.3. TEACHING SYSTEMS THINKING IN CHEMISTRY

In this section, the theoretical underpinning of systems thinking interventions will be discussed concerning learning frameworks commonly used in chemistry education. These frameworks, which include constructivism, meaningful learning, and cognitive load theory, have been identified as suitable for a systems thinking instructional approach (Pazicni & Flynn, 2019).

CONSTRUCTIVISM AND MEANINGFUL LEARNING

Constructivism and meaningful learning form part of the theoretical underpinning for teaching and learning systems thinking in first-year chemistry. Students' progression to higher levels of understanding is considered to be a result of their active involvement in continuously constructing and reconstructing their knowledge (Donald, Lazarus, & Moolla, 2014). Meaningful learning is achieved when students can purposefully link new knowledge to their existing knowledge frameworks (Ausubel, 1968). A systems thinking approach can facilitate connecting students' prior knowledge to relevant and real-world knowledge, enabling them to visualize chemistry as a unified system that connects to their human experience (Pazicni & Flynn, 2019). This requires lecturers to leverage a broad range of prior knowledge when employing a systems thinking approach (Pazicni & Flynn, 2019). Lecturers can also motivate students to learn more meaningfully by incorporating relevant experiences and content so that students can connect the new knowledge across the cognitive, psychomotor, and affective domains of learning (Bretz, 2001; Novak & Cañas, 2008).

The cognitive and psychomotor domains should be incorporated by ensuring that active agency is integrated into the design of the systems thinking teaching intervention. Students should be guided to draw on their prior chemistry knowledge and apply reasoning to make connections to understand a system's emerging behaviours, dynamic interactions, and cyclic nature. Concept maps and SOCME diagrams can enable students to connect their prior knowledge with newly acquired knowledge to visualize the complex interconnections of a system and learn chemistry in a more meaningful way. Systems thinking interventions should also encourage collaboration with "more capable peers" to promote cognitive development within their zones of proximal development (ZPD) (Pazicni & Flynn, 2019). Novak's learning theory states that "meaningful learning underlies the constructive integration of thinking, feeling, and acting, leading to human empowerment for commitment and responsibility" (Bretz, 2001; Novak, 2011). In the affective domain, a systems thinking approach can encourage meaningful learning by incorporating a relevancy motif and inspire chemistry students to take ownership to become agents of change for the benefit of society.

COGNITIVE LOAD THEORY

Cognitive Load Theory can guide the instructional design of systems thinking interventions in chemistry. This theory is an information-processing model that augments constructivist learning theories (Bentley & Sieben, 2019). The Information Processing Model (IPM), which explains how information is processed from sensory inputs into working memory and then stored in long-term memory, represents Cognitive Load Theory (CLT). Two factors relevant to CLT in a systems thinking approach are attention and working memory. Pazicni & Flynn (2019) recognized that skills lower in the STH model would be affected most if the representations are not meaningful, interesting or culturally relevant enough to hold students' attention. Students' working memory should also be considered, especially as skills higher up in the STH model constitute a higher cognitive demand (Pazicni & Flynn, 2019).

CLT considers the number of concepts simultaneously processed in the working memory during the learning of complex cognitive tasks (Paas, Gog, & Sweller, 2010). Students working memories are used to hold and process information (Johnstone, 2010). Johnstone was one of the first to consider working memory limits in chemistry and stated that students could hold "seven plus or minus two" units of knowledge at a time. He also stated that if there is too much information to hold in the working memory, then there will not be enough space for processing. By exceeding the limits of the working memory, learning can become ineffective and students are at risk of not understanding the content (Centre for Education Statistics and Evaluation, 2017). Therefore, a fundamental pillar throughout the design of systems thinking teaching resources and activities is to ensure that the cognitive load experienced by students is minimized. This is a challenging task as the inherent complexity of systems thinking can be overwhelming, not to mention its integration with chemistry, which is a difficult subject (Johnstone, 2010; Taber, 2013).

To reduce the cognitive load that students can potentially experience during systems thinking activities, visualization tools can be used as "scaffolds" to guide the learning process and to reduce the number of concepts and connections that students process simultaneously. Novak recommended the expansion of concept maps as skeleton frameworks from 20 concepts to 50-60 concepts to encourage high cognitive performance (Novak & Cañas, 2008). SOCMEs can also reduce cognitive overload, as a zoom-in and zoom-out strategy can be used during instruction to direct students' attention towards a specific subsystem (Pazicni & Flynn, 2019). In addition, group work and cooperative learning can allow students to share their cognitive load with their peers and in this way, students can be encouraged to steer away from rote learning to retain new knowledge in their long-term memories (Novak & Cañas, 2008). For this reason, it is important to promote social interactions throughout the activities so that students can utilize their metacognitive processes to attain higher-level skills as associated with the STH model (Assaraf & Orion, 2005; Pazicni & Flynn, 2019).

SUGGESTIONS FOR IMPLEMENTATION

Mahaffy et al. (2019) provided suggestions for the implementation of STICE to address the challenges of systems thinking, which include dealing with the complexity of expanding boundaries and including interconnections, dynamic behaviours, emergence and cyclic behaviour in chemistry, especially for students who are used to a reductionist perspective in chemistry. They suggested that the learning outcomes must be carefully considered to connect chemistry to “the dynamic, complex social, technological, economic, and environmental systems at work in our world.” and to teach the risks and benefits of chemistry and our role in the primary activities of chemistry. Also, that training must be provided to instructors to use systems thinking assessment and visualization tools such as concept maps and SOCMEs before implementation. It was noted that the STH model could be helpful in developing systems thinking skills from analysis to synthesis to implementation, including generalizations, hidden dimensions, and temporal thinking. However, the model requires refinement in a chemistry context. As discussed above, it was suggested to include learning theories to enhance meaningful learning and minimize cognitive load. Lastly, Mahaffy et al. (2019) also suggested that the molecular basis of sustainability must be integrated throughout the teaching of systems thinking in chemistry.

2.6. EVALUATING LEARNING OF SYSTEMS THINKING IN CHEMISTRY

In this section, the evaluation of student learning in systems thinking in chemistry will be discussed by providing an overview of the literature on the assessment of systems thinking learning from a teaching perspective and the analysis of systems thinking learning from a researcher’s perspective. In this study, we define evaluation as an overarching term that includes *assessment* and *analysis* to judge the educational gains achieved from this entire study. Assessment is the process whereby scores are assigned to measure students' learning progress. Analysis refers to interrogating evidence of the development of systems thinking skills for research purposes.

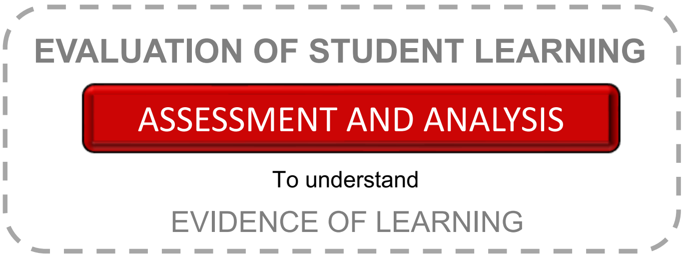


Figure 2.9. Evaluation of students’ systems thinking learning with assessment and analysis

2.6.1. ASSESSING SYSTEMS THINKING FROM A TEACHING PERSPECTIVE

Assessments are required to obtain feedback regarding students' progress in achieving the intended learning outcomes. Assessments elicit evidence of students learning based on their performance as they represent their knowledge and develop competence (Pazicni & Flynn, 2019). Formative and summative assessments of chemical systems thinking must align with the core components of systems thinking, which include a mechanistic reasoning approach, a context-based focus and a sustainable action perspective (Talanquer, 2019). According to Talanquer a sustainable action perspective is the ability to critically analyse complex interactions between societal and environmental systems and to engage in global sustainability by taking responsible action. Talanquer outlined that the core objectives when assessing systems thinking in chemistry should include the following:

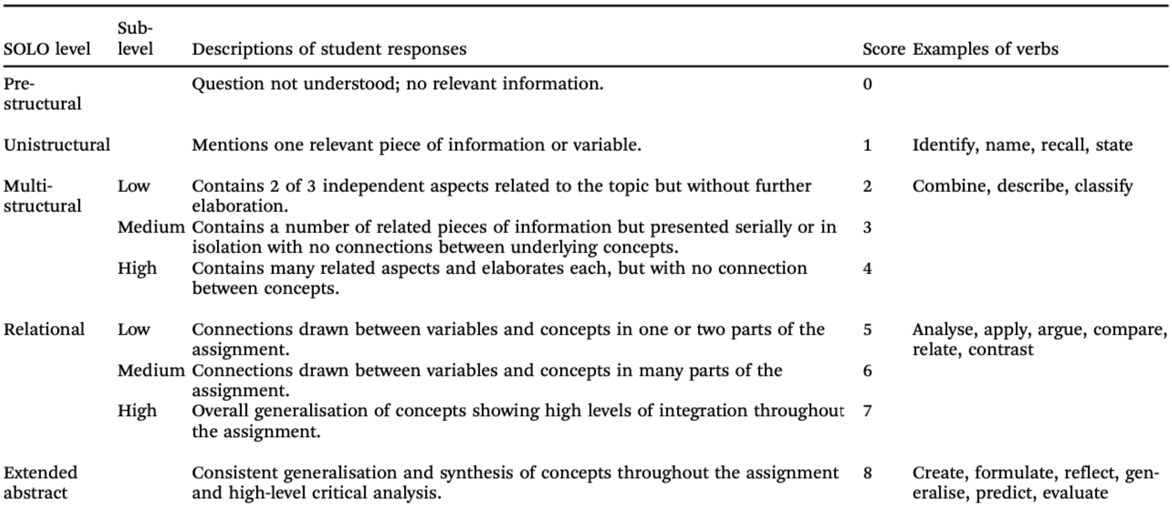
i) assessing the application of relevant understanding through reasoning,
ii) constructing models for productive integration of relevant chemical knowledge
iii) apply a reflective approach to chemistry, which includes sustainable action and reasoning about the society, economic, environmental and individual dimensions

Since STICE emerged recently as a new teaching approach, the development of assessment tools to assess systems thinking learning and skills in chemistry is limited. York et al. (2019) proposed that the assessment tools used in STEM education can also be used to assess STICE. as it draws from the same conceptual framework. The assessment tools used in STEM education can be grouped into rubrics with scoring guidelines, closed-ended tools such as questionnaires and coding schemes to assess written responses (York et al., 2019). Talanquer used scenario-based formative and summative assessments to evaluate first-year undergraduate students' ability to apply systems thinking. Vachiolotis et al. (2014) assessed students' systems thinking level and their meaningful understanding from systematic assessment questions (SAQs), which are presented as a concept map with a closed and cyclic systemic diagram. Lavi and Dori (2019) created an assessment rubric for conceptual models and written responses, for the evaluation of systems thinking skills relating to the function-structure behaviour (Lavi & Dori, 2019; York et al., 2019). Concept maps have also been widely used as tools to assess students' conceptual understanding and learning in STEM education (Besterfield-Sacre, Gerchak, Lyons, Shuman, & Wolfe, 2004; Martin, Mintzes, & Clavijo, 2000; Nicoll, 2001; Rye & Rubba, 1998; Songer & Mintzes, 1994).

Assessment rubrics have been used to directly assess systems thinking made evident by concept maps (Brandstädter et al., 2012; Stewart, 2012; Tripto et al., 2013; York et al., 2019). However, the quantification of concept maps remains controversial (Assaraf & Orion, 2005). 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" (Novak, 1990). Novak and Gowin (1984) suggested scoring with criteria to assess the number and significance of links between concepts and their hierarchy and provided examples (Novak & Gowin, 1984). White and Gunstone (1992) suggested refraining from scoring concept maps but instead assessing the amount of detail, variety of relationships and patterns in the concept maps (White & Gunstone, 1992). Concerns regarding the validity of concept mapping scoring mechanisms led to the idea that concept maps can be used to qualitatively assess learning over time by comparing concept maps before and after interventions (Hay, 2007; Pearsall, Skipper, & Mintzes, 1997; Ruiz-Primo & Shavelson, 1996; Stewart, 2012).

David Hay (2007) explained that learning is meaningful when there is evidence of deep learning, which can be seen from increased structural complexity and the integration of new knowledge with pre-existing knowledge. The Structure of Observed Learning Outcomes (SOLO) taxonomy was developed by Biggs et al. (1982) as a tool to judge learning quality in terms of progressive structural complexity. The SOLO taxonomy can be used to assess the quality of learning retrospectively in an objective and systematic way (Biggs, 1982). In our educational milieu, formative and summative assessments are required to drive learning and to get feedback about students' progress. However, unfortunately, quantity (how much is being learned) counts more than quality (how well something is being learned) (Biggs, 1982). Therefore, the SOLO taxonomy can also give a sense of absolute score so that performance can be judged based on acceptable and unacceptable levels.

Stewart (2012) modified the SOLO taxonomy and sublevels, based on the work of Biggs et al. (1982) and Chan et al. (2002), to measure the differences in complexity that students demonstrated during a concept mapping activity (Chan, Tsui, Chan, & Hong, 2002; Stewart, 2012). Stewart (2012) created a rubric and assigned SOLO coding scores to each SOLO level and reported it as an effective assessment tool that can be used to evaluate concept maps. Vogelzang (2020) modified the SOLO taxonomy rubric obtained from Stewart to measure students' quality of responses based on SOLO levels in chemistry (Vogelzang, Admiraal, & Van Driel, 2020). This is shown in Figure 2.10. below.



SOLO level	Sub-level	Descriptions of student responses	Score	Examples of verbs
Pre-structural		Question not understood; no relevant information.	0	
Unistructural		Mentions one relevant piece of information or variable.	1	Identify, name, recall, state
Multi-structural	Low	Contains 2 of 3 independent aspects related to the topic but without further elaboration.	2	Combine, describe, classify
	Medium	Contains a number of related pieces of information but presented serially or in isolation with no connections between underlying concepts.	3	
	High	Contains many related aspects and elaborates each, but with no connection between concepts.	4	
Relational	Low	Connections drawn between variables and concepts in one or two parts of the assignment.	5	Analyse, apply, argue, compare, relate, contrast
	Medium	Connections drawn between variables and concepts in many parts of the assignment.	6	
	High	Overall generalisation of concepts showing high levels of integration throughout the assignment.	7	
Extended abstract		Consistent generalisation and synthesis of concepts throughout the assignment and high-level critical analysis.	8	Create, formulate, reflect, generalise, predict, evaluate

Figure 2.10. SOLO levels, sub-levels, scores and verb examples (Vogelzang et al, 2020)

The SOLO taxonomy can measure the growth from surface learning to deep learning in five stages of SOLO levels, as shown in Figure 2.10. These SOLO levels indicate that the quality of learning can be on a pre-structural, unistructural, multi-structural, relational and extended abstract level of complexity (Biggs, 1982; Potter & Kustra, 2012; Stewart, 2012). Pre-structural answers demonstrate that students are incapable of answering or do not understand the question (Biggs, 1982; Potter & Kustra, 2012). At a unistructural level, students can identify simple connections and understand relevant parts of the whole. In contrast, at the multi-structural level, students understand more about the whole but find it challenging to see organization and significance in the system (Potter & Kustra, 2012). For the relational levels, students can integrate concepts into a whole by examining feedback loops and changes over time to recognize the interconnections within and between subsystems. At the extended abstract level, students can generalize, make predictions and organize systems components to understand the whole system (Potter & Kustra, 2012).

As indicated in the discussion above, we conclude that the SOLO taxonomy can be used to assess the increasing level of abstractness that is demonstrated on concept maps as reported by Stewart (2012) and it can be used to assess learning chemistry as reported by Vogelzang et al. (2020). Chan et al. (2002) also reported that the SOLO taxonomy can be used as an assessment tool in different kinds of subjects, with students of different ages (including undergraduate students) and for different types of assignments. However, as far as we are aware the use of the SOLO taxonomy to assess systems thinking skills has not been reported in the literature yet.

2.6.2. ANALYSING SYSTEMS THINKING FROM A RESEARCHERS’ PERSPECTIVE

Many assessment tools discussed above can also be valuable for getting insights about students’ learning from a researcher's perspective. Student learning of systems thinking and skills development can be analysed using various data collection tools, such as concept maps, rubrics and questionnaires, to understand students’ experiences, perceptions and what they have learned during a teaching intervention. These tools can be used as diagnostic tools to identify areas in teaching that require future improvement and to understand participant outcomes and the effectiveness of systems thinking teaching intervention. Since visualization tools are core to this study, literature with regards to analysing developing systems thinking learning from concept maps and SOCME diagrams will be discussed.

Concept maps can be considered adequate tools to analyse students' learning of systems thinking (Sommer & Lücken, 2010). Although using maps to gather evidence is a relatively new phenomenon, they provide a useful and novel way to communicate meaning and knowledge (Wheeldon & Faubert, 2009). Concept maps are graphical representations of reality in a short timeframe that can “provide a visual snapshot of experience from which to ground theory within the data" (Wheeldon & Faubert, 2009). According to Bretz (2001), it is a valuable tool used by constructivist researchers who emphasize the process to understand better how students learn meaningfully. Brandstädter (2012) also reported that concept maps could be used to assess mental models, which are cognitive representations of ideas to evaluate students' conceptual understanding.

Concept maps have been used in STEM education to assess systems thinking. Its use has been reported in Earth Sciences by Assaraf and Orion (2005) and Stewart (2012), in Biology by Brandstädter et al. (2012) and Tripto (2013), and in Science and Engineering education for teachers by Lavi and Dori (2019) to name a few. Concept maps have been used to assess developing systems thinking skills from the STH model in Earth Sciences and Biology (Assaraf & Orion, 2005; Tripto et al., 2013). Assaraf and Orion assessed the demonstrated systems thinking skills that resulted in the STH model from concept maps based on the number of concepts, linkages, and organization. Szozda et al. (2022) assessed emerging systems thinking skills from the ChEMIST table on concept maps using network motifs, modes of reasoning, a granularity scale and an environmental and sustainability triangular model (Szozda et al., 2022). They formulated an assessment rubric that can be used in the future to assess systems thinking skills from concept maps and verbal responses. Szozda's study is one of the first to analyse students' systems thinking skills on concept maps in a chemistry context (Szozda et al., 2022).

From this discussion, it is evident that much research has been done on analysing systems thinking skills from concept maps, with only limited studies within the chemistry context. Also, research has yet to be done on analysing systems thinking skills from SOCME diagrams. This study will address this gap in the literature.

2.7. THIS STUDY

The above discussion presented evidence of the use of visualization tools to teach, assess and analyse systems thinking in STEM disciplines. However, limited contributions have been made in chemistry education to advance teaching and assessing systems thinking with visualization tools from a teaching perspective and analyse the development of systems thinking from visualization tools from a researcher's perspective. Systems thinking teaching activities have not been implemented widely because of the challenge associated with the lack of available teaching resources and assessment tools (Mahaffy, Matlin, et al., 2019a). York et al.(2019) reported that assessment in systems thinking is important as it can guide student learning and curriculum development, however many questions are left unanswered about the systems thinking skills that should be assessed in chemistry, the assessment tools that should be used, the scale of assessment and the tools to analyse systems thinking learning for research.

To address the challenge concerning the shortage of systems thinking teaching and assessment resources and to contribute to addressing the gap in the research, this study seeks to design a systems thinking teaching intervention that incorporates concept maps and SOCME diagrams as visualization tools to scaffold the development of systems thinking skills in first-year organic chemistry students. The literature presented has shown that concept maps and SOCMEs can be used to facilitate meaningful learning in chemistry, and SOCMEs can provide a zoom-in and out approach that could help to minimize cognitive overload. It might be too challenging for first-year students to construct a SOCME diagram with limited or no prior systems thinking or concept mapping skills, and therefore in this study, a partial SOCME will be provided so that students can expand it.

The literature presented also highlighted that concept maps can be valuable as assessment tools from a teaching perspective. This study will use a rubric based on the SOLO taxonomy to assess the quality of the demonstrated systems thinking skills as students expand a SOCME diagram. From a researcher's perspective, the systems thinking learning throughout the intervention and the elicited skills on the SOCMEs can be analysed to understand the understanding, skills and attitudes students developed from this systems thinking intervention. The students' attitudes will be monitored for evidence of a developing sustainable action perspective. The findings can inform future research, and teaching interventions focused on developing and evaluating systems thinking in undergraduate chemistry.

This study is, therefore, novel as no attempts have been made to assess and analyse the development of systems thinking skills from SOCME diagrams, even though such diagrams have been used to teach and develop systems thinking skills (Holme, 2020). This study, therefore, set out to achieve the following aims

- Develop useful teaching and assessment resources to stimulate the growth of systems thinking in first-year chemistry, with a focus on organic chemistry.
- Introduce a collection of activities, incorporating visualization tools to scaffold the development of systems thinking skills.
- Encourage first-year chemistry students to recognize the real-world implications of chemistry to learn chemistry more meaningfully.
- Develop strategies to analyse the growth of systems thinking skills and a sustainable action perspective in chemistry.

The development of systems thinking skills and a sustainable action perspective will be scaffolded with the use of concept maps and SOCME diagrams and will be evaluated to inform future interventions aimed at developing systems thinking in undergraduate chemistry students. The next chapter will describe the design of this teaching intervention.

CHAPTER 3: INTERVENTION DESIGN

3.1. INTRODUCTION

This chapter is structured to discuss the teaching and assessment of systems thinking. The chapter will outline the context of the intervention, which informed its design and impacted its implementation in a first-year chemistry module. The teaching of systems thinking will then be discussed with reference to the learning outcomes that informed the intervention design. This will be followed by descriptions of the systems thinking activities, their sequence of implementation and the overall teaching design and principles. The chapter then concludes with a discussion on the assessment of systems thinking.

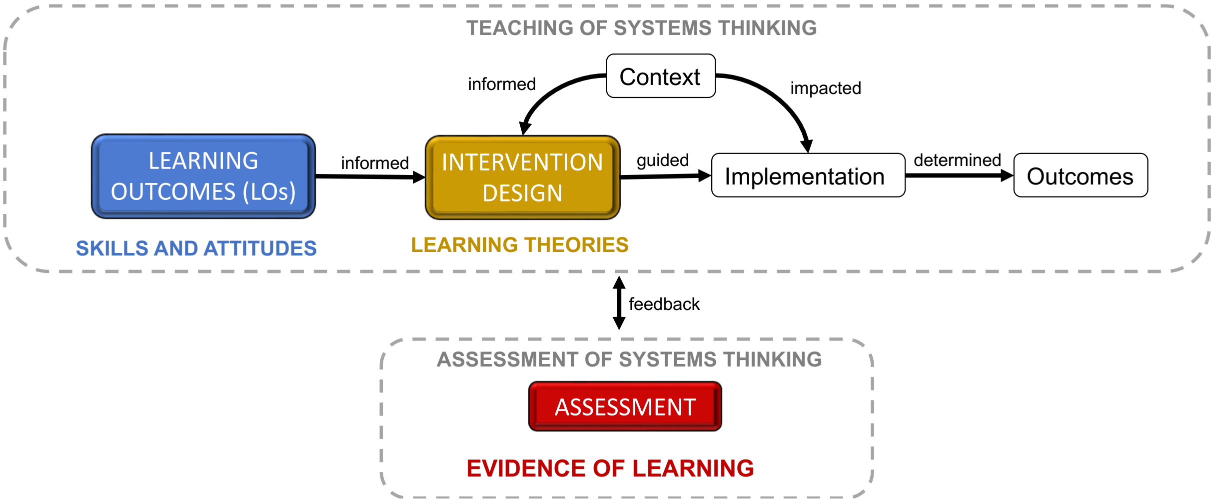


Figure 3.1. Overview of Chapter 3

3.2. CONTEXT

3.2.1. BACKGROUND

The intervention designed for this study took place at the University of Pretoria, where it was implemented in a first-year general chemistry module, CMY 127, which runs in the second semester. The CMY 127 module consisted of analytical and physical chemistry topics, which were followed by organic chemistry topics. Students who were enrolled in this module had prior knowledge from the first-semester general chemistry module, CMY 117. The two general chemistry modules are prerequisites for all Science undergraduate degrees and therefore attract a large enrolment of approximately 1500 students. The module consists of 14 weeks, with 56 hours of lecture time and 36 hours of time spent on laboratory work or tutorial sessions. Due to the Covid restrictions, students had weekly virtual tutorial sessions of 1-2 hours each and completed practical activities in their own time. The intervention was implemented online in two practical sessions towards the end of the CMY 127 module, where the quarter ended with organic chemistry topics.

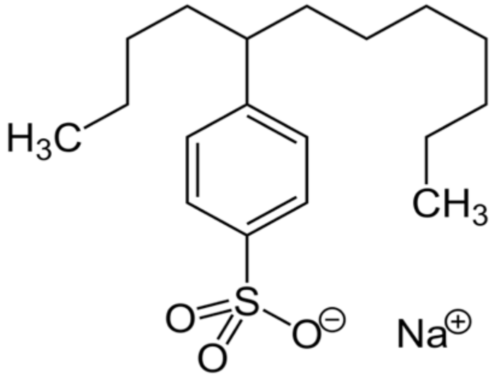
The intervention was structured in such a way as to engage students' relevant first-year general chemistry prior knowledge during the systems thinking activities. The intervention spanned two weeks and took three and a half to 4 hours in total to complete. However, students were given an additional week before the submission of their work for formative assessment.

3.2.2. FIRST-YEAR CHEMISTRY MODULE

To choose a topic to incorporate into the teaching of systems thinking and the design of the activities, the following criteria had to be met. The teaching and materials had to involve an organic compound, which had to be a chemical of relevance in daily life; it must align with the syllabus on a molecular level scale, be relevant on a larger scale within the society, economy and environment and have some relevance to the South African context. The topic of surfactants was chosen as it met these criteria and could be used to teach first-year students about its relevance and real-world implications in general and in the South African context. The teaching materials and content were focused on the anionic surfactant Linear Alkylbenzene Sulfonate (LAS), which is a surfactant commonly used in laundry detergents.

Teaching students about LAS required structuring the lecture and materials in such a way that students engage firstly with the core chemistry of surfactants on a molecular level and then learn about the relevance and real-world implications of the surfactant LAS. This can then enable students to make meaningful connections between the chemistry of LAS and its context in society, the environment, and the economy. This will be referred to as systems knowledge from here on. The chemistry and the systems knowledge that was taught in the intervention are summarised in Table 3.1.

Table 3.1. The chemistry taught in the systems thinking intervention

 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
	Industrial manufacture and detergent quality (economy) Hygiene, cytotoxicity, and our health (society) Ecotoxicity, foaming, and biodegradation (environment)

The chemistry knowledge of anionic surfactants and LAS aligned with the Physical and Organic Chemistry themes covered in the general first-year chemistry module. The Physical Chemistry themes that align with the topic of surfactants include types of mixtures, physical and chemical properties of substances, intermolecular forces, salts and solubility, acid-base chemistry, and reaction rates. Similarly, the Organic Chemistry themes include hybridization and bonding, skeletal structures, isomers, hydrocarbons, fractional distillation, functional groups, and organic reactions. Additional information that summarises how these themes align with this topic can be seen in Appendix C.

The systems knowledge of LAS aligned with the use of LAS in laundry detergents and the role LAS plays in our society, economy, and environment. In the system of LAS, various subsystems are interconnected, which includes the societal, environmental, and economic subsystems. In the societal subsystem, students learned about the amphiphilic structure of LAS and its role in laundry detergents to fight Covid-19 and the health implications associated with its use in our households and communities. In the economic subsystem, the organic reactions used in the industrial manufacture of LAS were connected to its sustainability, detergent quality, market demand, and environmental consequences. In the environmental subsystem, students learned about the isomers of LAS, its foaming abilities, rate of biodegradation, and ecotoxicity in rivers. Students also learned about what can be done to manufacture LAS in a more sustainable manner, as informed by some of the principles of green chemistry and what they can do going forward to rethink their use of laundry detergents and their role as responsible citizens.

In summary, the topic of LAS chosen for the teaching content and systems thinking activities was appropriate to teach students about the core chemistry of surfactants and about its implications in various subsystems. Incorporating this topic throughout the intervention can allow students to connect their prior knowledge to meaningful and relevant chemistry topics that they confront in their daily life, which can motivate them to learn more about the real-world implications of chemistry. In doing so, the teaching content and activities can enable first-year chemistry students to recognize the interconnectedness of chemistry and its role in future sustainability.

3.3. TEACHING OF SYSTEMS THINKING

In this section, the learning outcomes and activities of the intervention will be discussed, which will be followed by the overall teaching and design principles as established by the different learning theories

3.3.1. SYSTEMS THINKING ACTIVITIES

LEARNING OUTCOMES FOR THE INTERVENTION

The essential learning outcomes foundational to systems thinking in chemistry include the ability to develop systems thinking skills and the ability to demonstrate systems thinking knowledge

(Pazicni & Flynn, 2019). Not only should students develop and apply these skills, but they should be able to understand and recognize the interconnectedness and complexity of environmental, economic, and social systems in a sustainable world (Wheeler & Bijur, 2012). Orgill et al. (2019) stated that a systems thinking perspective in chemistry education can be achieved by investigating the environmental, social, and economic factors along with the chemical content of the system under consideration. The system under consideration can also be linked to local and international phenomena that relate to issues on a global scale (Orgill et al., 2019). The learning outcomes (LOs) designed for the intervention, therefore, guided the instruction to teach the chemistry of LAS to first-year chemistry students to enable them to recognize its role in the environmental, societal, and economic subsystems. Systems thinking skills are core to developing a systems thinking perspective to visualize the complex interconnections in the system of LAS on a local and global scale. The learning outcomes were designed to encourage the development of system thinkers in first-year chemistry so that students can apply their systems thinking skills to visualize how sustainable action can be integrated into the practice and understanding of chemistry.

The learning outcomes for the intervention were formulated after aligning the Systems Thinking Hierarchical (STH) model and the Characteristics Essential for designing or Modifying Instruction for a Systems Thinking approach (ChEMIST) table, which was discussed in detail in Chapter 2. Even though York and Orgill (2020) outlined the five essential characteristics of a systems thinker in chemistry and summarized these skills in the ChEMIST table, it was not empirically derived and did not provide guidance for scaffolding learning about systems thinking in terms of levels of challenge; therefore the STH model was also used to inform the learning outcomes. The STH model was suitable to use for the following reasons:

i) It can be used in chemistry education, and suggestions have been made for its implementation in chemistry systems thinking interventions (Mahaffy, Matlin, et al., 2019b; Orgill et al., 2019; Pazicni & Flynn, 2019).

ii) It was empirically derived from a study conducted on high school Earth Science learners who engaged in knowledge integration activities that included concept mapping (Assaraf & Orion, 2005, 2010).

iii) It has been used before to assess understanding of systems thinking from concept maps (Tripto et al., 2013).

iv) It demonstrated the hierarchical and sequential manner in which systems thinking skills developed, which can inform the scaffolding thereof in this intervention (Assaraf & Orion, 2010).

v) It recognizes the hidden dimensions that is relatable to chemistry's "hidden" parts and processes (Orgill et al., 2019).

vi) The STH model skills outlined eight skills, which makes it more manageable to assess from a teachers' perspective and to analyse from a researchers' perspective, in comparison to the 15 characteristics outlined by the ChEMIST table.

One of the limitations of the STH model is that it does not feature students' ability to identify emergent behaviour within a system, which has been outlined as a key characteristic by York and Orgill (2020). This skill has been identified as core to chemistry, as discussed in chapter 2. This highlights the other limitation of the STH model: it has not been tailored for chemistry education. Therefore to address these limitations, the STH model was aligned with the fifteen characteristics represented in the ChEMIST Table to formulate the nine LOs for the intervention, as shown in Table 3.2. The eight skills in the STH model are ordered from least challenging to most challenging, and the characteristics from the ChEMIST table are ordered on an analytical-holistic continuum of thinking. Each of the LOs has been condensed into eight systems thinking skills, which include *chemistry understanding, analysis: elements, analysis: relationships*, *integration: dynamic interactions*, *integration: organization, integration: cyclic behaviour*, *application*, and one attitude of *ownership* as aligned with the skills from the STH model.

Table 3.2. The nine learning outcomes formulated for the systems thinking intervention

STH model (Assaraf and Orion 2005)	**ChEMIST Table** (York, Orgill 2019)	**Formulated Learning outcomes**	**Systems thinking skills and attitude**
Analysis Skill 1: The ability to identify the components and processes within the system	**Analytical** Identify the individual components and processes within a system.	**LO2** Identify and illustrate the system-level concepts and processes relevant to a system	***Analysis: elements***
Synthesis Skill 2: The ability to identify relationships among the systems' components	**Analytical** Identify ways in which components of a system are connected	**LO3** Identify and illustrate the system-level concepts and processes relevant to a system	***Analysis: relationships***
Synthesis Skill 3:The ability to identify dynamic relationships within a system	**Analytical** Identify system-level behaviours that change over time **Analytic/holistic** Describe how a given system level behaviour change over time.	**LO6** Identify and describe interactions within and between subsystems that can change over time	***Integration: dynamic interactions***
Synthesis Skill 4: The ability to organize the system's components and processes within a framework of relationships	**Analytical** Identify and describe system boundaries **Analytic/holistic** Examine the organization of components within the system. **More holistic** Examine a system as a unified whole	**LO7** Organize system-level concepts in the whole system and identify new subsystem boundaries	***Integration: organization***
Synthesis Skill 5: The ability to understand the cyclic nature of systems	**Analytic/holistic** Examine positive and negative feedback loops within a system. **More holistic** Identify and explain the causes of cyclic behaviours within a system	**LO4** Explain causes of cyclic behavior and examine feedback loops in the system	***Integration: cyclic behaviour***

Implementation Skill 6: The ability to make generalizations	**More holistic** Use system -level behaviour -over-time trends under another set of conditions to make predictions about system-level behaviour under another set of conditions	**LO8** Predict factors that influence how a system changes over time	***Application***
Implementation Skill 7: The ability to recognise the hidden dimensions of the system	**Analytical** Identify the multiple variables that influence a given system-level behaviour; consider the potential effects of stochastic and hidden processes on the system-level behaviour. **Analytic/holistic** Examine the relative, potentially non-linear, effects that multiple identified variables have on a given system-level behaviour	**LO1** Examine and understand molecular level concepts and processes that influence system-level behaviour	***chemistry understanding***
STH model does not have a skill for emerging system level behaviour	**More holistic** Identify, examine and explain emergent system-level behaviour	**LO5** Analyze potential emerging system level behavior in the system	***Integration: emerging behaviour***
Implementation Skill 8: Thinking temporally: including the effects of past human action and predicting the effects of future human action.	**Analytic/holistic** Consider possible effects of a system's environment on the system's behaviours; consider how the system under study might be a component of an contribute to the behaviour of a larger system **More holistic** Consider the role of human action on a current and future system-level behaviour	**LO9** Consider the role of human activity on current and future system-level behaviour	***Ownership***

The ChEMIST table was developed as a tool to guide instruction in both analytical and holistic cognitive processes. Systems thinking requires analysing the parts and synthesising the whole (York & Orgill, 2020). Therefore, the learning outcomes were categorised according to structural systems thinking (*analysis* skills) and procedural (*integration* and *application* skills) during the intervention, which aligns with the idea of an analytical/holistic continuum of the ChEMIST table and the analysis, synthesis and implementation of the STH model (Assaraf & Orion, 2005). The STH model revealed that the higher levels in the hierarchy (synthesis and implementation) are more cognitively demanding and challenging for students to achieve than identifying elements and relationships (analysis skills). The skills and attitudes were scaffolded to develop in a sequence from *analysis* skills, followed by *integration* skills and then *application* skills to guide students to achieve the formulated learning outcomes. The hierarchical development of skills from less difficult to more difficult in the STH model was used in this intervention to inform the amount of scaffolding required for first-year-level students. However, the learning outcomes were unique to the chemistry intervention and were scaffolded in a different sequence. The LOs, therefore, did not align with the exact order of skills in the STH model as the order of difficulty became irrelevant based on the way in which the teaching was scaffolded, which is influenced by the capabilities of the students at a first-year level.

The LOs were designed to engage students to develop systems thinking skills in a sequence and not in hierarchical stages of difficulty, even though some are more challenging and cognitively demanding than others, as reported and discussed in chapter 2. That is why students received more mediation and guidance to achieve LOs with higher cognitive demand, such as LO 4-8. For example, LO 7, "understanding the hidden dimensions of the systems," was considered one of the most challenging skills based on its position in the hierarchy of skills development. However, in this intervention, the "hidden dimension" represents the underlying chemistry of the system of LAS, which was taught together with students' prior chemistry knowledge. The LOs were structured to engage students with *analysis* skills first from LO1 to LO3 and then with *integration* skills from LO4 to LO7. Students then had to engage with *application* skills that integrate both *analysis* and *integration* skills for LO8 to LO9. This is shown in Figure 3.2. below.

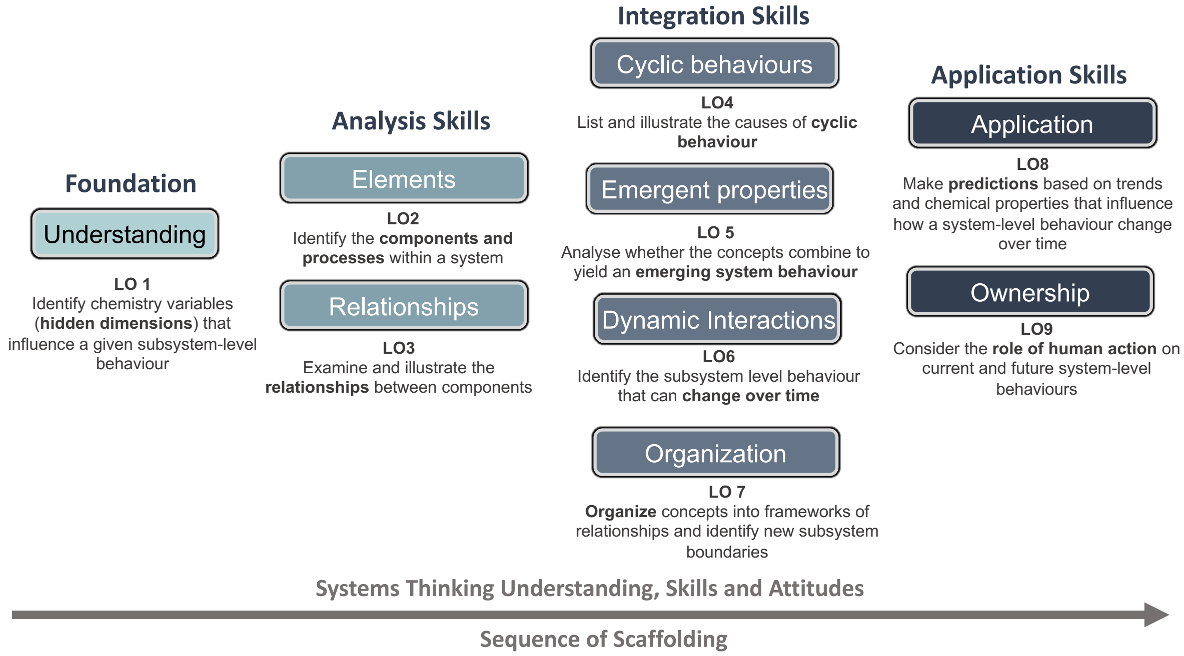


Figure 3.2. Sequence of scaffolding the learning outcomes of the intervention

LO 1 was formulated so that students can develop a *chemistry understanding* of the system's identity, which involves the chemistry of surfactants on a molecular level. Identifying these hidden dimensions involve recognizing the patterns and interrelationships that could result in emerging dynamic behaviours. The concept of hidden dimensions that result in emergent system level behaviour is not limited to the fundamental underlying chemistry. However, identifying hidden dimensions and emergent behaviour is complex and would be very challenging to develop in students with no prior knowledge of systems thinking in a short timeframe. To limit cognitive load, we did not expect that first-year students to engage with hidden dimensions beyond the chemistry Therefore, in this study students understanding of the hidden dimensions were limited to the macroscopic properties that emerge from the sub microscopic chemistry phenomena.

LO 2-3 were formulated so that students can develop their *analysis* skills to identify the elements and relationships within the system through gaining *analysis: elements* and *analysis: relationships* skills. LO4 to LO7 were formulated so that students can develop *integration skills, such as integration:* cyclic *behaviours, integration: dynamic interactions, integration: emergent properties and integration: organization* skills. The ability for students to identify, examine and explain emergent and cyclic system-level behaviours was considered too challenging for first-year students. They were, therefore, not expected to identify and explain emergent and cyclic behaviours *a priori* but were exposed to the dynamic nature of the system through suitably chosen examples to organize components into existing and new subsystem boundaries. Pazicni and Flynn (2019) suggested that such an approach can guide learners through their Zone of Proximal Development (ZPD). LO8 and LO9 were formulated so that students can apply both *analysis* and *integration* skills to develop *application* skills as they visualize the effects of the system and develop a systems thinking attitude of taking *ownership.*

DESCRIPTION AND SEQUENCE OF ACTIVITIES

The intervention was implemented during two live online practical sessions over two weeks. Instructors facilitated the activities on the University's Learning Management System (LMS). This approach allowed for interactive discussions between students during the group work activities and enabled communication between students and instructors, which provided opportunities for mediation. The systems thinking activities were designed with a jigsaw cooperative learning approach to encourage collaboration as students work through the complexity and cognitive load associated with systems thinking. This approach aligns with constructivist principles as it enables the construction of knowledge during group collaboration. Students become experts in their subsystem groups, which includes learning about the societal, environmental and economic subsystems before sharing what they have learned from each subsystem in their home groups, as shown in Figure 3.3.

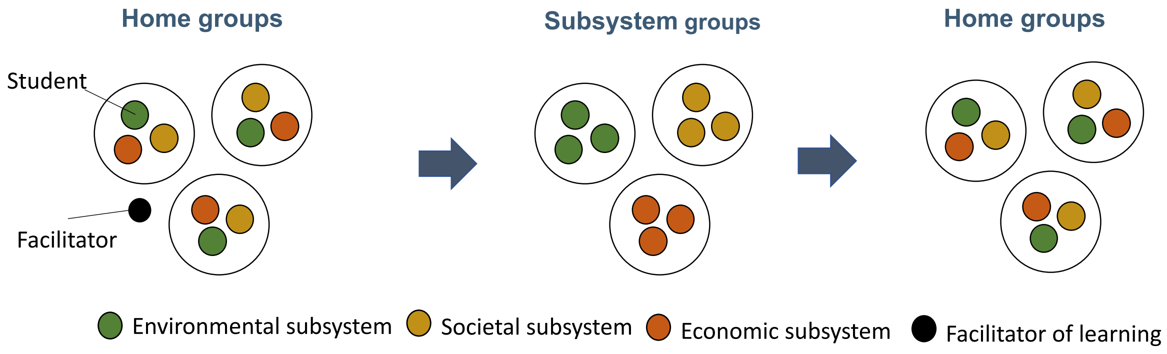


Figure 3.3. Jig-saw cooperative learning approach between home groups and subsystem groups

Each home group had three students with varying academic capabilities and roles, including a group facilitator, a presenter/recorder, and a strategy analyst/researcher, as shown in Table 3.3. There were also instructors present during the live collaboration sessions to facilitate the group work and provide guidance in the learning process where necessary. Group work and cooperative learning will be discussed further as one of the design principles of the intervention.

Table 3.3. Group Roles for each home group

Group Facilitator	**Group Presenter/Recorder**	**Group Strategy Analyst/Researcher**
Asks questions to the instructor Responsible for group work Makes sure all voices are heard Encourages group members Ensures active participation during practical sessions	Must share their screen during online group activities Record the collaborative session Work on PowerPoint on behalf of the group Reads the questions before the group engages in discussion	Takes care of time management Monitors group interactions and suggests improvements to group dynamics to ensure that the task is completed Conducts research to find additional information. Tries to resolve disagreements by researching for more information.

The systems thinking activities consisted of four pre-recorded videos, two quizzes, two practical activities, and a self-reflection questionnaire. Figure 3.4. outlines a timeline, the sequence, the group work and scaffolded systems thinking understanding, skills and attitude of the intervention activities that occurred throughout the intervention. Each of these activities shown in Figure 3.4. will be discussed in more detail.

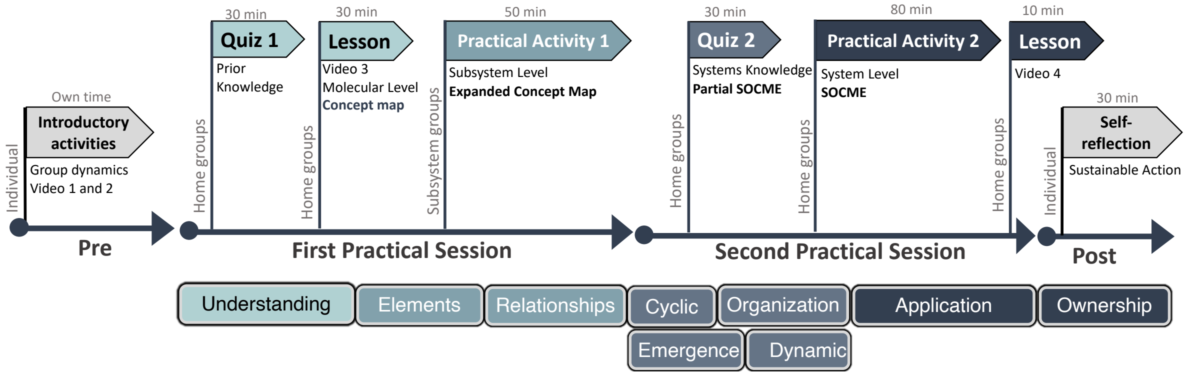


Figure 3.4. Sequence of the activities during the intervention with the scaffolded systems thinking skills

Pre-intervention

This session in the intervention started with an introductory video (video 1) where students were introduced to systems thinking and its importance for future sustainability. Students were taught about concept mapping, its terminology, and the use of a SOCME diagram as an extension to concept mapping to visualize the complexity associated with systems thinking. Students were then grouped into their home groups. Individually, they watched a second video (video 2) that explained the introductory activities they were to engage in to get to know their group members and that gave an overview of the subsystem content. Students were given instructions to choose group names, and group roles and to participate in an asynchronous ice-breaker activity.

Practical Session 1

During the first practical session, students completed an online prior knowledge quiz 1 for 30 minutes in their home groups. The quiz was designed to prompt students’ ability to recall their prior organic and physical chemistry knowledge regarding the chemical and physical properties of water and oil and how this could help them understand the chemistry of surfactants in laundry detergents on a molecular level. After completing the quiz, groups watched the third video, which connected the chemistry of surfactants with their prior knowledge. The prior knowledge quiz and surfactant lesson were designed to expose students to the system's identity (LO1) so that they could examine and understand molecular-level concepts and processes that influence system-level behaviour. Students were provided with a core chemistry concept map, shown in Figure 3.5., to guide them in the core chemistry concepts on a submicroscopic level to help them understand the macroscopic behaviour of surfactants in the system of LAS. Students were guided to develop *a chemistry understanding* that will become the “hidden dimensions” of the system of LAS.

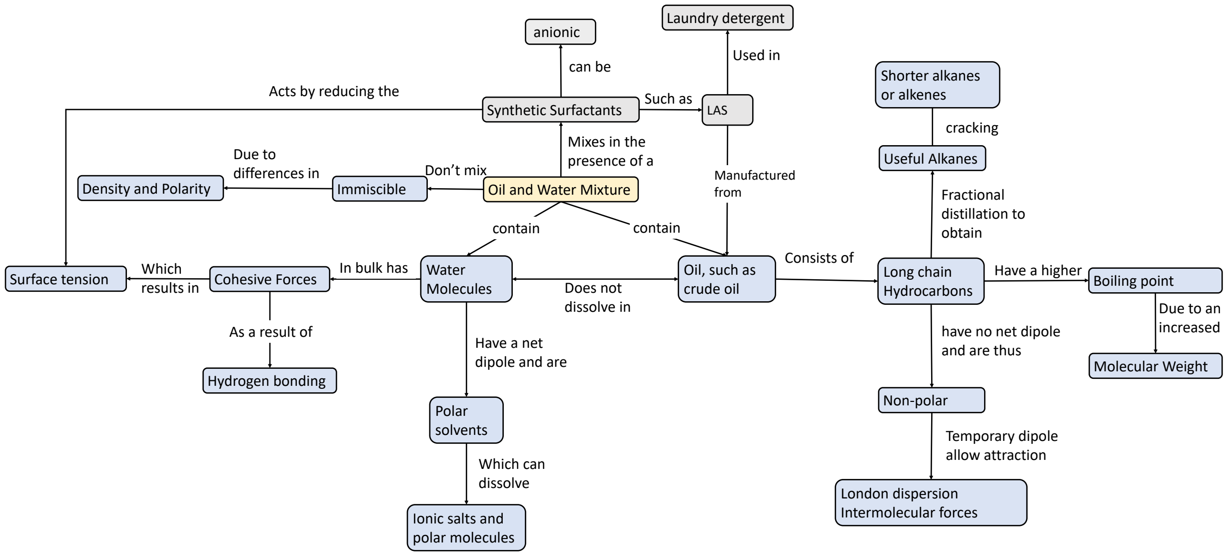
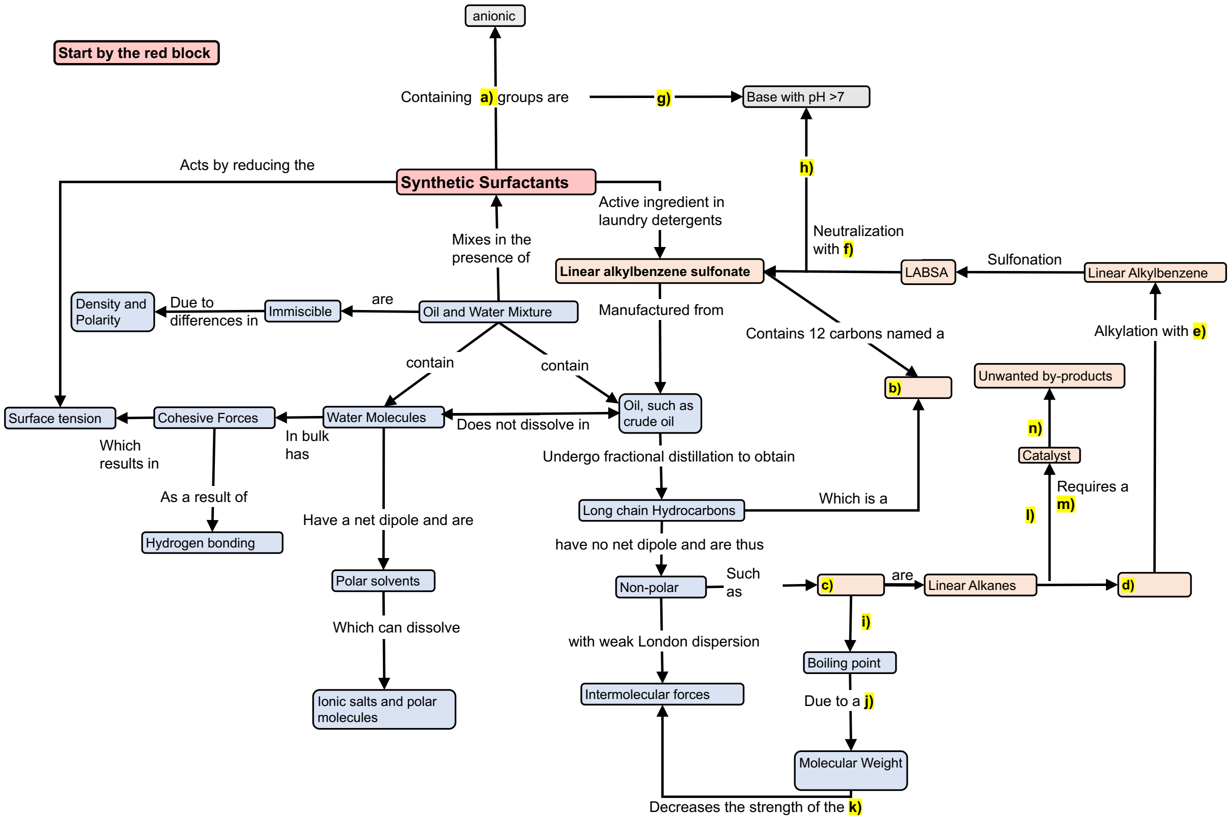


Figure 3.5. Core chemistry concept map that shows the hidden dimensions of the system of LAS

After students submitted the quiz, they spent 30 minutes watching the surfactant lesson video (video 3), where they learned about surfactants' physical and chemical properties. They also learned about linear alkyl benzene sulfonate (LAS), its role as a surfactant in laundry detergents and its impact on the economic, societal and environmental subsystems. Students then met in their subsystem groups for practical activity 1, where they engaged with expanded concept maps specific to their subsystem of focus. There were, therefore, three different expanded concept maps, where an example of the economic subsystem is shown below in Figure 3.6.



Practical Activity 1: Expanded Concept Map- Economic Subsystem

Figure 3.6. Expanded concept map used in practical activity 1 for the economic subsystem

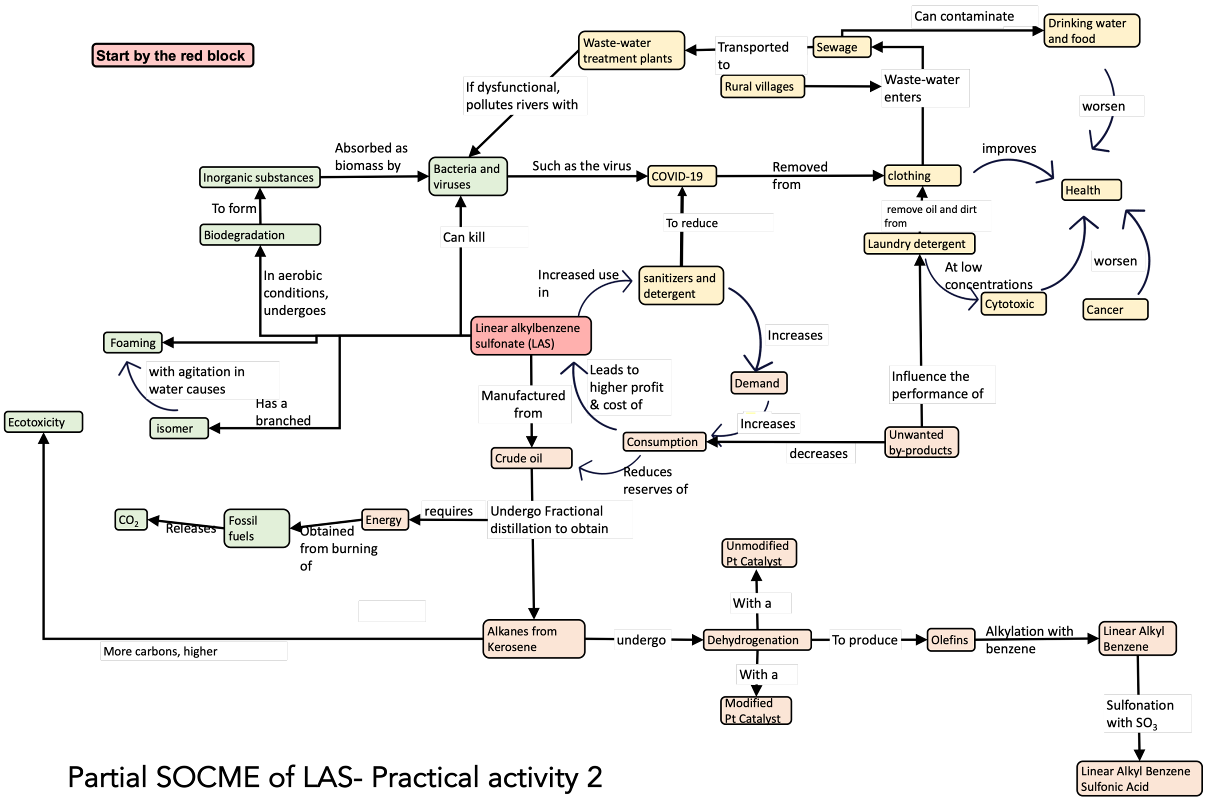
Students were prompted to apply their *analysis* skills to identify and illustrate the system-level concepts and processes and to identify and illustrate the relationships between system-level concepts within subsystems, as stated respectively in LO2 and LO3. Students were prompted to apply these skills by working through a range of question types, which included choosing answers from a drop-down list, a hot spot image, true-false statements and an expanded concept map where linking words had to be filled in, as shown in Figure 3.6. Some questions at the end of practical activity 1 prompted students to think about emergent, cyclic and dynamic behaviours as these skills from LO 4, 5, and 6 were considered as most challenging. In the societal subsystem, students had to identify the variables that can change over time, which can influence the effectiveness of surfactants. This influences its detergency power and use for household laundry. For the economic subsystem, students had to click on the concept from the expanded concept map that influences the activation energy of a reaction and could therefore reduce the reaction time required for synthesis in the industrial manufacturing process. In the environmental subsystem, students were asked to identify biodegradation as the variable responsible for changing the concentration of LAS over time, which is considered a dynamic and cyclic behaviour. Students also had to explain the mechanism of foaming, considered an emerging property, by ordering statements logically.

At the end of practical activity 1, students discussed whether certain concepts fit into the economic, societal, or environmental subsystem. This allowed students to engage with LO7 as they thought about how the concepts could be organized into subsystem boundaries to further understand the system's identity. They also received enrichment questions that encouraged them to think about possible connections and linking words between concepts in the specific subsystem. This prepared students to apply their *integration* and *application* skills to make predictions in the system, as stated in LO8.

Practical Session 2

In this practical session, students returned to their home groups, where they had to complete a systems knowledge quiz (quiz 2). In this quiz, students were prompted to mostly apply their *integration* skills as they answered questions relating to an incomplete, partial SOCME diagram. During the quiz, students studied zoomed-in parts of the partial SOCME, where they engaged with LO 4-7. Students had to interact with the biodegradation cycle and examine feedback loops related to the cyclic behaviour of LAS in the societal and economic subsystem. Students also learned about the variables contributing to the foaming emergent behaviour of LAS, including its biodegradation rate, its concentration, the anaerobic and aerobic conditions, and agitation in aquatic water systems. They had to reason to understand how the emergent and cyclic behaviour contributed to further implications in the system, such as its ecotoxicity.

In practical activity 2, students were guided to discuss whether they think the economic gain of LAS outweighs the environmental or societal impacts by considering the impacts of fractional distillation, sulfonation, and manufacturing good quality Linear Alkyl Benzene Sulfonic Acid (LABSA). Students then had to choose between two scenarios to make a prediction that would guide them in expanding the partial SOCME diagram. Students had to apply their chemistry understanding and systems thinking skills to expand the partial SOCME, shown in Figure 3.7. Students expanded the partial SOCME on PowerPoint in their home groups, by adding new concepts, linking words, and organizing these concepts into new subsystems. These activities were developed in line with LO8 so that students can predict factors that influence how a system changes over time. Students could have conducted further research on the journal articles provided, including example SOCME diagrams and relevant newspaper articles, provided to guide them in expanding their partial SOCME. Students had to submit their expanded SOCME diagrams in groups. They were given an additional week if they wanted to meet with group members to complete the SOCME before the submission deadline.



Partial SOCME of LAS- Practical activity 2

Figure 3.7. Partial SOCME of the system of LAS during practical activity 2

After students had spent 80 minutes expanding their partial SOCME diagrams in their home groups with the understanding that they had gained from their subsystem groups, they watched a 10-minute lesson video, which was the take-home message video of the intervention. In this video, students learned about what is being done at the moment to modify the chemical structure or manufacture of LAS to make it a more sustainable surfactant. Students also learned what they could do as responsible citizens to become agents of change for future sustainability. This was aligned with LO9 to enable students to consider the role of human activity on current and future system-level behaviour

Post-intervention

After students watched the take-home message video, they had to reflect on their learning in the self-reflection questionnaire to develop an attitude of taking ownership of their contribution to sustainability. Students were asked in the self-reflection questionnaire to identify the most important chemical properties and behaviour of LAS that contribute to its value in our economy, its health impacts on our society, and its environmental consequences. Students were asked to explain how the chemistry and engineering of LAS can be altered for more sustainable manufacturing, minimal environmental consequences, and safer laundry detergents. They also reflected on what they would do as responsible citizens to apply systems thinking and take sustainable action in their daily lives. The activity materials and resources discussed in this section can be viewed at the associated content in Appendix B at the end of the article under review.

3.3.2. DESIGN OF TEACHING

In this section, the principles that informed the teaching design will be discussed with examples of how it was implemented in the systems thinking activities. These design principles were formulated by combining principles of constructivism, requirements for meaningful learning and considerations of Cognitive Load Theory. The formulated eight principles, shown in Figure 3.8., were considered to inform the teaching of systems thinking and the structure of the activities. These constructivist principles can enable opportunities in the classroom for meaningful learning in chemistry. Meaningful learning occurs when students connect new knowledge with their prior knowledge when meaningful teaching materials are presented (Bretz, 2001). These design principles encourage active agency, metacognition, the social construction of knowledge, and working with tools of cognition that are essential factors during the active construction and reconstruction of knowledge by students as they progress to higher levels of understanding (Donald et al., 2014).

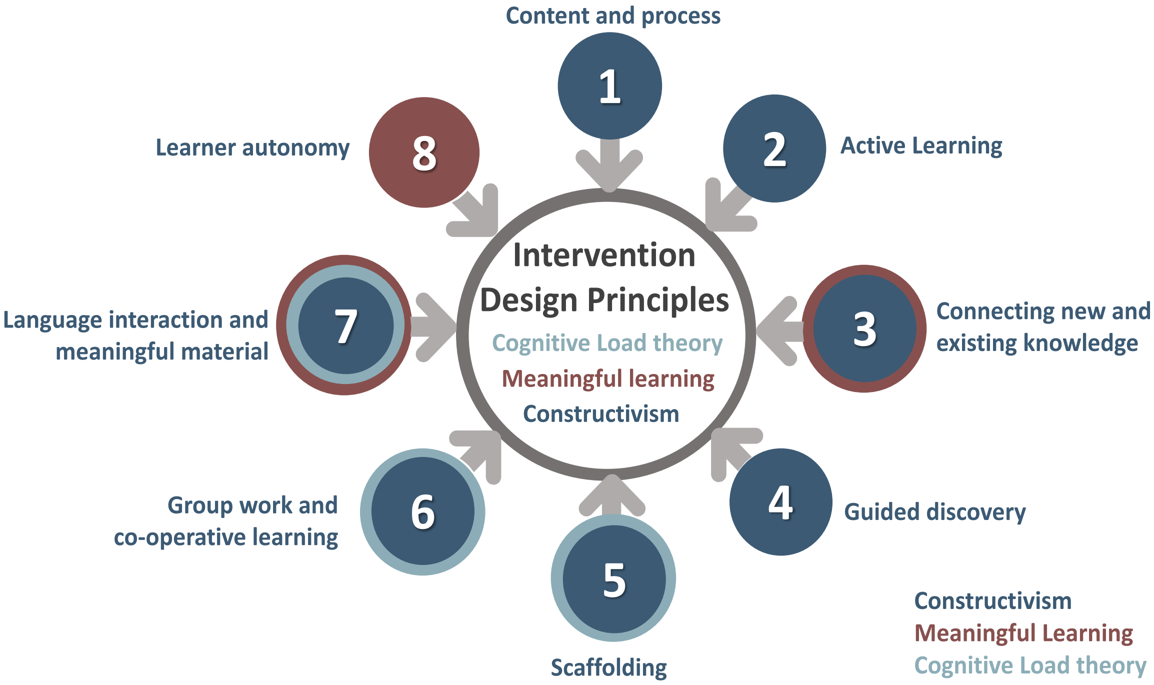


Figure 3.8. Intervention design principles based on constructivism, cognitive load theory and meaningful learning

Content and Process

In chemistry, multi-level thinking is required to link macro and sub-micro concepts with symbolic knowledge to interpret chemical phenomena (Taber, 2013). Students used multi-level thinking in quiz 1 to think about the submicroscopic, symbolic and representational levels of the chemistry of oil, water and surfactants. As students engaged with system-level knowledge, they applied multi-level reasoning to analyse the hidden dimensions, such as patterns and interrelationships that are not easily seen (Ben-Zvi-Assaraf & Orion, 2010; Pazicni & Flynn, 2019). The learning process is as important as the content so that students can comprehend the underlying structure of a topic by understanding the relationships between the core concepts (Donald et al., 2014). Concept mapping was used as a learning strategy throughout the activities to aid in visualizing the relationships between chemistry concepts to understand the “hidden” structure in the system of LAS. A core chemistry concept map was discussed at the end of the surfactant lesson to facilitate students during the development of their understanding of the system of LAS.

Active learning

An active learning approach guides learners to construct their knowledge through “action, reflection, abstraction and application” (Swan, 2004). Active learning promotes more profound engagement with chemistry content as students increase their ability to engage with higher-order cognitive skills (Freeman et al., 2014; Summerton, Hurst, & Clark, 2018). During the quizzes and practical activities, students were encouraged to work actively together in groups to submit answers to the University’s LMS. In practical activity 2, a partial SOCME diagram was expanded as students added new concepts and linked words, connections, and subsystems.

Connecting new with existing knowledge

Learning is about “knowing how to use what you already know to go beyond what you already think” (Bruner, 1985). Students should have recalled their prior knowledge when they completed quiz 1 to prepare them for the new chemistry learning about surfactants. As students learned about the unfamiliar chemistry of how surfactants work, they could have experienced cognitive conflict while making connections to their existing knowledge. This is where guidance or mediation by group facilitators or educators was essential to assist students in their zone of proximal development. The core chemistry concept map also guided in that regard as it facilitated connecting new knowledge to existing knowledge.

Guided discovery

Students need facilitation to discover key concepts in the conceptual structure of a topic (Donald et al., 2014). This is a valuable learning strategy as students are guided to discuss, reflect, and argue about possible solutions to the problems they need to solve with their group members (Donald et al., 2014). This design principle is essential to facilitate learning to develop students' confidence as they engage in active discussions and their higher-order cognitive skills. Throughout the systems thinking quizzes and practical activities, students were prompted to collaborate, conduct research, and consult the provided additional resources, such as example SOCME diagrams or journal articles and media reports. Guided discovery is process-oriented and promotes active learning, self-directive learning, and reflective thinking (Noer, Gunowibowo, & Triana, 2020). Students' reflective learning can be improved as they work on contextual problems that make them curious to learn more, which can be facilitated with guided discovery learning (Noer et al., 2020). Therefore, the case studies and literature chosen for discussion in the surfactant lesson were centred around locally relevant issues that students could relate to. Reflective thinking can also improve when students conclude the problem under study (Noer et al., 2020). Students were guided to identify the most important chemical properties and behaviour of LAS in society, the environment, and the economy as they reflect on their learning in the concluding activity of the intervention.

Scaffolding

Scaffolding involves the mediation of appropriate structures or strategies that can help facilitate teaching and learning in an area of knowledge (Donald et al., 2014). Similarly, just as a scaffold in construction supports the building process, it also supports the learning process until it is no longer needed. Throughout the systems thinking activities, the learning was scaffolded to reduce the cognitive load that students experienced. Students were guided through mediation, the use of visualization tools, and the structuring of the questions in the practical activities. This design principle ties the theoretical underpinnings of the intervention together and contributes significantly to the overall teaching design of the intervention.

Co-operative learning

During group collaboration, students have to consider different perspectives and modify their thinking when shown to be inadequate (Donald et al., 2014, pp. 81-82). The sharing of ideas through collaboration could reduce the cognitive overload students' experience as they work on the systems thinking activities. The cooperative jigsaw design encourages interdependence between group members and reduces the cognitive load associated with the system under consideration. The jigsaw design helps to promote comfort through interactive dialogues and discourages group dominators, which ensures equity amongst students with various cultural and social backgrounds (Theobald, Eddy, Grunspan, Wiggins, & Crowe, 2017). The design also encouraged active participation and language interaction and has contributed to students' confidence as they shared expert knowledge gained in their subsystem groups with their home groups to expand the SOCME diagram. For group work to be sufficient, it must have clear outcomes, support social interaction and be well organised and monitored so that all members participate actively to accomplish the group's shared goals (Donald et al., 2014, p. 109). The home groups were organised in such a way as to have varying academic abilities per group to ensure each group had a potentially more knowledgeable “other” that could start conversations. Social interaction in group work was supported as students worked through forming, storming, norming, and performing (Tuckman, 1965). Active agency and language as learning tools are encouraged during social collaboration. Collaborative learning allows for both the use of self-directed speech, which plays an essential role in self-regulation and outer speech, which aids in the creation of meaning and the development of understanding (Vygotsky, 1964, 1980).

Language interaction and meaningful material

Language is an essential tool in teaching and learning as knowledge transmits between learners who interact (Vygotsky, 1964). Students should be encouraged to interact with language through speaking, reading, presenting, writing, and expressing their views during discussions (Donald et al., 2014, p. 109). In the systems thinking activities, students worked in group discussions to solve problems, express themselves in their group roles, and refine their writing skills as they reflected on their learning in the self-reflection questionnaire. The activities were designed with different group roles to allow communication between group members. The expression of thoughts during collaboration plays a role in enhancing students' confidence. For meaningful learning, the language used in the learning materials must be clear and should relate to students' relevant prior knowledge (Novak & Cañas, 2008). The learning and teaching materials were also formulated to reduce cognitive load by keeping slides simple and ensuring the language are clear in the concept maps and SOCMEs. Another essential aspect of meaningful materials is that they must be structured in a suitable sequence to scaffold the learning process to build new knowledge into students' relevant prior knowledge (Novak & Cañas, 2008). This was achieved by introducing students first to what systems thinking and concept mapping is and why it is important, then prompting the recall of prior chemistry knowledge before teaching new chemistry content on surfactants and LAS.

Learner autonomy

Students' motivation and self-determination are related to the opportunities they have in the classroom to be autonomous (McCombs, 2015). Students can learn how to take ownership over their learning if they get more opportunities to make choices during the learning process. For students to learn meaningfully in chemistry, they must choose to take ownership of their learning. Students can be motivated to learn more meaningfully, when instructors incorporate relevant materials into the lesson that students can relate to. The real-world implications of chemistry can be related to students' everyday lives. Systems thinking provides opportunities for students to "connect chemistry with issues that matter to them from local to global levels" which enhances the value of chemistry learning and their motivation (Pazicni & Flynn, 2019). Therefore, the resources used in the surfactant lesson incorporated relevant economic, societal, and environmental issues in South Africa that students can relate to. During the intervention, students were encouraged to make their own decisions with regards to their group roles, subsystem groups and could add concepts, linking words and subsystems of their choice. This permits multiple entry points where students can focus their attention on what they found interesting, familiar, or culturally relevant.

3.3.3. SUMMARY

The teaching design is structured to scaffold the learning sequentially from a molecular level foundation to a sustainable action perspective through the development of systems thinking skills and an attitude as illustrated in Figure 3.9.

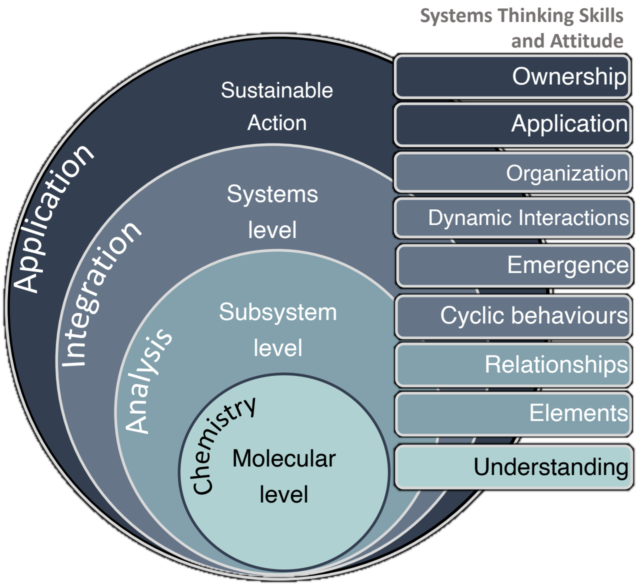


Figure 3.9. Scaffolding of the intervention from a molecular level foundation to sustainable action

Systems thinking visualization tools were used in this intervention to develop systems thinking skills in first-year chemistry students. A core chemistry concept map was used to develop students' *chemistry understanding* of the system on a molecular level. After that, students were guided to gradually zoom out of the chemistry to visualize the elements and relationships on a subsystem level with the help of expanded concept maps of the societal, environmental, and economic subsystems. Students were scaffolded to develop their *analysis* skills primarily. However, they were also introduced to *integration* skills as they engaged with the cyclic, dynamic, and emergent behaviours present within the system. Students were then guided with a partial SOCME to develop their *integration* skills. Thereafter students were prompted to use both their developed *analysis* and *integration* skills to develop *application* skills to expand the partial SOCME by adding new concepts, relationships, organizing these into existing and new subsystems and new making future predictions. After the activities, students were encouraged to reflect on their learning to understand chemistry's role and real-world implications and recognize our role as responsible citizens by taking ownership of future sustainability.

3.4. ASSESSMENT

In this section, the assessment of developing systems thinking skills from a teacher's perspective will be discussed using an assessment rubric designed from the SOLO taxonomy. Formative assessments, as discussed in Chapter 2, are valuable during teaching to drive learning and understand students' progress. The intervention's two quizzes and practical activities contributed to a final practical grade. In the organic chemistry module, CMY 127, the practical component contributed to 5% of students' final marks for the module. The intervention comprised individual and group work submissions which was scored out of 120 marks, where a rubric assessed 60% of the score and 40% computer graded. The final mark for the intervention contributed less than 1% to students' final course grades. The 60% grade was obtained from assessing the systems thinking skills that students demonstrated on their final SOCMEs. The design of the rubric to assess the skills will be discussed below.

3.4.1. DESIGN OF SOCME ASSESSMENT RUBRIC

a SOCME grading rubric was designed for low-stakes formative assessment to assess the developing systems thinking skills from SOCME diagrams. The design of the rubric was informed by the SOLO taxonomy, which was discussed in detail in Chapter 2. The assessment of SOCME diagrams can provide evidence of the systems thinking skills that students developed as a snapshot in time and can provide helpful information to enrich the teaching of systems thinking in chemistry for future implementation. The quality of the concepts, connections and added subsystems will be assessed with the SOCME rubric as evidence of how well students were able to use their *analysis*, *integration, and application* skills to understand the interactions of LAS within and between various subsystems. The SOCME scores obtained from the assessment of each SOLO level aligned with the assessed systems thinking skills, as shown in Table 3.4. The alignment of SOLO levels with systems thinking skills enabled two independent raters and the researcher to assess SOCME diagrams for the systems thinking skills demonstrated. Table 3.4. below outlines the alignment of SOLO levels assessed using the SOCME rubric with systems thinking skills.

Table 3.4. A short version of the SOCME grading rubric

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

The designed rubric allows for assessing the structural complexity demonstrated by students as given by the SOLO levels, which can then be used to understand the systems thinking skills that students have developed as a result of what they were able to demonstrate on their SOCMEs. The unistructural and multi-structural SOLO levels align with the skill *analysis: elements.* The relational low and medium SOLO levels align with *analysis: relationships.* The relational high *SOLO* level aligns with *integration: dynamic interactions,* and the extended abstract SOLO levels align with *integration: organization* and *application* skills. Students' understanding, skills, and attitudes not assessed by the SOCME rubric included *chemistry understanding, integration:* c*yclic behaviour, and integration: emergence and ownership.* These skills were taught (*chemistry understanding*) or scaffolded explicitly throughout the intervention due to their challenge (*integration:* c*yclic behaviour, integration: emergence)* and were not assessed by the rubric. *Ownership* as an attitude will not be assessed for grades but analysed in students' self-reflections.

The article submitted to the Journal of Chemical Education that is currently under review can be consulted in appendix B to read more about the design of the SOCME rubric. The article contains a slightly modified rubric and an improved rater training manual that resulted from the research component of the study. However, the short and original rubric and a flow chart contained in a rater training manual can be found in Appendix C.

3.5. CONCLUDING REMARKS

Systems thinking was incorporated into a first-year teaching intervention on surfactants to encourage meaningful learning in chemistry. The intervention was designed to scaffold the development of systems thinking knowledge, skills, and attitudes from a molecular-level foundation to a sustainable action perspective using concept maps and SOCME diagrams. The systems thinking skills embedded in nine learning outcomes originated from the STH model, and the characteristics of a systems thinker included in the ChEMIST table. The intervention implemented a jigsaw cooperative learning approach, where students completed activities first in their home groups and then in their subsystem groups, where they learned about the role of LAS in the societal, economic and environmental subsystems. They then returned to their home groups to expand a partial SOCME diagram drawing on knowledge gained from group members, each with specific subsystem knowledge. Students then reflected on their learning to foster the development of an attitude of ownership to potentially become agents of change for future sustainability. Students' systems thinking skills were assessed using a rubric informed by the SOLO taxonomy.

CHAPTER 4: METHODOLOGY AND RESEARCH DESIGN

4.1. INTRODUCTION

The purpose of this chapter is to outline the steps taken to gather evidence of learning to answer the research questions. This chapter starts by revisiting the research questions before discussing the research design and methodology. The selection of participants will then be presented together with the data collection and analysis approaches to investigate the systems thinking skills and attitudes that were developing in first-year chemistry students. The interpretive framework adopted before data collection and analysis will be disclosed, followed by steps taken to ensure the data collection and analysis process's reliability, validity, and trustworthiness. This chapter will conclude with a discussion of the ethical considerations and the limitations of the chosen research methodology and design.

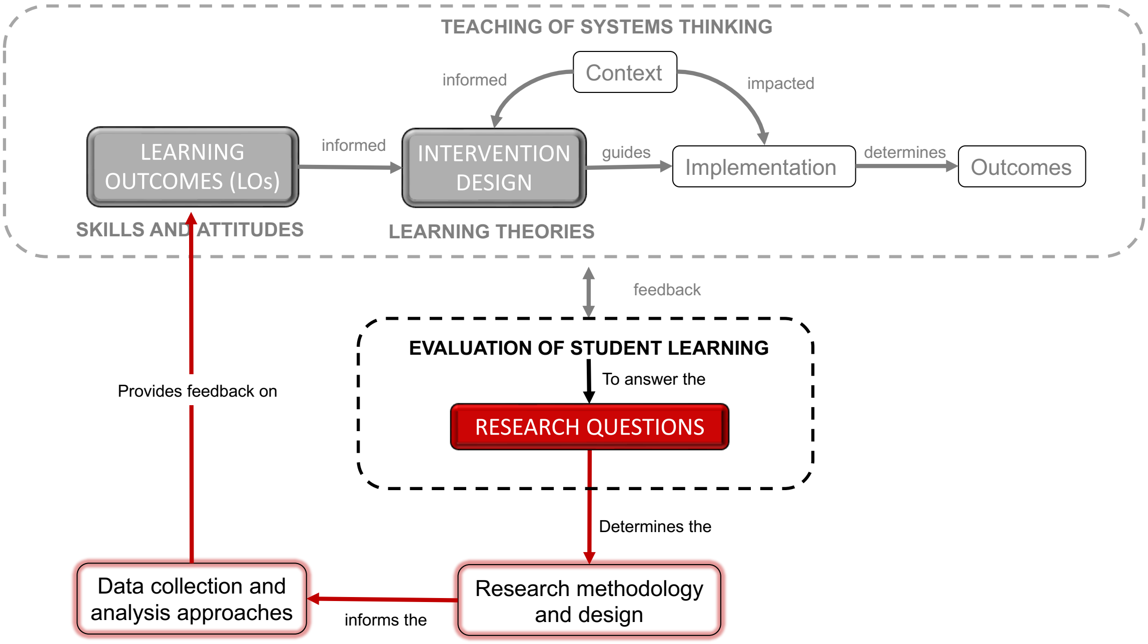


Figure 4.1. Overview of Chapter 4

4.2. RESEARCH QUESTIONS

The study aimed at addressing the following two research questions:

1. Which systems thinking skills were developing in first-year chemistry students as they engaged in a systems thinking intervention?

2. What evidence suggests that a sustainable action perspective was developing in first-year chemistry students?

4.3. RESEARCH METHODOLOGY AND DESIGN

This study adopted a single-case study methodology to answer the research questions. This methodology was suitable because the strategy of inquiry was closely examined with a limited number of participants. Researching a smaller number of participants was beneficial, as it had aspects of a pilot, where research protocols, data collection instruments, sample recruitment strategies, and other research techniques could be tested in preparation for more extensive studies. The small number of participants in this study also contained the data collection and analysis procedures to make it more practicable and achievable in a short time frame.

A single-case study methodology allows for the investigation of a phenomenon within its real-life context where the boundaries between the phenomenon and context are not evident and in which multiple sources of evidence are used. The methodology was suitable to investigate the complexity inherent to systems thinking as various sources of evidence would be incorporated to develop a description of the systems thinking skills being developed in a natural educational setting. This methodology allowed for the gathering of qualitative and quantitative evidence to provide detailed descriptions and a holistic understanding of systems thinking learning in first-year chemistry students.

In this study, quantitative methods revealed superficially what skills students were developing shining a light on what systems thinking skills were demonstrated. Qualitative methods were used to develop a deeper understanding of the systems thinking learning in this intervention, characterising students' experiences, perspectives and reflections. This constituted a mixed methods approach with qualitative and quantitative data being used to substantiate the validity of this study and enhance its credibility and trustworthiness.

The study adopted a concurrent triangulation research design to maximise the benefit of the mixed methods approach. This design was chosen to reduce the time frame required for data collection. Triangulation was used to compare qualitative and quantitative data to determine whether there was “confirmation, disconfirmation, cross-validation, or corroboration” (Creswell, 2009). This design is depicted in Figure 4.2.

In summary, this study adopted a single-case study methodology with a mixed methods approach designed to collect quantitative and qualitative data concurrently for the following three purposes. First, to allow for the validation of data obtained from both methods, to use the quantitative methods to strengthen the qualitative findings and finally, to enrich the quantitative findings with the qualitative findings. The qualitative research methods contributed more to the overall data analysis to allow for findings with more profound interpretations.

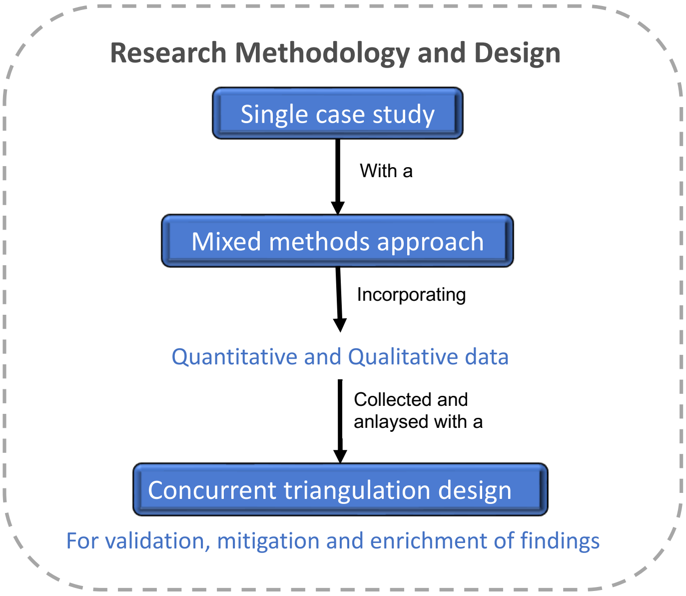


Figure 4.2. Research methodology and design of this study

4.4. INTERPRETIVE FRAMEWORKS

The research methodology draws on two interpretative frameworks: pragmatism and social constructivism. Social constructivism guided this research study as subjective meanings and interpretations of participants' experiences were created to acknowledge the complexity of individual views. A social constructivist interpretive framework was adopted to understand the reality of the participants' views of the system under consideration. This study acknowledges that the responses from participants could be influenced by their experiences and social interactions during the intervention. Furthermore, data interpretation could have been influenced by the researchers' past experiences, background and social interactions. However, the interaction of the researcher with participants was limited to minimize the influence of positionality in this study.

A pragmatic approach was also adopted as an interpretive framework in this study to better understand what is practicable in addressing the research problem. This paradigm enables the use of various collection and analysis techniques that are appropriate to answer the research questions. Therefore, this paradigm was useful in investigating the evidence of developing systems thinking skills and a sustainable action perspective. Since the interpretations in this study are made from subjective and objective evidence, qualitative and quantitative approaches are used to investigate outcomes of reality that describe first-year chemistry students' engagement with system thinking. These first-year students were the participants selected for this study, which is described in the following section.

4.5. PARTICIPANTS

The participants for the study were all enrolled in the CMY 127 Chemistry module at The University of Pretoria, South Africa. This module is a pre-requisite for all undergraduate science degrees; it, therefore, has a large enrolment of approximately 1500 students. All CMY 127 students were invited to participate in this study, but a purposeful selection was made from the volunteers. Volunteers had to indicate their availability to attend practical sessions in the given timeslots shown in Table 4.1.

Table 4.1. Practical Timeslot enrolment

Practical Timeslot Availability	Number of volunteers
Tuesday (11:30-13:20)	94
Tuesday (15:30-17:20)	0
Wednesday (11:30-13:20)	20
Thursday (11:30-13:20)	8
Friday (15:30-17:20)	9

The Wednesday practical timeslot was chosen for the study to allow two pilot interventions, the Tuesday groups, to address logistical issues before collecting data. From the group of 20 volunteers for the Wednesday session, 18 participants were randomly selected to form a convenience sample for the study. The 18 participants were then ordered according to their prior performance based on their final grade for the first-semester chemistry module, CMY 117. Students' marks for this course were a proxy for their prior knowledge. The following classification of high, medium and low prior performance groups was used, as shown in Table 4.2. to ensure that from the 18 participants, there would be six students from each prior performance subgroup.

Table 4.2. Classification according to performance bands

Academic performance	Percentage
High	More than 65%
Medium	Between 56% and 65%
Low	Less than 55%

The 18 participants were allocated to home groups of three students, with one from each academic performance band, to ensure maximum variation in each home group. This would enable the more knowledgeable others to guide the group discussions and enhance the group dynamics, as discussed in the design principles in Chapter 3. The participants were then grouped into the subsystem groups of their preferred choice after having discussions with their home group members.

4.6. DATA INSTRUMENTS

Three different types of instruments, SOCME diagrams, self-reflection questionnaires and focus group interviews, were used to collect data to answer the research questions of this study. Quantitative data in the form of scores were obtained from the assessment of SOCME diagrams using the rubric designed from the SOLO taxonomy and from counting responses to closed-ended questions in the self-reflection questionnaires. The qualitative data were collected from open-ended questions in the self-reflection questionnaires, content analysis of the SOCME diagrams, rater feedback, and focus group interview transcripts. The type of data collected from these instruments, the research tools, the mode of collection and the number of submissions collected are summarized in Table 4.3.

Table 4.3. Data collected for the research questions of this study

Research Question 1
Which systems thinking skills were developing in first-year chemistry students as they engaged in a systems thinking intervention?

Data grouping	Data collection instrument	Data type	Research tool	Mode of collection	Submissions collected
Demonstration of systems thinking skills	SOCME diagrams	Qualitative	Content added to partial SOCMEs	Online submission received from LMS and downloaded in a PowerPoint format	6 SOCMEs
	SOCME rubric	Quantitative	Scores	Downloaded into an excel spreadsheet	6 rubrics with feedback from 2 raters
		Qualitative	written feedback from raters	Emailed and downloaded into a Word format	
Perception of systems thinking skills	Self-reflection Questionnaires (SRQ)	Quantitative	closed-ended questions Q 2,3,4	Online submission of responses from LMS downloaded into an Excel Spreadsheet	14 respondents
	Focus Group Transcripts (FGT)	Qualitative	Semi-structured open-ended questions Q1,2	Transcribed word document and Recordings downloaded from Microsoft Teams.	2 transcripts and 2 video recordings

Research Question 2
What evidence suggests that a sustainable action perspective was developing in first-year chemistry students?

Reflection of systems thinking skills	**Data collection instrument**	**Data type**	**Research tool**	**Mode of collection**	**Submissions collected**
	Self-reflection Questionnaires	Qualitative	Open-ended questions Q5,7	Online submission of responses from Blackboard Collaborate, downloaded into an Excel Spreadsheet	14 responses

4.6.1. SOCME DIAGRAMS

Concept maps are graphic representations used as data collection tools providing evidence of the demonstration of systems thinking skills. This study used SOCME diagrams, which are extended concept maps, as qualitative data collection tools to collect evidence of the systems thinking students demonstrated in this intervention. SOCME diagrams also communicate information regarding the structural complexity of students thinking and represent the quality of learning as students expand their partial SOCME. The expanded SOCME diagrams produced by the six home groups were assessed using the designed rubric to collect quantitative data in the form of scores to reflect the systems thinking skills that the participants demonstrated.

4.6.2. SELF-REFLECTION QUESTIONNAIRES

The self-reflection questionnaire consisted of ten questions. Five of these questions, shown in Appendix C2, were not considered for data analysis and was used to orient students to recall their learning (questions 1,6) and to get feedback regarding the intervention, which is beyond the scope of this study (questions 8,9,10). The other five questions (question 2,3,4,5,7) were used to collect quantitative and qualitative data from the 18 participants. The survey was administered online via the learning management system in keeping with the online nature of the course. The purpose of the questionnaire was to collect students' reflections on their learning of systems thinking skills and the impact of the intervention on their lives. This data was essential to answer both research questions as it would reveal the systems thinking skills students perceived to have developed and what they would do from here on going forward to take sustainable action.

Closed-ended questions (question 2, 3 & 4 shown in Figure 4.3.) incorporating multiple-choice options were asked to understand participants' views regarding the achievement and difficulty level of demonstrating the systems thinking skills on their SOCMEs. Figure 4.3 shows the systems thinking skills that students could have selected as answers.

Question 2
Which of the systems thinking skills do you feel you have successfully achieved during practicals 4 and 5? (tick the applicable boxes)

Question 3
Which of these skills did you find the most challenging during the construction of your SOCME diagram? (tick the applicable boxes)

Question 4
Which of these skills did you find the least challenging during the construction of your SOCME diagram? (tick the applicable boxes)

☐ Identify the components of a system and processes within the system
☐ Identify relationships among the system's components
☐ Identify dynamic relationships within a system
☐ Organize the system's components and processes within a framework of relationships
☐ Understand the cyclic nature of systems
☐ Make generalizations
☐ Identify the hidden dimensions of the system (intermolecular forces, surface tension, molecular geometry, acidity, and basicity, nucleophilicity, solubility, polarity)
☐ Thinking temporally: retrospection and prediction

Figure 4.3. Questions from the self-reflection questionnaire on students' perceptions

Multiple-choice data are easy to collect and allow for quick data analysis as participants respond to the same questions, which enables standardized answers (Fraenkel, Wallen, & Hyun, 1993). Open-ended responses allow for more individualized responses. However, they require more intensive data analysis as interpreting responses is more challenging (Fraenkel et al., 1993, p. 336). Open-ended questions in the self-reflection questionnaire were used to elicit students' reflection on the application of systems thinking knowledge and skills during the intervention, as shown by question 5 below. Question 7 in the self-reflection questionnaire was incorporated so that interpretations could be made regarding students' motivation to indicate that they appreciated learning about systems thinking and if they felt motivated to contribute to sustainable action in their personal lives. The two open-ended questions, shown below in Figure 4.4, were considered for data analysis. For question 5 students enrolled for CMY 127 were given a choice between doing the traditional aspirin practical or volunteering for a new learning activity. Both were leading questions to guide the reflection on what skills and understanding students perceived to have learned and whether they were developing an attitude of taking ownership.

Question 5

A student that did the aspirin practicals, asks you to briefly explain what skills (systems thinking, communication, technological, problem solving, creativity, etc.) and understanding you have gained in these practicals. What would you tell the student to answer their question?

Question 7

What would you do as a responsible citizen and an upcoming scientist from here on forward to ensure you apply systems thinking in your daily life and take sustainable action after participating in these practicals?

Figure 4.4. Questions from the self-reflection questionnaire on students' perceptions

4.6.3. FOCUS GROUP INTERVIEWS

To develop a holistic understanding of students' perceptions regarding the systems thinking terminology and the skills they found most challenging to demonstrate during the expansion of their SOCME diagrams, focus group interviews were employed to supplement the data obtained from self-reflection questionnaires and SOCME diagrams. Students' perceptions discussed in the focus group interviews were used to validate and enrich the quantitative data collected and analysed from the closed-ended questions in the questionnaire. The analysis of focus group interviews would generate themes and ideas that represent the voice of the whole focus group in the form of direct quotes or words. Questions for the interview were drafted after working through preliminary quantitative data regarding the skills that students found most challenging. Questions were also drafted to investigate how students' understanding of terms influenced their conceptual understanding of the systems thinking skills. These semi-structured questions will be presented in Chapter 5. In this study, all the participants were invited to participate in the focus group interviews. The interviews were conducted online because lockdown restrictions limited social interaction. The online focus group interviews over Microsoft Teams enabled all participants to join, irrespective of location. It also made the recording and transcription of the discussions easier. Online transcription software made processing the interview data more accessible. It also reduced time and cost commitment for data analysis.

4.7. DATA COLLECTION

The method and timeline of data collection for each of the above data collection instruments discussed will be considered in this section. In this study, the data collection processes were treated as a puzzle-building activity, where puzzle pieces had to be collected, organized, and assembled to visualize a bigger picture that could aid in answering the research questions from a more holistic perspective. Figure 4.5. demonstrates the data considered as puzzle pieces of qualitative and quantitative information collected during and after the intervention. Data were collected from SOCME diagrams, the SOCME scores and rater feedback to understand students' *demonstration* of system thinking skills. Data were collected from closed-ended questions of the self-reflection questionnaire and focus group interviews to understand students' *perception* of their growth of systems thinking skills. Data were also collected from the open-ended questions of the self-reflection questionnaire to explore students' *reflections* on their learning.

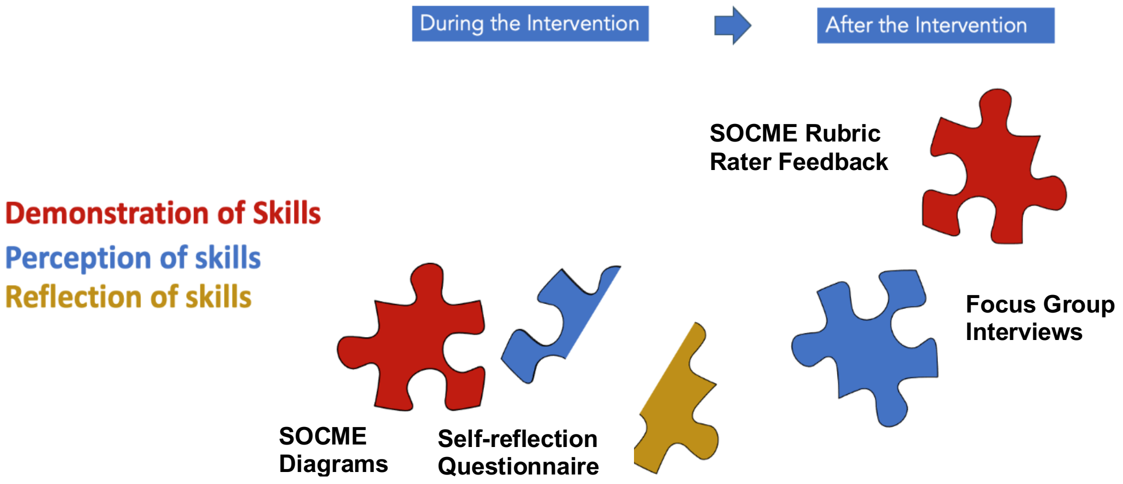


Figure 4.5. Data collection instruments during and after the intervention

After obtaining informed consent from students their data were collected in various forms, as described in Table 4.3. The quantitative and qualitative data were collected online through the LMS. The intervention design guided the data collection process to obtain six SOCME diagrams, six SOCME rubrics with rater feedback and 14 self-reflection questionnaire responses from the 18 participants. The focus group interviews required planning to ensure meaningful discussions were held that could contribute to the study. Students were invited to attend one of two online focus group interview sessions scheduled on Microsoft teams that lasted approximately one and a half hours with four participants in the first and five participants in the second.

4.8. DATA ANALYSIS

Qualitative and quantitative data were collected and analysed concurrently to create a fuller picture of what students could demonstrate, what systems thinking skills they perceived to have developed and what systems learning they reflected on developing. These data fragments were analysed so that they could be compared and triangulated to obtain findings presenting the reality of the developed systems thinking skills and sustainable action perspectives.

4.8.1. QUANTITATIVE ANALYSIS

Descriptive statistics

Descriptive statistics were used to analyse students' skills quantitatively and create visualizations to understand their perceptions and the systems thinking skills they demonstrated or perceived to have achieved during the intervention. The data collected for analysis included SOCME scores obtained from the rubric and closed-ended responses from the self-reflection questionnaire. These will be described in more detail below.

The descriptive statistics from SOCME rubrics include measures of variation of total SOCME scores and scores for each SOLO level. Other than assessing consistency amongst raters, the interpretations made from the scores were used to understand quantitatively what skills students demonstrated on their SOCME diagrams. Quantitative data collected from closed-ended questions were analysed to represent the skills that students perceived to have achieved and what they experienced as the most and least challenging systems thinking skills to demonstrate on their SOCME diagrams. The closed-ended responses (questions 2,3,4) were grouped to manage and organize the data. The frequency of occurrence of the selected systems thinking skills was represented in a bar chart. Reflections were written for each bar chart, and interpretations were made to formulate questions for the focus group interviews. These bar charts allowed for interpretations and comparisons between questions 3 and 4 to determine the frequency of students who perceived some skills as the most and least challenging skills to demonstrate on a SOCME diagram and to interpret how many of the students perceived to have achieved these skills.

4.8.2. QUALITATIVE ANALYSIS

Content analysis and grounded theory methods were used for the analysis of qualitative data. The rationale for the choice of approach and the objectives for its application are discussed below.

Content analysis

Content analysis of SOCME diagrams was conducted to create a better picture of the skills and understanding that students have demonstrated to expand their partial SOCMEs. It was also used to compare to the SOCME scores for validation of the findings. The rubric, designed from the SOLO taxonomy, was used to guide the content analysis where six SOCME diagrams were compared in terms of the systems thinking skills demonstrated. To analyse the SOCMEs for their content, the following questions, as shown in Table 4.4. below, were asked to investigate SOCME diagrams for evidence of students' experience and their ability to achieve the learning outcomes of the intervention.

Table 4.4. SOCME content analysis

ST skills	Question for analysis	Alignment with LOs
chemistry understanding	How many concepts did students add to their SOCME that relate to the physical or chemical properties of surfactants?	LO1: Examine and understand molecular-level concepts and processes that influence system-level behaviour
Analysis: elements	How many new concepts were added that were relevant to the system of LAS, which relate to any of the concepts learnt in the surfactant lecture?	LO2: Identify and illustrate the system-level concepts and processes relevant to a system
Analysis: relationships	What was the quality of the connections and linking words made between concepts within the subsystems?	LO3: Identify and illustrate the relationships between system-level concepts within subsystems
Integration: cyclic behaviour	How many concepts and linking words were added that indicated a cyclic behaviour or feedback loop? (other than the biodegradation cycle and supply and demand cycle provided)	LO4: Explain causes of cyclic behaviour and examine feedback loops in the system
Integration: emergence	How many concepts and linking words were added that were factors that contribute to an emergent behaviour (foaming of LAS) in the system?	LO5: Analyse potential emerging system-level behaviour in the system
Integration: dynamic interactions	How many new concepts or linking words were added between subsystems and how many of these linkages within and between subsystems are dynamic?	LO6: Identify and describe interactions within and between subsystems that can change over time
Integration: organization	How well were students able to fit new concepts and link words into an appropriate subsystem and were any new subsystems added?	LO7: Organize system-level concepts in the whole system and identify new subsystem boundaries
Application	What was the quality of concepts and linking words added to make predictions based on the options given and was there a coherent story about the whole system of LAS?	LO8: Predict factors that influence how a system changes over time
Ownership	How many concepts did students add that related to the connection between surfactants and sustainability and the role of human action?	LO9: Consider the role of human activity on current and future system-level behaviour

Coding

Coding was conducted from a pragmatic approach grounded in the participants' voices. The pragmatic approach enabled the use of many different coding strategies that would be appropriate to get codes, categories and themes from students' responses that describe their perceptions and reflections to best represent the reality of their experiences. A two-phased coding approach was employed in this study. The text was analysed during the first coding phase to take the “whole” apart, which was then put together during the second phase to consolidate meaning from emerging themes. The five steps, as proposed by Creswell and Poth's data analysis spiral (Creswell & Poth, 2018) were layered over the two coding phases, as shown in Figure 4.6. Various steps were repeated at different stages until satisfactory codes were developed.

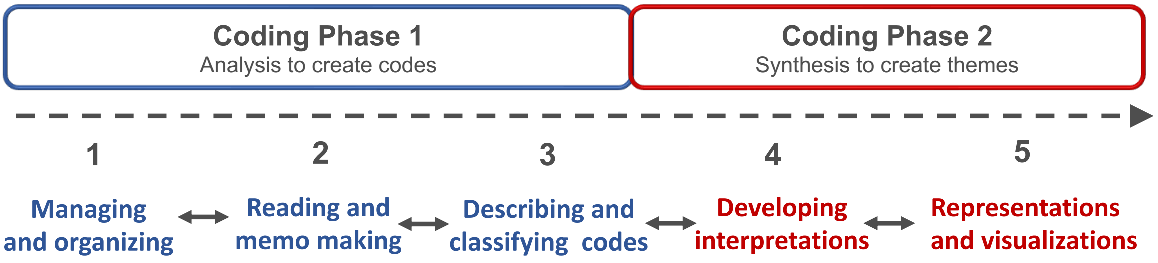


Figure 4.6. Modified data analysis spiral taking into consideration two phases of coding

The data from questions 5 and 7 of the self-reflection questionnaire were managed and organized first before starting the first coding phase. The raw data from the questionnaires were grouped per question, and student identifiers were assigned for anonymization. During the first coding phase, extensive reading and memo-making occurred with a paper and pencil method to formulate ideas for pre-coding. The coding documents were uploaded onto Atlas.ti, which is a Computer Assisted Qualitative Data Analysis (CAQDA) software program where the process continued.

During the initial analysis, the codes were kept open and were revised later to identify a particular coding technique. The approach aligns with what Saldaña described as "pragmatic eclecticism", which starts with open coding before deciding on a coding method for substantive analysis (Saldaña, 2021, p. 90). The responses in the questionnaire were coded inductively using *in vivo* and descriptive codes. For the second coding phase, the developed codes were refined and re-defined in the context of relevant literature until the codes had suitably accurate descriptions. Saldaña stated, ″as an inductive coding system is constructed and becomes solidified, it then becomes a deductive coding system for the data analysis that follows." (Saldaña, 2021, p. 41).The data were thus reanalysed using a deductive approach. The overall coding approach utilised constituted inductive and deductive coding approaches that aided in building an understanding of the student's perceptions of their learning of systems thinking skills. This will contribute to answering the first research question regarding the evidence that suggests that systems thinking skills were developing in students, which would aid in answering the second research question regarding the evidence suggesting that a sustainable action perspective was developing.

The data obtained from the focus group interviews were organized first to prepare the transcripts for analysis. The focus group interviews were transcribed by Microsoft teams software. After relistening to the interview recordings several times, the transcripts were then "cleaned up" by editing the text with an intelligent verbatim and denaturalized approach. Care was taken to limit editing to preserve the originality of students' responses so that it conveys the substance of perceptions and meanings. The transcripts were edited to enhance readability by removing repetitive words and fillers. This was also done to minimise student embarrassment when participants read the transcripts after the interview for member checking (Nascimento & Steinbruch, 2019). For the focus group transcripts, “macro-coding” was done as a “lumper” to assign one code per paragraph or data excerpt. Lumping aids in categorising data to identify the primary ideas from students' responses (Dey, 1993, p. 104). *In vivo* coding techniques were also used to code direct words from participants and holistic coding to code keywords that emerge from the data. Inductive holistic coding was used as an exploratory coding strategy to capture an overview of the overall responses to identify emerging categories.

Thematic analysis was used during the second coding phase for both questionnaire data and interview transcripts to report narrative summaries of the main ideas that emerged from the data. As a final stage of the qualitative data analysis process, the interpretations were made from themes. The following section describes how the interpretations made from the qualitative data were compared with quantitative data and triangulated to make trustworthy inferences about the systems thinking skills that students have demonstrated, their perceptions regarding these skills and their reflections on learning about systems thinking.

4.8.3. RELIABILITY, VALIDITY, AND RIGOUR

Various strategies were considered to ensure reliability, validity and rigour throughout the data analysis. These strategies are summarized in Table 4.5. Each of these strategies will be discussed in more detail in Chapter 5 after the findings of students' perception, reflection and demonstration of systems thinking skills are presented.

Table 4.5. Data collection and analysis to answer the research questions of this study

Research Question 1 Which systems thinking skills were developing in first-year chemistry students as they engaged in a systems thinking intervention?					
Data grouping	**Data collection instrument**	**Data type**	**Research tool**	**Data analysis**	**Reliability, validity and rigour**
Demonstration of systems thinking skills	SOCME rubric	Quantitative	Rubric scores	Descriptive statistics	Inter-rater reliability of grading SOCMEs Compare scores with rater feedback and content analysis Triangulation with students’ perceptions and reflections
		Qualitative	Written feedback from raters	Content analysis	
	SOCME diagrams	Qualitative	Content added to partial SOCMEs		
Perception of systems thinking skills	Self-reflection Questionnaires	Quantitative	closed-ended questions Q 2,3,4	Quantitative counting and descriptive statistics	Comparison of perceptions Member-checking and memo making for

	Focus Group Interviews	Qualitative	Semi-structured open-ended questions Q1,2	Thematic analysis	Focus group interviews Triangulation with students' demonstrations and reflections
Research Question 2 What evidence suggests that a sustainable action perspective was developing in first-year chemistry students?					
Reflection of systems thinking skills	**Data collection instrument**	**Data type**	**Research tool**	**Data Analysis**	**Reliability, validity and rigour**
	Self-reflection Questionnaires	Qualitative	Open-ended questions Q5,7	Inductive and deductive coding	Inter-coder agreement and audit trail of codebook

4.9. ETHICAL CONSIDERATIONS

This study identified ethical issues before the research questions were formulated to ensure that participants also benefit from the study. The research participants were not disadvantaged in any way or lost out on any learning that occurred during the second semester. In addition, the level of risk to the student's performance and throughput for participating in a new teaching intervention was minimal because of the small contribution their marks would make to their overall grade for the course (<1.5%). By contrast, the participants had an opportunity to gain new skills not formally included in the existing curriculum, such as systems thinking, concept mapping and collaboration skills.

Care was taken not to marginalize or disempower the participants. The content of the lesson videos and activities was carefully constructed to ensure no stereotyping or images that might be disrespectful to participants. An open invitation was extended to all students without needing personal data access. Volunteers were informed about the nature of the study, how their data would be used, and the commitment required before giving informed consent. Students were also told that they could withdraw from the study at any time without being penalized.

The primary ethical consideration concerning data management for this project was to protect the identity of the participants. If participants referred to other participants by name, for example, in the focus group transcripts, the names were replaced with code names. Student identifiers were used during the processing and storage of data to ensure confidentiality. Participants' identities, therefore, remained anonymous when the results were reported. The study aimed to investigate broad trends in the data rather than focusing on responses from individual students, even though student quotes might be reported in the findings chapter. Only data directly relevant to the research project was collected, i.e., no contact details, demographic data, performance data, or opinions relating to other aspects of the module were collected. All invitations to interviews were done via the learning management system's email function to protect student identities. After collection, all raw data was stored on computers under password protection. The final processed data was of such a nature that it could not be traced back to individuals. Before the study commenced, ethical clearance was obtained from the Faculty of Natural and Agricultural Sciences Ethics Committee at the University of Pretoria (see appendix A).

4.10. LIMITATIONS AND ASSUMPTIONS

The limitations inherent to this study are associated with the nature of case study research. Since the researcher needs to choose the participants to investigate in the case study, boundaries must be constructed to contain the study and select the research participants. This, together with convenience sampling, might have excluded participants that could have contributed significantly to the study. Therefore the study acknowledges that a small sample of 18 participants and a single-case study, which is narrow in scope, resulted in findings that should be carefully considered before generalisations are made to other contexts. Due to the diverse context in which the study was implemented, a decision was made to exclude demographic data as a contributing factor to the findings. This assumption that the demographic nature of the students would not substantially influence their learning may need to be revised.

Another limitation was associated with using a particular method to ensure the trustworthiness of the findings based on the type of data collected and analysed. There may need to be more than these methods to remove all bias and misinterpretation. It is possible that quantitative and qualitative data collected from questionnaires do not accurately reflect participants' true responses and that the interpretation of especially open-ended questions can be subject to misinterpretation. Students could have provided dishonest answers in the questionnaire responses and could have conformed to the thoughts and opinions of others in the interviews. From the responses provided, the data could have been misinterpreted. However, countermeasures were introduced to reduce bias by asking students to answer honestly and triangulating findings from questionnaire data with interview responses. Also, peer debriefings, member-checking and inter-coder agreement contributed to minimising misinterpretations.

CHAPTER 5: FINDINGS

5.1. INTRODUCTION

In this chapter, the focus will be placed on the evaluation of systems thinking from three different perspectives. Figure 5.1. shows the three perspectives that will be considered to understand the development of systems thinking skills in first-year chemistry students. Evidence from students' perception of achievement and the most challenging systems thinking skills, reflections on their learning, and demonstration of systems thinking skills to expand their SOCMEs will be presented.

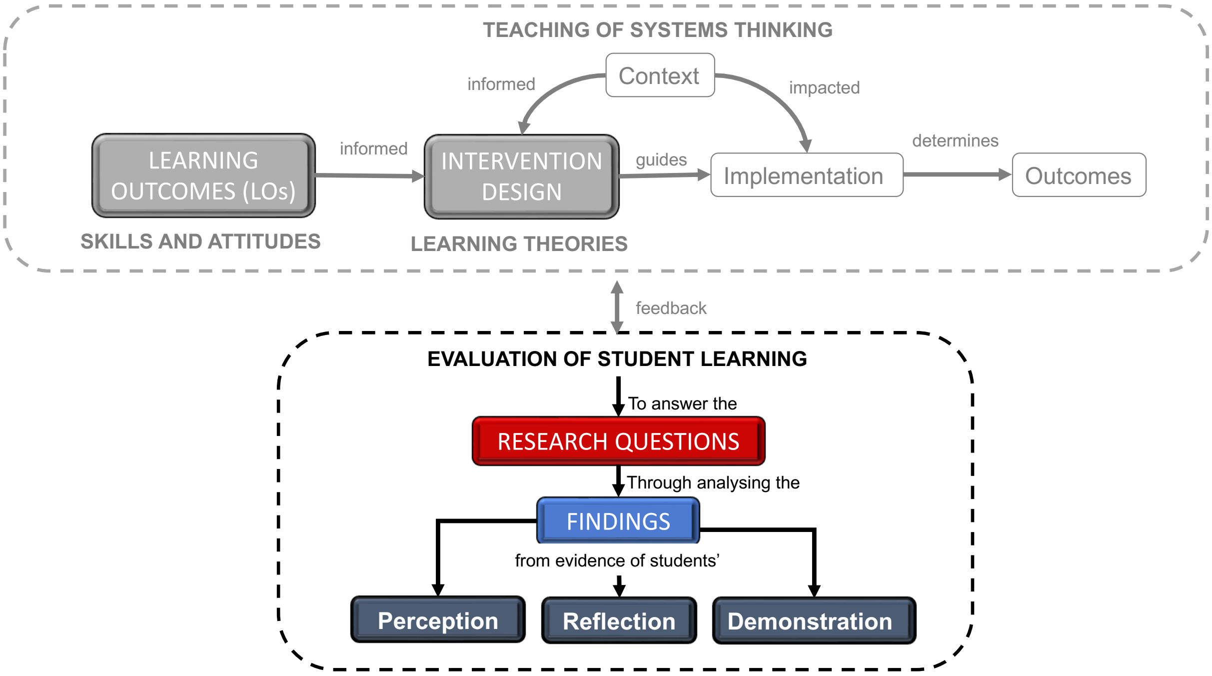


Figure 5.1. Overview of Chapter 5

5.2. STUDENTS' PERCEPTION OF SYSTEMS THINKING SKILLS

In this section, findings will be discussed concerning students' perceptions. This section starts by highlighting students' conceptual understanding of the systems thinking terminology, followed by their perception of achievement of systems thinking skills and the skills they found to be most challenging to demonstrate during the expansion of a SOCME diagram. This section will then be concluded with the trustworthiness of the findings from students' perceptions.

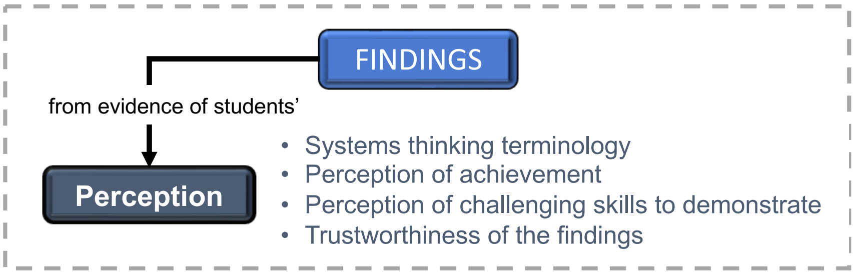


Figure 5.2. Overview of the section on students' perception of systems thinking skills

5.2.1. SYSTEMS THINKING TERMINOLOGY

Students' perception regarding the difficulty of systems thinking skills could have been associated with their lack of understanding of systems thinking terminology. Therefore, it was important to analyse students' understanding of the terminology before interpretations were made from the data. The following question, shown in Figure 5.3., was asked in the focus group interview to understand better whether students were able to comprehend the terminology used in this intervention.

Terminology

Systems thinking on its own is a term that you might have not been familiar with, before the start of practicals 4 and 5. However, throughout the intervention, there might have been other terminology and constructs or ideas that were new and not easy to understand.

- Can you recall any of these challenging terms?
- Why did you find these terms challenging?
- Suggest how we could define these terms to make it easier for future students?

Figure 5.3. Focus group interview questions regarding students' perceptions of the terminology

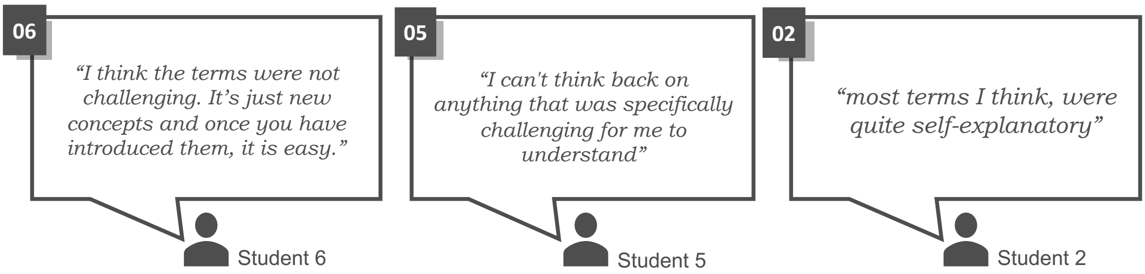
The focus group transcripts were coded holistically with in-vivo codes taken directly from students' words and descriptive codes using an inductive approach to make sense of the responses to this question. These codes were grouped into three categories, shown with the codes and code descriptions in Table 5.1. below. The quotes to which these codes were applied in Atlas.ti can be viewed in Appendix D.

Table 5.1. Codes used for analysing students' perceptions of the terminology

Code Categories	Codes	Code description
Perceptions of terminology	*"easy"*	Applied if students stated that the terminology was easy or not difficult
	"familiar"	Applied if students described terminology as familiar that they could have encountered before
	"more difficult"	Applied if students described terminology that they found as "more difficult"
Perceptions of challenging terminology	*"context"*	Applied if students perceived that the terminology used in the context of the intervention was challenging.
	"new"	Applied if students perceived that terminology was challenging as it was new.
Understanding	*progressive*	Applied if students perceived that their understanding of the terminology was progressing during the intervention.

	conducting research	Applied if students perceived that conducting research helped them to understand the terminology better.
Suggestions	*“make it easier”*	Applied if students made suggestions to make the terminology easier

We found that most students experienced the systems thinking terminology as “familiar” and “easy”. The student comments supporting this finding are shown in Figure 5.4.



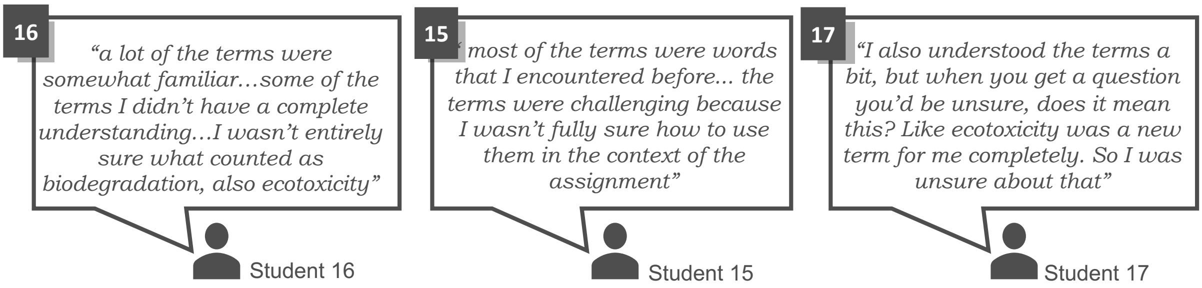
“I think the terms were not challenging. It’s just new concepts and once you have introduced them, it is easy.”

“I can't think back on anything that was specifically challenging for me to understand”

“most terms I think, were quite self-explanatory”

Figure 5.4. Students’ responses regarding their uncertainty regarding the context of terminology

The perceptions about challenging terms were related to their newness. Student 5 stated, *“We've never heard some of them or haven't been taught or educated about the terms that we used, so I guess it was just very new to us and some things that we haven't heard of before.”* Other students expressed that they felt unsure about the use of the terminology in the context of the intervention, which could have made the terms challenging, even though many of the terms seemed familiar. Students felt unsure about the terms ecotoxicity and biodegradation, as seen in the following responses in Figure 5.5.



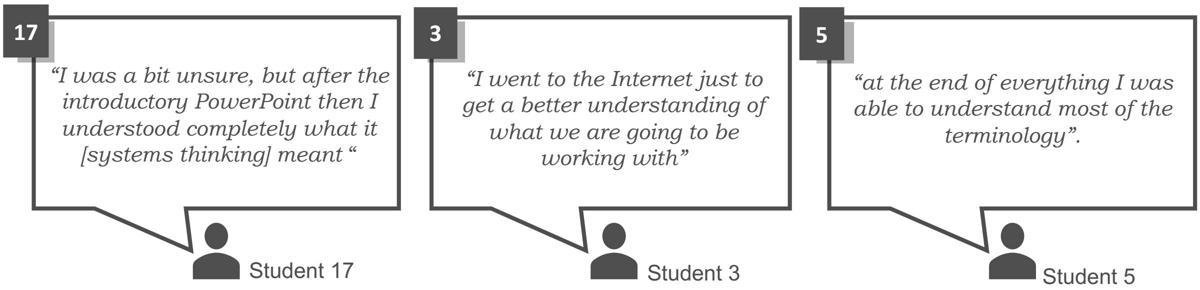
“a lot of the terms were somewhat familiar…some of the terms I didn’t have a complete understanding…I wasn’t entirely sure what counted as biodegradation, also ecotoxicity”

most of the terms were words that I encountered before... the terms were challenging because I wasn’t fully sure how to use them in the context of the assignment”

“I also understood the terms a bit, but when you get a question you’d be unsure, does it mean this? Like ecotoxicity was a new term for me completely. So I was unsure about that”

Figure 5.5. Students’ responses regarding the difficulty of systems thinking terminology

Evidence also suggested that students developed a progressive understanding of the terminology as the intervention proceeded. Students gained understanding from the lesson materials and from conducting research. These responses are shown in Figure 5.6.



“I was a bit unsure, but after the introductory PowerPoint then I understood completely what it [systems thinking] meant “

“I went to the Internet just to get a better understanding of what we are going to be working with”

“at the end of everything I was able to understand most of the terminology”.

Figure 5.6. Students’ responses regarding a progressive understanding of terminology

In summary, even though students experienced some terms as challenging due to their newness and the context in which it was used, they felt that they gained a progressive understanding of the terms as they engaged with lesson materials or additional resources. As a result, we found that the language of the unknown terminology did not have a considerable influence on students' judgement regarding their perceptions of the skills. Students' perceptions of achievement and of the most and least challenging systems thinking to demonstrate on SOCMEs will be presented in the following section.

5.2.2. PERCEPTION OF ACHIEVEMENT

Student perceptions regarding the achievement of systems thinking skills were investigated by question 2 in the questionnaire. Of the 14 responses received, only 11 responses were considered complete as students answered all the questions. Students' perceptions regarding the achievement of skills are shown in Figure 5.7. below. If students did not select a skill as achieved, it was considered not achieved.

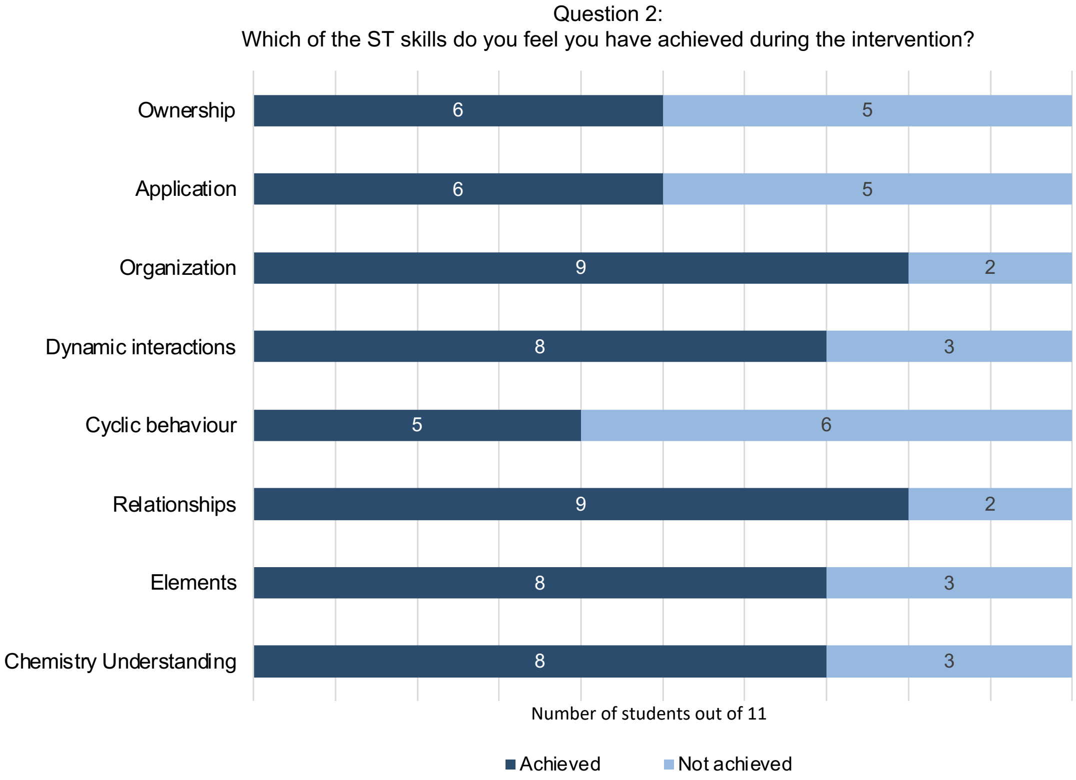


Figure 5.7. Bar chart illustrating the perception of achievement of systems thinking skill (n=11)

The bar chart illustrates that most students (nine out of the eleven) perceived having equally achieved the ability to identify relationships within the system (*analysis: relationships*) and to organize the concepts within the system into existing and new subsystem boundaries (integration: organization). Eight students perceived that they were developing a *chemistry understanding*, the ability to identify concepts in the system (*analysis: elements) and integration: dynamic interactions* skills. For the *integration* skills *cyclic behaviour*, *application*, and *ownership*, an overall trend cannot be inferred as the number of students who reported their achievement was too similar, indicating that almost half of the students reported it as achieved or not achieved.

To further understand students' perceptions regarding systems thinking skills, their perception of applying these skills during the expansion of a SOCME diagram was investigated in more depth. Students' perception of achievement could have been influenced by their experience of expanding a SOCME diagram, as it made up the most significant part of the intervention where students were asked to apply their systems thinking skills.

5.2.3. PERCEPTION REGARDING MOST AND LEAST CHALLENGING SKILLS

Students were asked to indicate which systems thinking skills they experienced as most and least challenging during the expansion of their SOCME diagram. The results are presented in Figure 5.8.

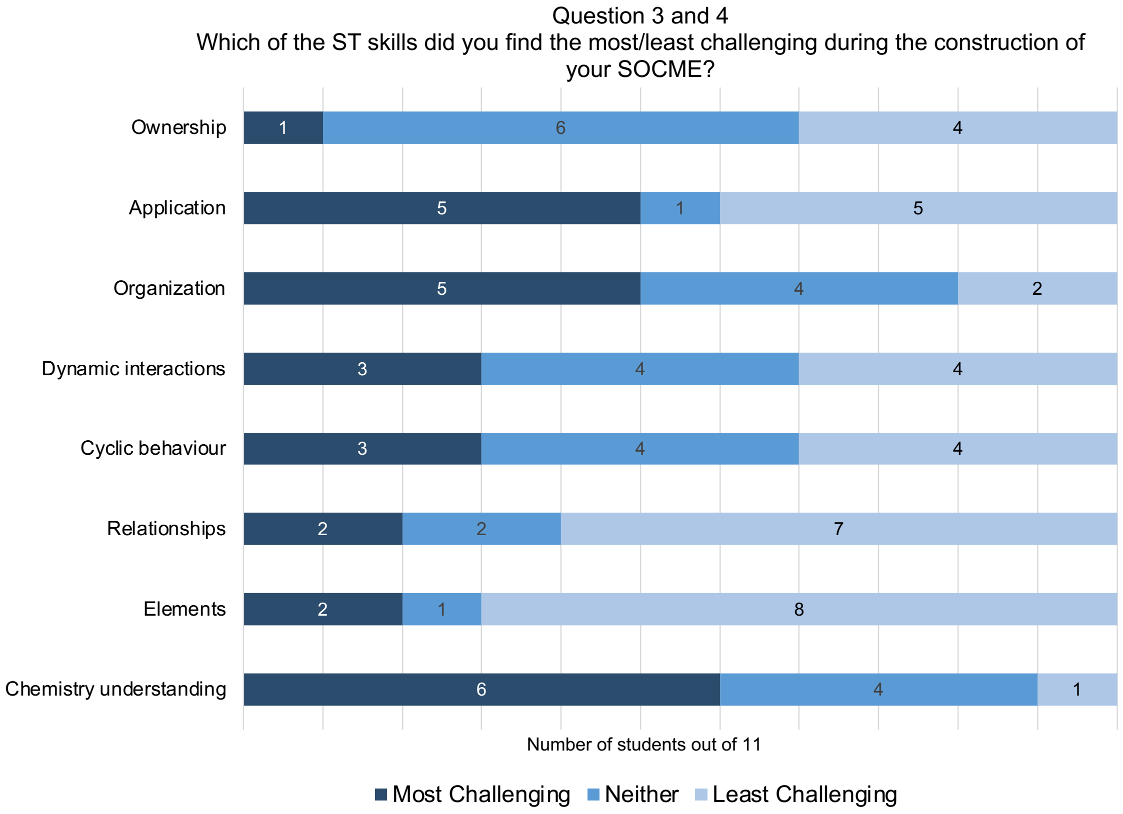


Figure 5.8. Bar chart illustrating the perception of most and least challenging systems thinking skills (n=11)

For each of the systems thinking skills, the number of students choosing it as the most challenging was added to the number choosing it as least challenging. Students who did not select the skill as most or least challenging were placed into the "neither" category. The bar chart indicates a correlation between the most and least challenging skills, as a high selection of the most challenging skills generally aligned with a low selection of that skill as least challenging. The evidence is in Figure 5.8. suggests that students found identifying *elements* and *relationships* the least challenging. Interpretations regarding *cyclic behaviour* and *dynamic interactions* were difficult to make due to the similarity in responses. Most students experienced *integration* skills as least challenging or as neither most nor least challenging. For *application*, students perceived it as equally the most and least challenging and for the attitude of *ownership*, most students perceived that it was neither the most nor least challenging.

Findings also showed that students perceived their *chemistry understanding* and organizing concepts into a framework of relationships as the most challenging to demonstrate on their SOCMEs. These were also the two abilities identified as most achieved in the previous question. This interesting finding was investigated further by asking students the following questions during focus group interviews about their *chemistry understanding* (skill seven according to the STH model) and *integration: organization* (skill four according to the STH model), as shown in Figure 5.9 below. Students' responses were coded inductively after the data were prepared for analysis; refer to chapter 4.

Integration: Organization

the ability to organize the system's components and processes within a framework of relationships.

- What is your understanding of systems thinking skill 4?
- This skill was indicated by most of you as one of the most challenging skills to demonstrate on your SOCME. What made it so challenging?
- Most groups did not indicate any new subsystems (other than economic, social, and environmental) in the SOCMEs. How could we support groups so that they are better placed to identify other subsystems?"

Chemistry understanding

the ability to recognize the hidden dimensions of the system (intermolecular forces, surface tension, molecular geometry, acidity, and basicity, nucleophilicity, solubility, and polarity)

- What is your understanding of systems thinking skill 7?
- This skill was indicated by most of you as one of the most challenging skills to demonstrate on your SOCME? What made it so challenging?
- In practical 4 you were given a core chemistry concept map from which you had to work to interpret an expanded concept map. In practical 5 you were given a partial SOCME and had to construct a final SOCME. During which part of this gradual process were you able to demonstrate the hidden dimensions of the system of Linear Alkylbenzene Sulfonate? Please explain.

Figure 5.9. Focus group interview questions regarding *integration: organization* and *chemistry understanding.*

The codes that emerged from the data for both a *chemistry understanding* and *integration: organization* were used to explain why students perceived these skills as challenging to demonstrate on their SOCMEs. These codes are presented in Table 5.2 with the code descriptions.

Table 5.2. Understanding of "hidden dimensions" and "organization" and students perceptions relating to its challenge to demonstrate on a SOCME

Code Category	Code	Code description
Perception of systems thinking skills	*"hidden dimensions"*	Applied if students described their understanding of hidden dimensions and refer to the surfactant knowledge, content or their chemistry understanding
	"organization"	Applied to students' responses describing their perception about the systems thinking skill *integration: organization* and to excerpts where students refer to fitting concepts into the system.

Challenges	*Reductionism*	Applied if students felt that they only focused on one thing at a time to reduce the complexity, to make the interconnections less daunting and if students referred to their unfamiliarity with systems thinking.
	Expectation	Applied when students felt uncertain about the expectations because of different interpretations of the instructions, their unfamiliarity with applying the skill and worried about getting marks.
	Complexity	Applied if students felt overwhelmed or if students didn't know where to start as they are thinking about everything and how everything connects.
	Lack of creativity	Applied if students struggled to think outside of the box and found it difficult to add new concepts or subsystems.
	Relevance	Applied if students expressed that they are not used to thinking about the real-world implications of chemistry or how it affects real life and applies to everyday life.
	Difficult to visualize	Applied if students struggled to visualize the skill or see the effects of the skill on the SOCME
	Lack of practise	Applied if students felt that the skill is not practised enough or that students feel that the skill is unfamiliar because of limited exposure to practise the skills
	Time	Applied if students referred to time as a limitation, which made it difficult to demonstrate the skill on the SOCME.

A bar chart, Figure 5.10. is presented to better understand the challenges considered more specific to each of these systems thinking skills. The coded focus group excerpts can be read in Appendix D. Figure 5.10. shows that students' familiarity with reductionism featured in their discussion regarding the challenges associated with demonstrating their *chemistry understanding* and *integration: organization* skills. The code *reductionism, expectation, complexity, lack of practise and time* were coded as challenges in students' discussion on the skill *integration: organization.* For *chemistry understanding*, it was seen that students' unfamiliarity with the relevance of chemistry and the difficulty in visualizing the skill on the SOCME was unique to the skill. Students also discussed that *reductionism, expectation, complexity, and lack of creativity* were challenges they experienced while developing a *chemistry understanding*

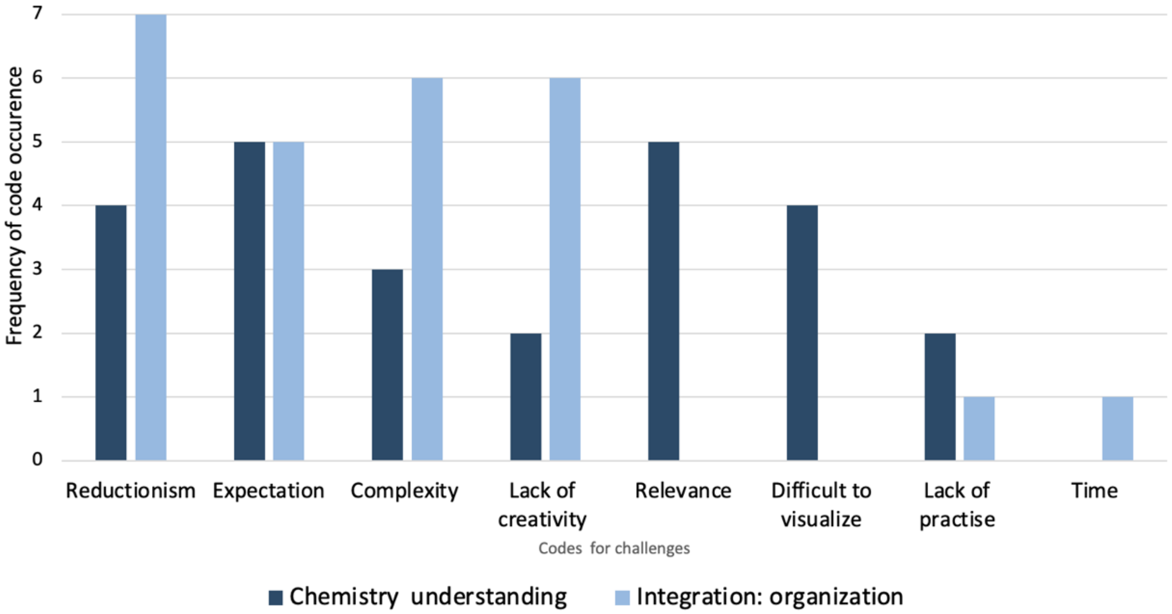
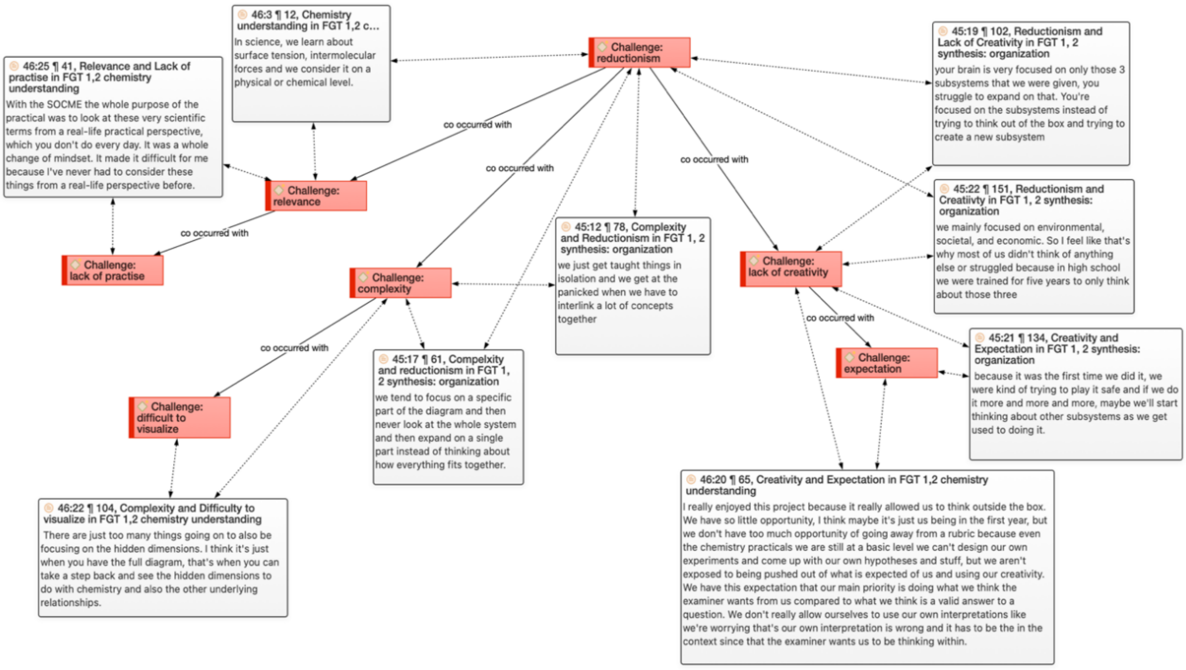


Figure 5.10.Challenges associated with demonstrating chemistry understanding and integration: organization

Even though these codes should be grouped into themes for thematic analysis, it was recognized that grouping these codes into isolated themes to reduce the complexity, would adopt a reductionist approach to data analysis, which is against the very nature of this study. These challenges are interrelated and could have amplified students' perceptions regarding the reasons why they experienced *chemistry understanding* and *integration: organization* as the most challenging skills to demonstrate on their SOCMEs. To visualize some of the interconnectedness of codes, a network diagram, is presented to show the quotations where the codes co-occurred, Figure 5.11.



46:3 ¶ 12, Chemistry understanding in FGT 1,2 c...
In science, we learn about surface tension, intermolecular forces and we consider it on a physical or chemical level.

46:25 ¶ 41, Relevance and Lack of practise in FGT 1,2 chemistry understanding
With the SOCME the whole purpose of the practical was to look at these very scientific terms from a real-life practical perspective, which you don't do every day. It was a whole change of mindset. It made it difficult for me because I've never had to consider these things from a real-life perspective before.

45:19 ¶ 102, Reductionism and Lack of Creativity in FGT 1, 2 synthesis: organization
your brain is very focused on only those 3 subsystems that we were given, you struggle to expand on that. You're focused on the subsystems instead of trying to think out of the box and trying to create a new subsystem

45:22 ¶ 151, Reductionism and Creatiivty in FGT 1, 2 synthesis: organization
we mainly focused on environmental, societal, and economic. So I feel like that's why most of us didn't think of anything else or struggled because in high school we were trained for five years to only think about those three

45:12 ¶ 78, Complexity and Reductionism in FGT 1, 2 synthesis: organization
we just get taught things in isolation and we get at the panicked when we have to interlink a lot of concepts together

45:17 ¶ 61, Compelxity and reductionism in FGT 1, 2 synthesis: organization
we tend to focus on a specific part of the diagram and then never look at the whole system and then expand on a single part instead of thinking about how everything fits together.

45:21 ¶ 134, Creativity and Expectation in FGT 1, 2 synthesis: organization
because it was the first time we did it, we were kind of trying to play it safe and if we do it more and more and more, maybe we'll start thinking about other subsystems as we get used to doing it.

46:22 ¶ 104, Complexity and Difficulty to visualize in FGT 1,2 chemistry understanding
There are just too many things going on to also be focusing on the hidden dimensions. I think it's just when you have the full diagram, that's when you can take a step back and see the hidden dimensions to do with chemistry and also the other underlying relationships.

46:20 ¶ 65, Creativity and Expectation in FGT 1,2 chemistry understanding
I really enjoyed this project because it really allowed us to think outside the box. We have so little opportunity, I think maybe it's just us being in the first year, but we don't have too much opportunity of going away from a rubric because even the chemistry practicals we are still at a basic level we can't design our own experiments and come up with our own hypotheses and stuff, but we aren't exposed to being pushed out of what is expected of us and using our creativity. We have this expectation that our main priority is doing what we think the examiner wants from us compared to what we think is a valid answer to a question. We don't really allow ourselves to use our own interpretations like we're worrying that's our own interpretation is wrong and it has to be the in the context since that the examiner wants us to be thinking within.

Figure 5.11. Interconnections and code co- occurrence between the codes used for challenges

Figure 5.11. shows where the challenges were coded together at least once, indicating a potential relationship between reductionism and complexity, relevance, and lack of creativity as these codes co-occurred. There is a relationship between i) relevance and lack of practise, ii) complexity and difficulty to visualize and iii) lack of creativity and the expectation of achievement. Therefore, instead of presenting isolated themes for both skills, the codes that represent challenges will be discussed based on their potential interactions with other emerging challenges.

CHEMISTRY UNDERSTANDING

It was evident that some students felt uncertain about the meaning of "hidden dimensions" as it seemed unfamiliar creating doubt regarding the achievement of the skill. However other students felt that they developed a better understanding of the skill after receiving help from their peers. These comments, as expressed by the students, are shown below in Figure 5.12.

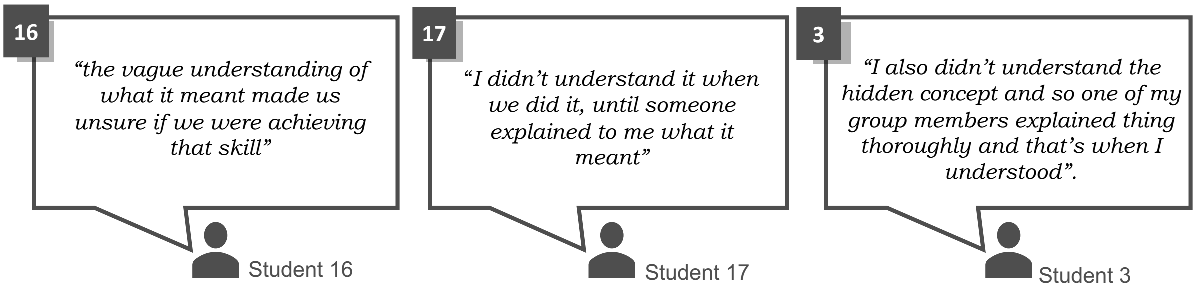


Figure 5.12. Students' responses regarding their understanding of the hidden dimensions of the system

Even though some students felt uncertain about their understanding of the underlying chemistry of the system, other students expressed a rich understanding of what the hidden dimensions represented in the system. These comments are shown in Figure 5.13. where the hidden dimensions are described as:

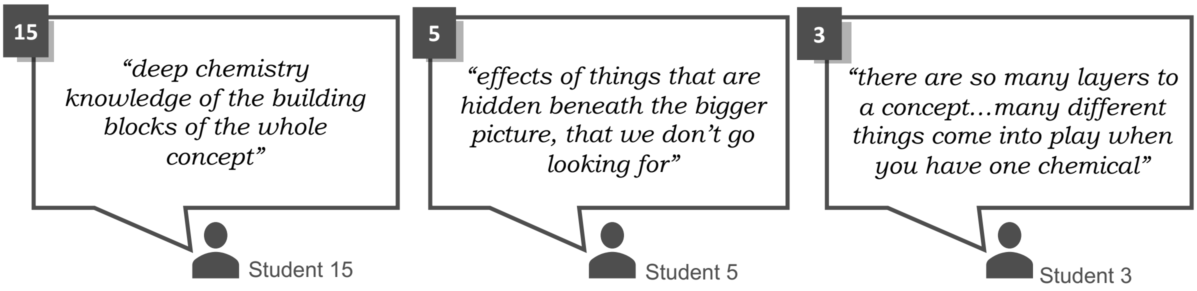


Figure 5.13. Students' responses describing the hidden dimensions of the system

Students were asked to discuss why they found it challenging to demonstrate their *chemistry understanding* and we found that they were not used to thinking about the relevance of chemistry. Students recognized that they are used to a reductionist approach in chemistry education. The agreement between the comments is shown in Figure 5.14. reinforced these findings.

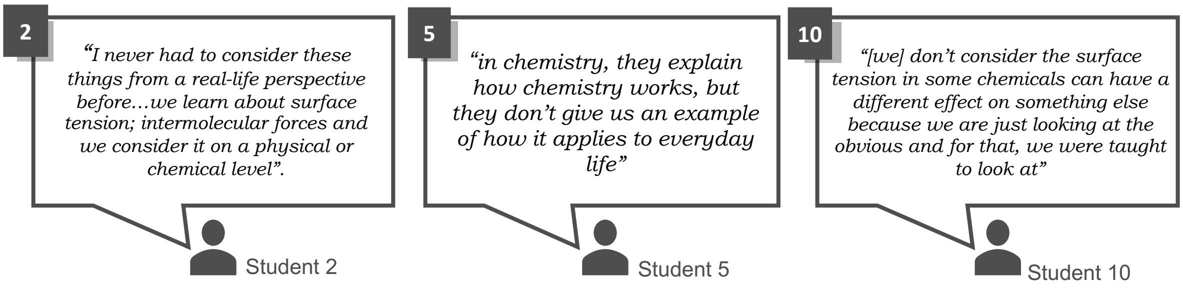
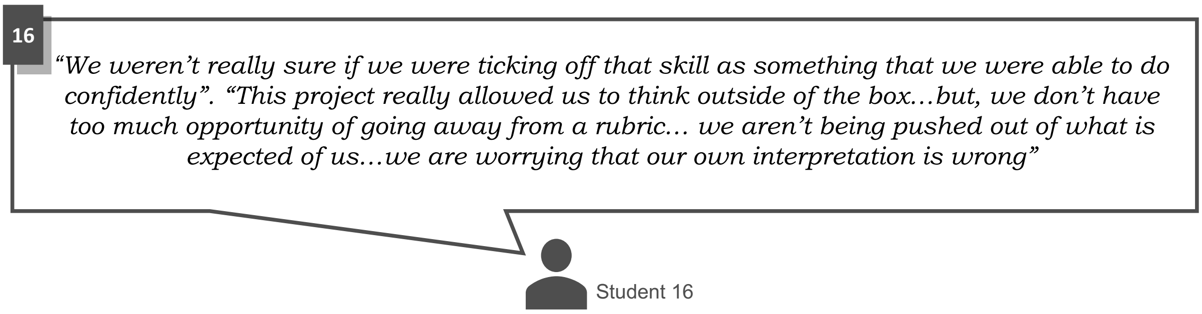


Figure 5.14.Students' responses regarding their unfamiliarity of thinking about the relevance of chemistry

Students also felt that it was not easy to visualize the overall effects that the physical and chemical properties of LAS surfactants can have on a system. Student 6 said: *"It's not always easy to look deeper and see the overall effect, even the effects of the effects and to dig deeper and expand the* *layers of the aspect”*. This was emphasized when the student added: *“if you can’t see it directly, it is difficult to visualize”*. To reduce the complexity of visualizing the chemistry of LAS on the SOCME, students preferred to focus on one thing, such as one level of granularity, at a time. *Student 16 said, “there are just too many things going on to also be focusing on the hidden dimensions”* which demonstrates how they applied a reductionist perspective to deal with the complexity of the system.

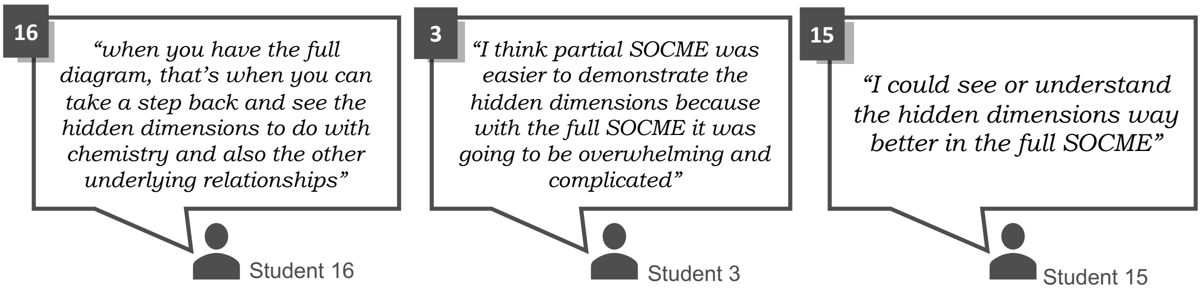
Students also stated that they were not used to applying their chemistry understanding as they don’t have many opportunities to practise it. Student 10 stated*: “we are not used to practicing that skill in our everyday life”.* This might have contributed to students' concerns about achieving the skill as they felt unsure about what was expected from them. The uncertainty regarding what was expected could have contributed to their hesitance to be creative. Student 17 stated *“I was really worried about marks. I wanted to get as much as possible. I didn't want to indicate concepts or words I didn’t understand or take a gamble with something.”* Most students agreed with student 16's comment confirming these findings as shown in the comment below in Figure 5.15.



“We weren’t really sure if we were ticking off that skill as something that we were able to do confidently”. “This project really allowed us to think outside of the box…but, we don’t have too much opportunity of going away from a rubric… we aren’t being pushed out of what is expected of us…we are worrying that our own interpretation is wrong”

Figure 5.15. Students’ response regarding their uncertainty regarding expectations.

Students differed in opinion concerning whether they were able to demonstrate their chemistry knowledge on the partial or final SOCME. However, students agreed that they were able to understand chemistry better after they engaged with their expanded SOCME as it helped them to *“take a step back”* to visualize the whole system and then the hidden dimensions of the system. These perceptions are presented in Figure 5.16.



“when you have the full diagram, that’s when you can take a step back and see the hidden dimensions to do with chemistry and also the other underlying relationships”

“I think partial SOCME was easier to demonstrate the hidden dimensions because with the full SOCME it was going to be overwhelming and complicated”

“I could see or understand the hidden dimensions way better in the full SOCME”

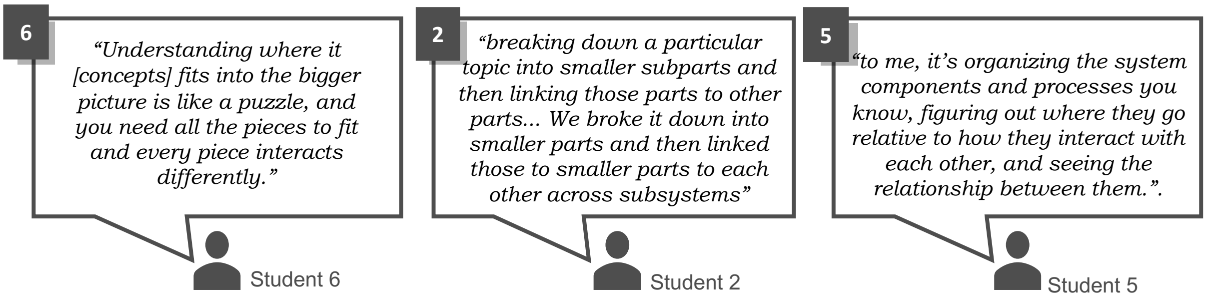
Figure 5.16. Students’ response regarding the demonstration of hidden dimensions on the SOCME

The difficulty of the surfactant content could have influenced students' perceptions about the difficulty of demonstrating the skill on the SOCME diagram. Students expressed during the focus group interview that they experienced the surfactant content to be more challenging than learning about systems thinking, which included making connections and constructing a SOCME diagram. Most students agreed with student 2: *"I found the surfactants more difficult than actually having to assemble the diagram and the linking things"*.

To summarize, students found it challenging to demonstrate their chemistry understanding on the SOCMEs because they were not used to applying systems thinking in chemistry to visualize its effects and relevance in real-life. Their lack of practise made them uncertain whether they had achieved the skill, and as they were worried about marks, they might have hesitated to think creatively.

INTEGRATION: ORGANIZATION

Integration: organization was perceived by students to be one of the most challenging skills to demonstrate on their SOCME. Yet most students felt that they achieved it. Students interpreted this skill as understanding where concepts fit into the bigger picture. Students emphasized the importance of having an *"overview perspective"* by *"looking at the detail of looking at how these concepts link together, but still keep the general broad idea in mind" (student 16).* Students emphasized that the whole needs to be broken into parts and linked into various subsystems. They, therefore, recognized that applying this skill required the ability to identify the elements, the relationships, and the dynamic interactions within the system. These findings are supported by evidence from students' responses, shown below in Figure 5.17.



"Understanding where it [concepts] fits into the bigger picture is like a puzzle, and you need all the pieces to fit and every piece interacts differently."

"breaking down a particular topic into smaller subparts and then linking those parts to other parts... We broke it down into smaller parts and then linked those to smaller parts to each other across subsystems"

"to me, it's organizing the system components and processes you know, figuring out where they go relative to how they interact with each other, and seeing the relationship between them.".

Figure 5.17. Students' response regarding their conceptual understanding of integration: organization

Students felt unsure about the expectations for *achieving integration: organization* because they felt it was unfamiliar and different points of view made them interpret the instructions differently. Students also felt that their unfamiliarity regarding the systems thinking skills could have resulted from being taught chemistry from a reductionist approach. Student 16 also stated that *"we're so used to being taught things in isolation"* and *"it's a skill that we haven't really been super like trained in and it's a bit unfamiliar"*. Students also expressed that their lack of practising the skill could have made it challenging to demonstrate. These findings are supported by the following comments shown in Figure 5.18.

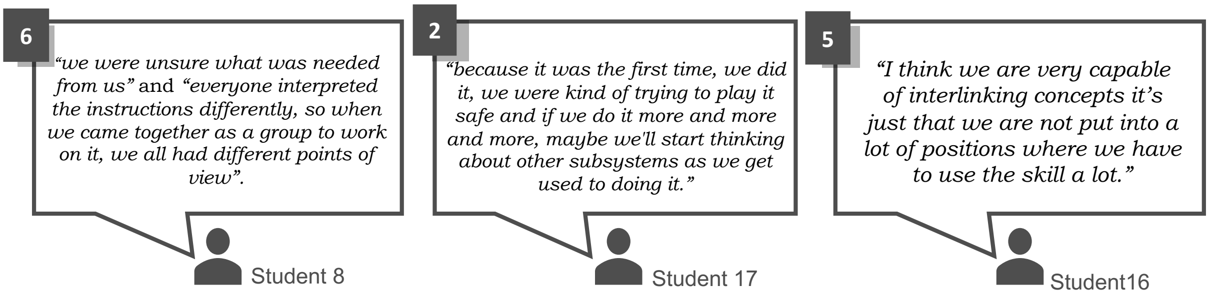


Figure 5.18. Students' response regarding the skill integration: organization

Students also felt it was challenging due to the complexity of connections as they had to identify where the concepts and connections fitted amongst all the interconnectedness. The following comments shown in Figure 5.19. support this claim.

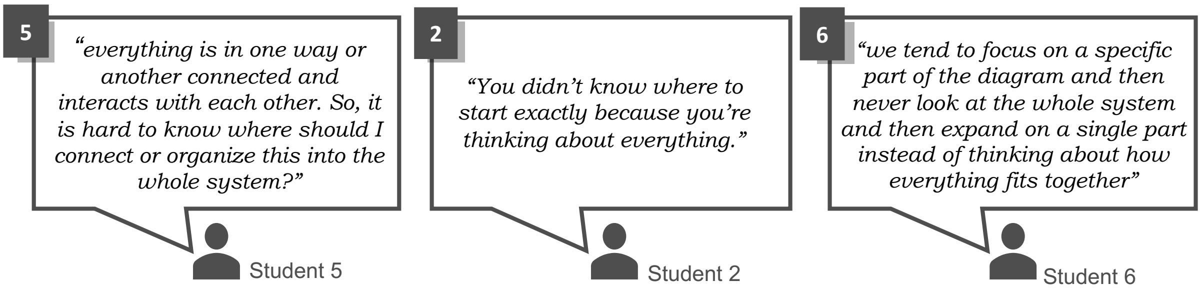


Figure 5.19. Students' response regarding why they found integration: organization as challenging

Students also found it challenging to add new subsystems to their SOCME diagrams as they were focused on the existing subsystems and struggled to think creatively about new concepts and relationships, especially under pressure. This also supported the fact that students were used to a reductionist approach to dealing with the complexity of the system by studying one concept or part of the system at a time. The following explanations shown in Figure 5.20. support this finding.

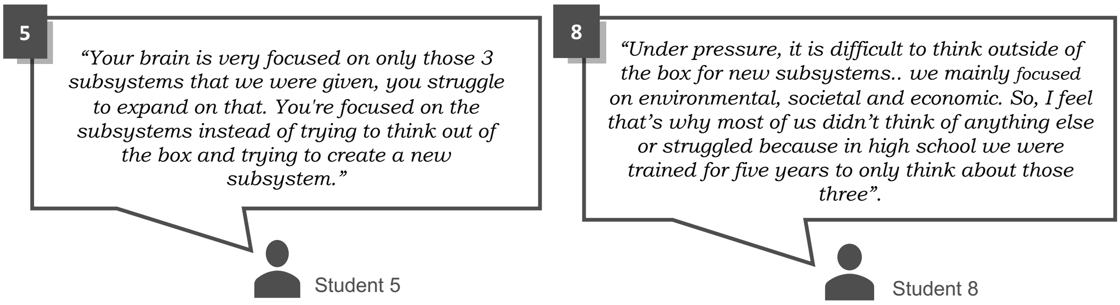


Figure 5.20. Students' response regarding why they found integration: organization as challenging

In summary, most students found the skill *integration: organization* to be challenging to demonstrate on the SOCMEs as students were not used to identifying new subsystem boundaries. It required systems thinking to visualize the complex interconnections. This limited their creativity as they focused on one part of the system to deal with its complexity. Students also acknowledged that they could apply their *analysis* and *integration* skills to identify new subsystem boundaries. However, they require more practise to be better equipped to demonstrate it.

5.2.4. TRUSTWORTHINESS OF THE FINDINGS

Several steps were taken to maximise the trustworthiness of the interpretations made from student perceptions. As a first step, self-reflection questionnaire data were prepared by removing the students' responses that selected a particular systems thinking skill as both the most and least challenging. As a second step, the findings of students' perceptions were probed further in focus group interviews. The trustworthiness of the interpretations made from the focus group discussion was increased by taking reflective notes during the interview to clarify and confirm general ideas that emerged from the discussion to verify the accuracy of students' overall perspectives or perceptions. Member checking were also conducted on students' responses to reflect an accurate account of what they can recall from our interview. Students were encouraged to provide additional feedback or comments as they reflected on the discussion transcripts for member checking. Furthermore, the interviews were facilitated carefully to minimise the influence of the most dominant voice. This was done by asking each participant to share their thoughts. The participants were also briefed beforehand to be respectful of others' opinions, to be truthful and to engage in the discussion by stating whether they agreed or disagreed.

5.3. STUDENTS' REFLECTION ON SYSTEMS THINKING SKILLS

This section will discuss the development of a codebook as an analysis tool for the open-ended questions 5 and 7 of the self-reflection questionnaire. This will be followed by the understanding, skills and attitude that developed from analysing students' reflections. This section will conclude with the trustworthiness of the codebook.

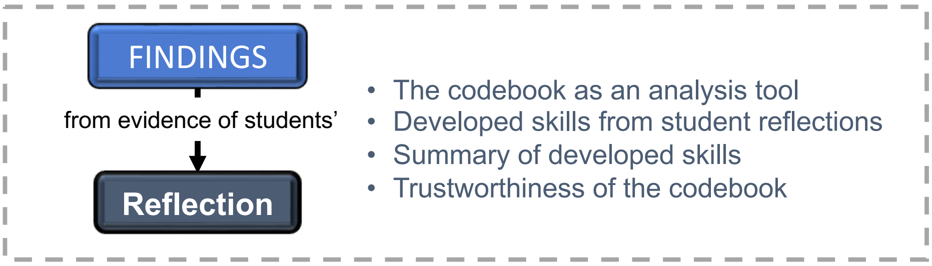


Figure 5.21. Overview of the section on students' reflections on systems thinking skills

5.3.1. THE CODEBOOK AS AN ANALYSIS TOOL

The codebook was developed as an analysis tool to investigate the evidence that suggests that systems thinking skills were developing in students. The data collected from questionnaire questions 5 and 7 presented in chapter 4, as shown in Figure 5.22. were prepared for analysis. Three of the 14 students who completed the questionnaire left questions unanswered, and only 11 responses were considered for further analysis and interpretation. The prompts given in the text of questions 5 and 7 were considered during data analysis.

Question 5
A student that did the aspirin practicals, asks you to briefly explain what skills (systems thinking, communication, technological, problem solving, creativity, etc.) and understanding you have gained in these practicals. What would you tell the student to answer their question?

Question 7
What would you do as a responsible citizen and an upcoming scientist from here on forward to ensure you apply systems thinking in your daily life and take sustainable action after participating in these practicals?

Figure 5.22. Two open-ended questions from the self-reflection questionnaire

The codes were formulated and refined to develop a codebook consisting of different semantic domains representing different areas of meaning. Each semantic domain is made up of mutually exclusive codes that were developed throughout various coding cycles. The semantic domains are *understanding, analysis, integration, evaluation, application, ownership,* and *social abilities*. Each of these semantic domains with its respective codes will be presented below.

UNDERSTANDING

From inductive coding, it was seen that students gained an understanding of chemistry and the system of LAS. Therefore, the codes applied to the data were grouped into two semantic domains: *chemistry understanding* and *systems understanding.* Students' understanding of chemistry is about their ability to examine and understand the physical and chemical properties that influence system-level behaviour (LO1). These physical and chemical properties include LAS's sub-microscopic and macroscopic properties that influence the system. Therefore, from a zoomed-out level of granularity, the chemistry becomes "invisible" and is, therefore, the "hidden dimensions" of the system. These codes are described in the codebook section in Table 5.3. below

Table 5.3. Codebook section for the semantic domain chemistry understanding

Code: *Chemistry understanding: physical properties*	**Description:**	"Physical properties are characteristics a substance shows by itself, without changing into or interacting with another substance." (Silberberg & Amateis, 2018) Examples of physical properties include molecular geometry, polarity, solubility, melting and boiling point, intermolecular forces, mass, and density.
	Typical Exemplars:	Apply the code if any physical properties of LAS are referred to, such as its "amphiphilic" structure ("hydrophilic" head and "hydrophobic" tail), chain length, polarity, functional groups such as the anionic sulfonate group, intermolecular forces, and other properties that can be used to identify surfactants.
	Atypical Exemplars:	Apply the code if physical properties of LAS such as density, molecular shape, mass, boiling, or melting point are stated.
	Close but no:	The code should not be applied if reference is made to chemical action, behaviour, or changes that LAS can undergo as this will be coded as *chemistry understanding chemical properties.*
Code:	**Description:**	Chemical properties are characteristics or behaviours of a substance that can be observed as it undergoes a chemical change, examples

Chemistry understanding: chemical properties		include flammability, corrosiveness, reactivity, toxicity, chemical stability, acidity or basicity, and radioactivity (Helmenstine, 2020; Silberberg & Amateis, 2018)
	Typical Exemplars:	In the system of LAS, apply this code if chemical properties or behaviour that includes ecotoxicity and concentration, reactivity, chemical stability or acidity, or basicity of LAS is discussed.
	Atypical Exemplars:	Apply the code if chemical properties relating to surfactant action are stated for example the ability of LAS to bind to polar and non-polar molecules, and its ability to break down the bilipid membrane of a virus.
	Close but no:	The code should not be applied to the physical properties of surfactants or LAS and should not be misinterpreted as *integration: emergence*

It also emerged from students' responses that they gained an understanding of the whole without considering the “hidden dimensions”. Students reported their learning about the context of chemistry and its relevance in everyday life. Students also reported on their understanding of systems thinking after the intervention as they revisited the underlying chemistry. Therefore the in-vivo code “*systems thinking*” and the descriptive code *chemistry context* emerged to describe their *systems understanding.* These codes are described in Table 5.4. below.

Table 5.4. Codebook section for the semantic domain systems understanding

Code: *Systems understanding: chemistry context*	**Description:**	This code describes the relevance and real-world implications of chemistry
	Typical Exemplars:	Apply the code if students refer to the “impacts of LAS”, its consequences on various subsystems, or the “real-world implications” of chemistry by placing it into perspective and viewing it with a “wider range.” The words chemistry, LAS, or surfactants must be explicitly stated for the code to be applied.
	Atypical Exemplars:	Apply the code if students use the word “surfactants”, “LAS” or “linear alkylbenzene sulfonate” and its impacts on various subsystems. Examples include the “implications of chemistry” and “surfactants are a very big issue” or that surfactants have “negative effects”, impacts, or “consequences”
	Close but no:	Do not apply this code to excerpts if physical properties or chemical properties/behaviour are referred to.
Code: *Systems understanding: “systems thinking”*	**Description:**	This code emphasizes holistic thinking or the bigger picture to visualize the whole system. This code describes students’ knowledge of “systems thinking”. Systems thinking in simple terms involves visualizing the whole by seeing the interconnectedness between the subsystems or parts within the system.
	Typical Exemplars:	Apply the code if students reflect on their understanding of how they view “systems thinking” by describing their thoughts on it. The words “systems thinking” or “systematic thinking” or “holistic thinking” or think about the “big picture” and seeing “complex” relationships are examples
	Atypical Exemplars:	Apply the code if students reflect for example on the “impact one thing has on all three subsystems and how to link these systems together” and to statements referring to the interconnectedness of subsystems.
	Close but no:	Do not apply the code if a reference is made specifically to chemistry or LAS as this will be coded as *systems understanding: chemistry context*

ANALYSIS

This semantic domain emerged from inductive coding as students claimed to have learned about the parts, concepts or elements within a system and the relationships between these parts. The codes *analysis: elements* and *analysis: relationships* were formulated after a deductive second coding cycle. These codes are described in the codebook section in Table 5.5 below.

Table 5.5. Codebook section for the semantic domain analysis

Code: *analysis: elements*	**Description:**	Elements in a systems thinking context are the components that make up the system and its characteristics (Orgill et al., 2019).
	Typical Exemplars:	Apply the code if reference is being made to “various components”, “keywords and concepts”, and “factors that are involved”.
	Atypical Exemplars:	Apply the code when words such as “analyse” or “broke down” are used to emphasize the analysis of parts.
	Close but no:	Do not apply the code if students refer to the relationships or interactions between concepts as this will be coded as *analysis: relationships.* Also don’t apply the code if reference is being made to combining the parts to form a whole as that is part of the semantic domain: *integration*
Code: *analysis: relationships*	**Description:**	Meaningful connections between concepts or parts of a system describe the relationship between concepts. The relationships between concepts are made meaningful by linking words.
	Typical Exemplars:	Apply the code if reference is made to the relationships between parts or elements, components, or processes within the system. Examples include “analyze these relationships”, or “relationships, “are all related”, using “linking words” or “link things together” or “to make connections” or “intersectional”
	Atypical Exemplars:	Apply the code if words such as “influence”, “effects”, “decreases”, and “increases” are used to describe a relationship between components on a micro-level (in other words only between concepts)
	Close but no:	If students refer to interactions or interconnections between subsystems that are dynamic in that the relationship changes over time or if relationships are emphasized between subsystems, then *integration: dynamic interactions* should be used as a code.

INTEGRATION

This semantic domain was created to summarize the codes that were applied deductively to students' reflections as they gained the ability to integrate the parts of the system to create a more complete picture of the system of LAS. The codes, *dynamic interactions, organization and emergence* were taken from the formulated LOs and are described in Table 5.6. below.

Table 5.6. Codebook section for the semantic domain integration

Code: *Integration: dynamic interactions*	**Description:**	In a dynamic system, interactions occur both between systems’ parts and between various systems (Tripto et al., 2013). The interactions or relationships between elements as identified through analysis are “subject to constant evolution” as imposed by the context of a dynamic system, which is not readily observable. (Barile & Saviano, 2011; Yoon, 2008)

	Typical Exemplars:	Apply the code when students refer to “interactions” or connections between different subsystems. Specific reference to time is not required as a change in time is implied and it is too challenging to capture change in time in a snapshot of interactions.
	Atypical Exemplars:	Apply the code if dynamic connections, such as feedback loops or variables that change over time explicitly stated
	Close but no:	If words such as “analyse these relationships”, or “relationships, “are all related”, using “linking words” or “link things together” or “to make connections” between concepts these are coded as *analysis: relationships*
Code: *Integration: organization*	**Description:**	the “ability to organize systems’ components and processes within a framework of relationships” and identify new subsystem boundaries.
	Typical Exemplars:	Apply the code if students used the words “fit into” to describe the process of organizing concepts to fit into subsystems in the whole system.
	Atypical Exemplars:	Also, apply the code if students refer to their “organization skills” or “organizing their thoughts” during the construction of a SOCME diagram.
	Close but no:	If students use “organize” without the context of fitting concepts into subsystems or in the whole system or to a SOCME diagram.
Code: *Integration: emergence*	**Description:**	Emergence is a process of forming new collective entities established by the coherent behaviour of interacting elements, which cannot be predicted based on the properties of parts alone. (Barile & Saviano, 2011; Orgill et al., 2019)
	Typical Exemplars:	Apply the code if factors that contribute to the emerging behaviour are given or explained, examples include chemical/physical properties that contribute to foaming (agitation, concentration, surface tension)
	Atypical Exemplars:	Statements regarding the factors involved in biodegradation (low oxygen content) or detergent power (Critical Micelle Concentration, concentration, impurities)
	Close but no:	Any predictions and generalisations made based on foaming, biodegradation, or detergency power will be coded as *application: predictions*

EVALUATION

This semantic domain was chosen to describe two codes that emerged from the data inductively. Students' learned about conducting research and engaging deeper in topics regarding the system under consideration. Therefore the codes of *conducting research and deeper engagement* were used to describe evaluation as the process whereby judgements and informed decisions are made based on conducting research and developing a deeper understanding of a topic. These codes are presented in Table 5.7. below.

Table 5.7. Codebook section for the semantic domain evaluation

Code: *Evaluation: conducting research*	**Description:**	This code describes the process of conducting research and checking for possible answers and solutions, which is a key component of the cognitive dimension (Krathwohl, 2001).
	Typical Exemplars:	Apply the code when students refer to doing research and “doing your homework” or if their answers were “checked through research”
	Atypical Exemplars:	If students state that they have used google or the lecture slides or other resources to check for their answers

	Close but no:	Do not apply the code if reference is being made to figuring things out, thinking deeper, or brainstorming as these concepts will be coded as *evaluation: deeper engagement*
Code: *Evaluation: deeper engagement*	**Description:**	Deep engagement involves being "personally absorbed in and committed to participation in the processes of learning and the mastery of a (chosen) topic, or task, to the highest level" (Crick, 2012). Deep engagement is one of the characteristics of a critical thinker.
	Typical Exemplars:	Apply the code if students refer to having developed “deep understanding” or “critical thinking” skills where students learned how to “think deeper”.
	Atypical Exemplars:	Also, apply the code if students used words such as “make sense of it” or “brainstorming” or other similar words where students “figure things out”
	Close but no:	Do not apply the code if students describe the process of conducting research or checking for answers, as this will be coded as *evaluation: conducting research*

APPLICATION

This semantic domain appeared from the responses as students reported learning how to apply their knowledge to make predictions, solve problems and be creative. Therefore the codes in this semantic domain are *“problem-solving”, “creativity”,* and the ability to make *predictions. The* first two codes are direct words of students emerging from their responses. During the expansion of the SOCME diagram, students were guided to indicate predictions. Therefore the code *predictions* were applied deductively. All of these codes are presented in Table 5.8.

Table 5.8. Codebook section for the semantic domain application

Code: *Application: predictions*	**Description:**	Predictions and generalisations are made if knowledge regarding positive or negative impacts because of dynamic interactions is applied. Predictions are about what we can expect in the future, even if an indication of time is not explicitly given.
	Typical Exemplars:	Apply the code if students make predictions about an overall future impact or future impacts resulting from the dynamic interactions of chemistry or other subsystem variables within the whole system, examples include “more negatives in the big picture” and knowing what the “effects” and “consequences” are or could be.
	Atypical Exemplars:	Applied if students made any predictions because of fractional distillation and its contribution to global warming, foaming, biodegradation, and river quality specific to the system of LAS.
	Close but no:	Predictions should not be misinterpreted as the real-world implication of LAS, which will be coded *knowledge of systems: chemistry context* or as *ownership: problem recognition*
Code: *Application: “problem-solving”*	**Description:**	Problem-solving requires previously acquired knowledge, skills, and understanding to resolve a situation, which an individual sees no obvious path to obtain a solution for. (Carson, 2007)
	Typical Exemplars:	Apply the code if students use the words “problem solving”, “solve the problem” or to find a solution or “outcome” to a problem as they describe working towards a solution, whether it refers to the construction of a SOCME diagram or the broader problem of sustainability challenges.
	Atypical Exemplars:	Use the code if students refer to “approaching the problem” or if students state that they have learned “problem-solving skills”

	Close but no:	Do not apply the code if reference is being made to the actual problem from students' perspectives or if solutions are proposed to achieve a better outcome, this will be coded as *ownership: problem recognition* and *ownership: future improvement.*
Code: *Application: "creativity"*	**Description:**	Creativity is a higher-order cognitive skill that is defined as "the ability to produce original and unusual ideas or to make something new or imaginative"- Cambridge dictionary.
	Typical Exemplars:	Apply the code if students used the word "creativity" when describing the skills and understanding that they have learned.
	Atypical Exemplars:	Apply the code if students refer to thinking out of the box or coming up with new ideas during the construction of a SOCME diagram.
	Close but no:	Do not apply the code if students refer to creating a SOCME diagram.

OWNERSHIP

Students' responses revealed their intentions to develop an attitude of taking ownership if they reported on sustainability challenges and what they can do to make improvements in the future. These improvements could have been a change in their thinking or taking sustainable action by making better-informed consumer decisions. This semantic domain emerged inductively from the data and is described by the codes *challenge recognition* and *future improvement.* The code descriptions used for analysing students' responses are shown in Table 5.9. below.

Table 5.9. Codebook section for the semantic domain ownership

Code: *ownership: challenge recognition*	**Description:**	The recognition of the challenge in this context refers to global challenges. These include sustainability challenges, human ignorance of sustainability challenges, systems thinking incompetence, and a reductionist approach to chemistry education which has resulted in a lack of concept integration and holistic thinking.
	Typical Exemplars:	Apply the code if students state the problem explicitly, even though it is implied in taking future action. Problems could refer to sustainability challenges and the inability of humans to consider the "consequences or disadvantages" or how things affect each other and that "we don't normally think about" it or "the difficulty in finding a balance"
	Atypical Exemplars:	Apply the code if students refer to the lack of systems thinking and the impact that that has had on subsystems or the whole system
	Close but no:	Do not apply the code if students provide examples and place emphasis on the connections between concepts and the negative impacts of LAS or as this is coded as *knowledge of systems: chemistry context*
Code: *ownership: future improvement*	**Description:**	The role of human activity on current and future system-level behaviour, after identifying the problem, is to take initiative and to act more responsibly to make better-informed decisions for future sustainability.
	Typical Exemplars:	Apply the code if students reflect on what they will do or change in their day-to-day activities or daily choices that can contribute to a more sustainable future. Examples include "creating technologies", "educate people in their community, becoming a "more responsible citizen" or changing their thinking such as becoming a holistic thinker, a "critical thinking" or taking a more "open-minded approach" to contribute to future sustainability.
	Atypical Exemplars:	Apply the code if students refer to general statements of what they can do in the future about laundry detergents and LAS, even

		though some of these facts were given in the take-home message video.
	Close but no:	Do not apply the code if students state what they have learned

SOCIAL ABILITIES

Social abilities emerged from students' responses and were coded inductively as *listening and communication* skills and *collaboration* skills. The description of these codes is shown in the codebook section below in Table 5.10.

Table 5.10. Codebook section for the semantic domain social abilities

Code: *social abilities: listening and communication*	**Description:**	Social abilities include being aware of others, which involves observing what others say and think to contribute meaningfully to a discussion. Therefore, communication is key to awareness of others' knowledge and perspectives.
	Typical Exemplars:	Apply the code if reference is made to communication skills and listening skills such as "different takes and points of views", "different approach to every idea", "listening to people's perspective" "' thinking patterns of other students".
	Atypical Exemplars:	Apply code if reference is made to observations that students have made
	Close but no:	Do not apply the code if reference is being made to collaboration or problem-solving skills
Code: *social abilities: collaboration*	**Description:**	Cooperative learning can be defined as a "student-centred, active learning approach that uses structured situations in which a fixed small group interacts in a non-competitive manner to accomplish a common goal".
	Typical Exemplars:	Apply the code if students developed collaboration skills because of working together, "teamwork, "work in a group", "work in a team"
	Atypical Exemplars:	none
	Close but no:	Do not apply the code if group work or collaboration is not the key component

5.3.2. TRUSTWORTHINESS OF THE CODEBOOK

The quotations in the data were coded twice, contributing to the rigour of developing the codebook. During the first and second cycles of coding, two independent coders, other than the researcher, applied the codes to students' reflections. After the first round of coding by the two independent coders, the Inter-Coder Agreement (ICA) was calculated as a measure of the trustworthiness of the codebook. The ICA was used to investigate the measure of agreement between independent coders and their consistency in applying the codes to excerpts of students' reflections. The ICA result from the first round was used to enhance the clarity of instructions or language used for better individual judgements in the second round of coding. This was possible by briefly discussing unclear instructions or language use amongst the coders without placing focus on getting consensus for better reproducibility, as this is a common mistake made by coders (Friese, 2020).

Inter coder agreement is measured and inter-coder reliability is inferred from the agreement or disagreement between coders. The percentage agreement can be used to determine the number of times the coders have agreed to apply a code to a quotation in the data. The absolute percentage agreement of the whole codebook coded by two independent coders across the semantic domains of *understanding, analysis, integration, application, evaluation, social abilities*, and *ownership* was calculated as 76.4% on Atlas.ti. The ICA exceeded the minimum percentage of acceptability of 75% stipulated by Matthew (2012) (Matthew, 2012). Even though, this percentage revealed that the codebook was applied consistently amongst the coders, there were still concerns regarding the disagreement amongst particular codes. We found that the coders agreed between 45-50% of the time when they applied the codes *systems understanding: "systems thinking"*, *analysis: elements*, *application: predictions*, *application: creativity* and *ownership: challenge recognition*. Coders only agreed 38% of the times when coding for *analysis: relationships* and only 11% of the times when coding for *integration: dynamic interactions*. The discrepancies identified were mostly related to the lack of coherence in the codebook definitions for these codes. Therefore, the codes that were considered as trustworthy given it's percentage agreement that were used for the interpretation of the findings were *systems understanding: chemistry context* (90.3*%), integration: organization* (100%), *application: problem solving* (76.5%), *evaluation: deeper engagement* (64.4%), *evaluation: conducting research*(82.2%), *ownership: future improvement*, (84.5%), *social abilities: collaboration*(72.4%) and *social abilities: listening and communication*(80%).

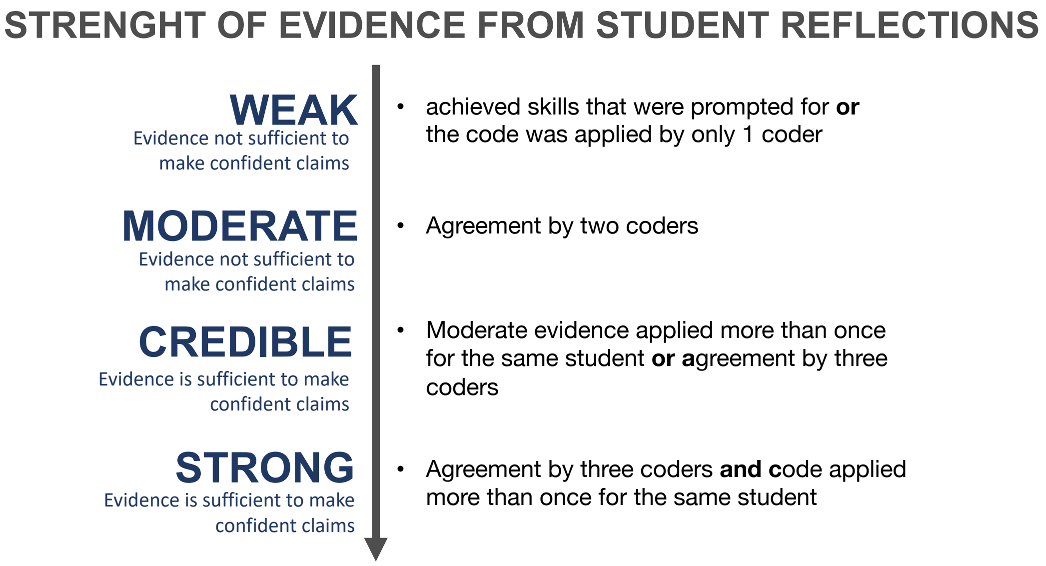
Percentage agreement has been critiqued as a measure of reliability as it does not account for variation between coders or chance agreement (Watts & Finkenstaedt-Quinn, 2021). Krippendorff's alpha is considered a better measure of reliability than percentage agreement, as it accounts for the probabilities that coders agree due to chance. As a result, Krippendorff's alpha has also been identified as the most acceptable and applicable measure of reliability (Krippendorff, 2004; Neuendorf, 2017). This statistic has also been chosen for this study as it is useful for small data sets coded by multiple coders (Krippendorff, 2004). Since, coders had to identify the semantic domains that fit the provided quotations; the cu-alpha could be calculated to understand whether multiple coders could distinguish between the codes within a semantic domain. Each semantic domain was mutually exclusive, and therefore during coding, codes within the same semantic domain could not be applied to the same quotation as specified (Friese, 2020). Altas.ti was used to calculate the Krippendorff cu-alpha statistic per semantic domain to understand better which semantic domains were less well delineated. Krippendorff (2019) recommended that coded data be accepted if the ICA coefficients are above an alpha value of 0.667, and semantic domains can be considered reliable if the alpha value is above or equal to an alpha value of 0.800 (Krippendorff, 2019). All the semantic domains had Krippendorff cu-alpha values of 1.00, except for the semantic domain *application* (0.80), *integration* (0.677) and *social abilities*(0.797). Krippendorff's cu-alpha was calculated as 0.677 for all the semantic domains amongst the two coders and 0.736 amongst three coders. Therefore, the codebook had acceptable reliability that can be used to draw tentative interpretations from students' reflections.

In conclusion, following the second coding cycle, the codes applied by the two independent coders were merged to calculate an overall agreement on Atlas.ti, The percentage agreement and Krippendorff's cu-alpha values were calculated to determine whether the codebook was reliably applied.After considering the inter coder agreement analysis from the simple percentage agreement values of all the codes in the codebook and the Krippendorff cu-alpha of each semantic domain, it was found that claims regarding the development of a *systems understanding: "systems thinking"*, *analysis: elements*, *analysis: relationships, integration: dynamic interactions*. *application: predictions*, *application: creativity* and *ownership: challenge recognition* should be interpreted with caution due to its lack in trustworthiness. For these codes, the strength of evidence won't be considered for further discussion, however the quality of students' reflections will be considered, instead of the number of students who have developed the skill.

5.3.3. STRENGTH OF EVIDENCE

Having coded student responses to Questions 5 and 7, the codes were analysed per student. The strength of the evidence was weighed based on i) the number of times the code was applied for a response, ii) agreement amongst coders and iii) the prompts given in the question. Claims made by students regarding the achievement of skills that were prompted for were considered weak evidence in comparison to claims of skills that were not prompted. Students were prompted in question 5 with examples of developing systems thinking, communication, technological, problem-solving, and creativity skills. In question 7, students were prompted to report an attitude of taking ownership of sustainable action. The presence of weak evidence due to prompting does not imply that the skills were not developing. It signifies that it becomes more challenging to claim confidently that a particular skill developed. The strength of evidence was also judged to be weak if only one coder interpreted the response as a claim of a specific skill that was achieved.

The evidence had a moderate strength if two coders agreed that the student achieved the specific skill. The evidence had a credible strength if there was agreement by two coders and it was applied more than once for the same student or if there was agreement amongst three coders. The evidence was strong if three coders agreed that the student reported achieving a skill and the code was applied more than once for the same student. Overall, credible, and strong evidence was considered sufficient to make confident claims regarding the development of skills. The criteria for weak, moderate, credible, and strong evidence are summarised in Figure 5.23.



STRENGHT OF EVIDENCE FROM STUDENT REFLECTIONS

WEAK
Evidence not sufficient to make confident claims

- achieved skills that were prompted for **or** the code was applied by only 1 coder

MODERATE
Evidence not sufficient to make confident claims

- Agreement by two coders

CREDIBLE
Evidence is sufficient to make confident claims

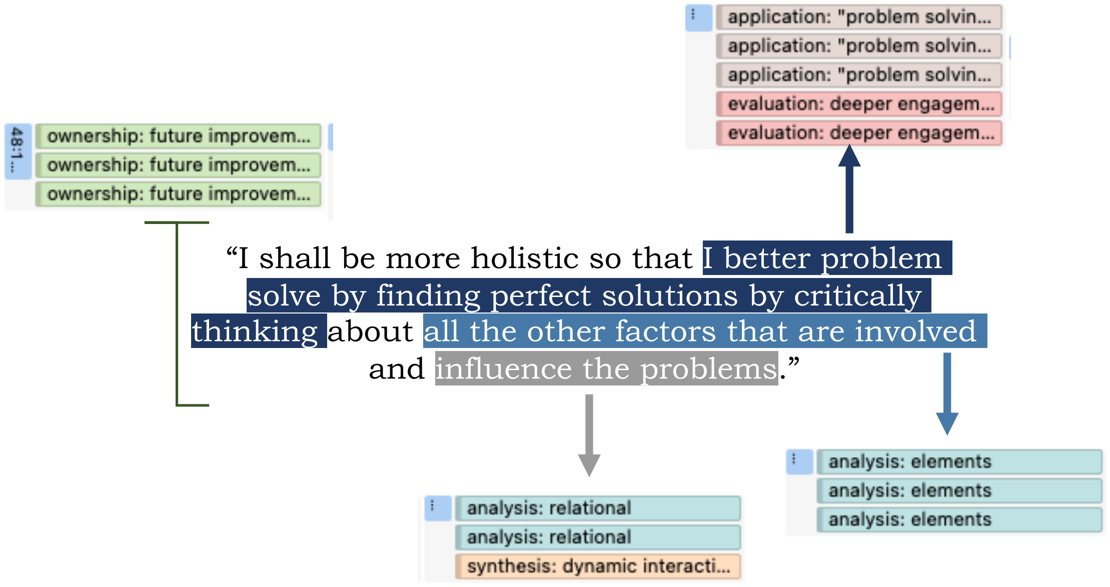
- Moderate evidence applied more than once for the same student **or a**greement by three coders

STRONG
Evidence is sufficient to make confident claims

- Agreement by three coders **and c**ode applied more than once for the same student

Figure 5.23. The criteria for weak, moderate, credible, and strong evidence in students' reflections

As an example, consider the following excerpt from student 12's response to question 7 in the self-reflection questionnaire presented in Figure 5.24.

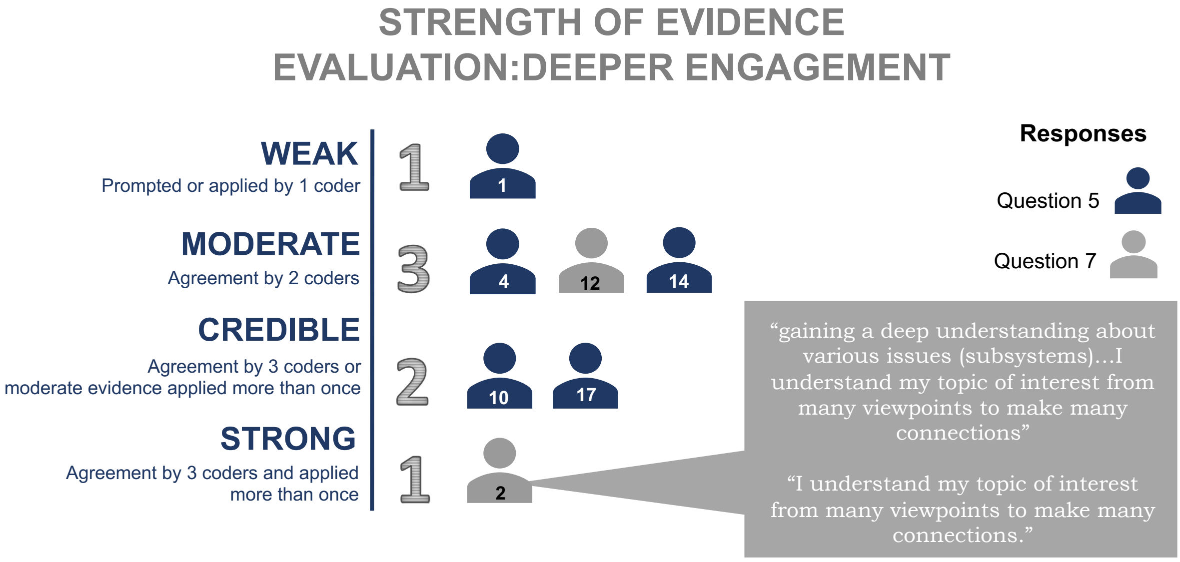


"I shall be more holistic so that I better problem solve by finding perfect solutions by critically thinking about all the other factors that are involved and influence the problems."

Figure 5.24. Excerpt taken from the response of student 12 on question 7 as coded on Atlas.ti

On Atlas.ti, student 12's complete response was coded by all three coders with the code *ownership: future improvement. However*, because this skill was prompted for in question 7, it is considered weak evidence, even though it has an agreement by all three coders. Therefore, from this response, the evidence is insufficient to claim confidently that this skill was developing in student 12. Evidence of moderate strength revealed that *evaluation: deeper engagement* and *analysis: relational* might have been developing, as there was agreement amongst two coders; however, it cannot be confidently claimed. Student 12's response provides credible evidence that the skill *application: problem-solving,* was developing as it was not prompted for in question 7 and had a high agreement between all three coders. The same findings are observed for the skill *analysis: elements.* If, for example, the code *analysis: elements* appeared once more in question 7 or 5, then the evidence would have been considered strong to claim confidently that student 12 developed the ability to identify the elements in the system.

After analysing the responses for each student in terms of strength of evidence, the results were combined to generate an overview of skills achieved in the whole sample. The interpretations were based on the number of students whose responses provided weak, moderate, credible and strong evidence for each system thinking skill. As an example, Figure 5.25. shows the classification of students for the skill *evaluation: deeper engagement* based on the discussed criteria. Three students' responses, students 10, 17 and 2, provided sufficient evidence to claim with confidence that these students were developing *evaluation: deeper engagement.* Three other students' reflections (students 4, 12, 14) provided evidence of moderate strength; however, it was not sufficient to claim with confidence that they were developing this skill. This was also seen for student 1, who provided weak evidence of skill development.Similar figures summarizing these findings graphically for each skill can be found in Appendix D.



"gaining a deep understanding about various issues (subsystems)...I understand my topic of interest from many viewpoints to make many connections"

"I understand my topic of interest from many viewpoints to make many connections."

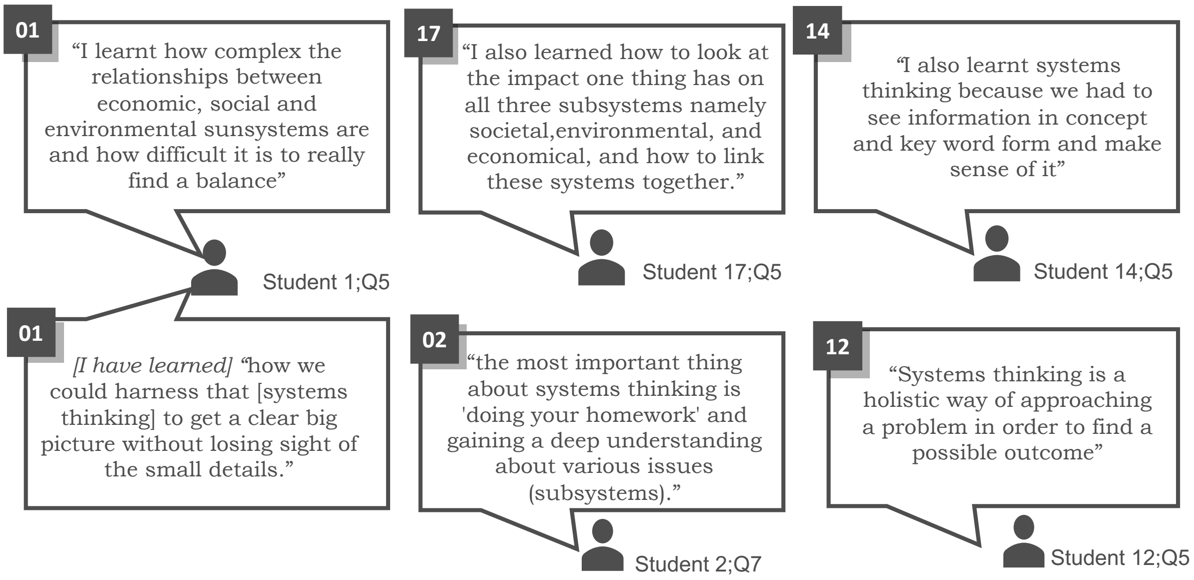
Figure 5.25. Evidence of evaluation: deeper engagement

5.3.4. DEVELOPING SYSTEMS THINKING SKILLS

In this section, the findings will be shared regarding the number of students who gained systems thinking abilities as coded in terms of each semantic domain. Firstly, a detailed discussion on the *chemistry understanding*, *analysis, integration, evaluation*, *application*, and *ownership* skills will be presented. This will be followed by a summary of which systems thinking understanding, skills and attitudes students were developing during the intervention.

UNDERSTANDING

None of the students mentioned LAS's physical and chemical properties in their reflection as the question did not prompt students' chemistry understanding. Therefore, the absence of evidence thereof in students' reflections does not mean that students did not learn chemistry. Students clearly gained an understanding of the system of LAS. The evidence was sufficient to claim that five students (1, 2, 8, 10, 17) gained an understanding of the chemistry context of LAS. Student 1 claimed in question 7 to have *"learned that surfactants are a very big issue when it comes to river pollution"* and felt motivated to *"educate people around* [me] *about the impact of surfactants on the environment".* Other students learned *"how to take a step back to look at the real-world implications of chemistry"* (student 2) and to think about chemistry in a *"wider range"* (student 10). They recognized the "*negative effects it* [surfactants] *could have" (student 17* and other *"impacts of LAS"* (student 8). They also gained an understanding of systems thinking, students reflections on this skill was considered to better understand it's development. Student 8 claimed to have developed an understanding of "*systems thinking"* from their response to question 7. This student stated to have "*… learnt from the systematic thinking of these practicals to look at the bigger picture of things."* Seven other reflections provided rich insights into students' progress in understanding the system in such a short timeframe. A sample of these reflections is presented in Figure 5.26.



"I learnt how complex the relationships between economic, social and environmental sunsystems are and how difficult it is to really find a balance"

"I also learned how to look at the impact one thing has on all three subsystems namely societal,environmental, and economical, and how to link these systems together."

"I also learnt systems thinking because we had to see information in concept and key word form and make sense of it"

[I have learned] "how we could harness that [systems thinking] to get a clear big picture without losing sight of the small details."

"the most important thing about systems thinking is 'doing your homework' and gaining a deep understanding about various issues (subsystems)."

"Systems thinking is a holistic way of approaching a problem in order to find a possible outcome"

Figure 5.26. Reflections of students regarding their learning of systems thinking from question 5 and 7

ANALYSIS

It was evident from students' reflections that they developed the ability to identify elements and relationships within the system. The code *analysis: relationships* appeared in more responses than *analysis: elements,* revealing that most students perceived that they were developing the ability to identify relationships between concepts. Before students can identify relationships between concepts, they have to identify the concepts. Hence, it could imply that the students who gained *analysis: relationships skills* potentially also developed the ability to identify the elements in the system. For both *analysis: elements* and *analysis: relationships* no claims were made based on the strength of evidence due to its trustworthiness as discussed in section 5.4.2. Student 14 might have developed *analysis: elements* as they stated that: *"I learnt systems thinking because we had to see information in concept and key word form to make sense of it, as well as brainstorm ideas and turn ideas into key words and concepts"* (student 14). Other students could have been developing *analysis: relationship* skills. One student stated that they would *"think about how things link to one another"* (student 13), other students learned how to "*analyze these relationships"* (student 1) and use "*linking words to solve the problem"* (student 10). Students 10 and 14 recognized that *"one thing can influence a lot of other things"* (student 10) and these *"things could be affected"* (student 14).

INTEGRATION

Most students did not report that they acquired *integration* skills; therefore, this skill was developing to a lesser extent. Students did not mention learning about the system's emerging behaviours or properties. Hence the code *integration: emergence* was not applied once. Evidence of the development of the skill *integration: dynamic interactions* were based on the quality of responses, and not on the strength of evidence. One student, student 17, recognized the complex interactions between subsystems from a broad perspective and stated that: *"I have realised that stuff influence each other and the subsystems and something I might think has a small effect might actually have a big negative effect if there is looked at all the interactions between the subsystems". The skill integration: organization* was analysed for it's strength of evidence to find that two students reflections (13, 17) provided sufficient evidence to claim that these two students were developing the ability to organize system-level concepts in the whole system within existing and new subsystem boundaries. Student 13 stated, *"I learned how to organise my thoughts into a universal diagram or idea."* And student 17 reported on learning *"with critical thinking how to identify in which subsystem a component would fit."*

APPLICATION

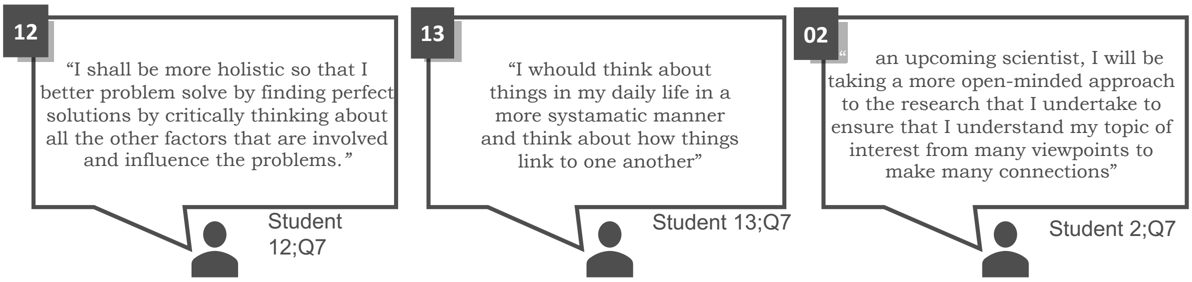
Evidence from students' reflections showed that more students were developing the ability to make predictions compared to applying problem-solving and creativity skills. The skills *application: creativity* and *application: predictions* were only analysed from the quality of students' reflections. Students could have developed the ability to make predictions as one student stated to have learned *"what the environmental and economic consequences are"* (student 13) and think about the *"effects and consequences of using such products*" (student 8). Student 17 recognized that *"a small effect might actually have a big negative effect"*. Some students also felt they gained creativity skills as they learned how to *"become creative and think out of the box to help figure things out"* (Student 4), another *"learned to be creative in my think process by means of the SOCME diagram"* (student 10) and a third student intends to be creative through innovation to "*create new technologies*" (student 12). The skill *application: predictions* was analysed for its strength of evidence showing that one student (student 12) was developing *problem-solving* skills. Student 12 stated, "*I shall be more holistic so that I better problem solve by finding perfect solutions".* Five other students (4, 8, 10, 11, 14) made progress in developing the skill, as mentioned in question 5. However, the evidence was weak to claim with confidence that it was developing in these students as they were prompted to reflect on this skill in question 5.

EVALUATION

Evaluation skills were not prompted for in questions 5 and 7 and were not one of the systems thinking skills embedded into the LOs of the intervention, the emergence of this skill is considered noteworthy. Students claimed they conducted research and engaged deeply with the topic of surfactants. Overall, more students reported developing *evaluation: deeper engagement* than *evaluation: conducting research.* The codes in this semantic domain was analysed for its strength of evidence based on the discussion in section 5.4.2. Evidence was sufficient to claim confidently that two students (2,14) were developing the ability to conduct research, where students understood research to mean searching for answers by consulting additional resources. Student 2 stated that *"the most important thing about systems thinking is 'doing your homework"* which has contributed to this student's motivation to adopt *"a more open-minded approach to the research".* This aligns with student 14's response, who recognized that in their group they *"came up with ideas that had been checked through research"*. One more student (student 8) gained *evaluation: conducting research*, but the evidence was insufficient to claim that this student was developing this skill, even though the student felt motivated to conduct research to be *"well informed on what products"* they are using. Evidence was sufficient to claim with confidence that three students (2, 10, 17) were developing evaluation: deeper engagement. Students gained *"critical thinking" skills* (student 17). They learned "how t*o think deeper by using linking words to solve the problem"* (student 10) and to *"gain a deeper understanding about various issues"* by *"understanding the topic of interest from many viewpoints."* (student 2). Reflections from four other students (1, 4, 12, 14) were considered insufficient to make claims regarding its development. One of the students (student 12) described how problem-solving would be possible with critical thinking, saying *"I shall be more holistic so that I better problem solve by finding perfect solutions by critically thinking".*

OWNERSHIP

Students reflections were read to understand whether some developed the skill *ownership: challenge recognition*, without assessing its strength of evidence. It was seen that student 8 was developing the skill *ownership: challenge recognition* who stated that "*I learnt that a product can be beneficial to one sphere but detrimental to another and we as a population often tend to focus on the advantages instead of the consequences of the disadvantages.".* Two other students (1 and 10) made progress towards developing this skill as they learnt "*how complex the relationships* *between economic, social and environmental sunsystems [subsystems] are and how difficult it is to really find a balance" (student 1)* and *"One thing can influence a lot of other thing[s] and we don't normally think about that."* However, the evidence is insufficient to claim they were developing this skill. It was also noted that these challenges are related to the difficulty in finding a balance between the economic, societal, and environmental subsystems (student 1).All the students mentioned taking ownership by making better-informed choices and changing their actions for future improvement. The strength of evidence was considered for the skill *ownership: future improvement.* Interpretations of responses in question 7 were considered weak evidence since students were prompted to reflect on developing *ownership* and taking sustainable action. However, the presence of *ownership: future improvement* unprompted in question 5 was noteworthy. Evidence was sufficient to claim that two students (students 1, 17) were developing the skill *ownership: future improvement*. These students described that they have learned what is needed for future sustainability, which is to "*educate my peers and people I come in contact with, and hopefully, everyone can start transitioning to safer laundry detergents that are more sustainable"* (student 1) and to *"become a more responsible citizen*" (student 17). All of the other students mentioned this skill; however, it cannot be said with certainty if they were developing an attitude of taking ownership. Yet, their intentions reveal their willingness to take sustainable action. A sample of these responses is represented below in Figure 5.27



"I shall be more holistic so that I better problem solve by finding perfect solutions by critically thinking about all the other factors that are involved and influence the problems."

"I whould think about things in my daily life in a more systamatic manner and think about how things link to one another"

" an upcoming scientist, I will be taking a more open-minded approach to the research that I undertake to ensure that I understand my topic of interest from many viewpoints to make many connections"

Figure 5.27. Student reflections on their intentions to take ownership for future improvement

SOCIAL ABILITIES

Lastly, evidence indicates that *collaboration* skills developed the most throughout the intervention. For social abilities, the strength of evidence was considered, which revealed that six students (students 1, 4, 8, 10, 11, 16) were developing *social abilities: collaboration.* Students especially took note of learning how to collaborate and work in groups. Student 11 stated, *"I learnt how to work in a team at university where we don't normally get such opportunities during this pandemic." Social abilities: listening and communication* were prompted in question 5. Therefore despite seven students reporting that they have developed this skill, the evidence is considered insufficient to claim with confidence that this skill was developing in students. Student 16 stated: *"my communication skills were greatly improved"*. Other comments can be seen in appendix D.

5.3.5. SUMMARY OF DEVELOPED SKILLS

An overview of the systems thinking understanding, skills and attitudes that were developing based on the strength of evidence is shown in in Figure 5.28. It must be noted that the absence of evidence based on the analysis for the skills *understanding: "systems thinking", analysis: elements*, *analysis: relationships, integration: dynamic interactions*, *application: predictions* and *ownership: challenge recognition* does not mean that the skills were not developing. It was not analysed for its evidence as a result of the unreliable consistency amongst coders in coding for these skills. To better understand the other skills that were developing throughout all the evidence, the abundance of both the strong and credible, as well as the moderate and weak evidence was considered.

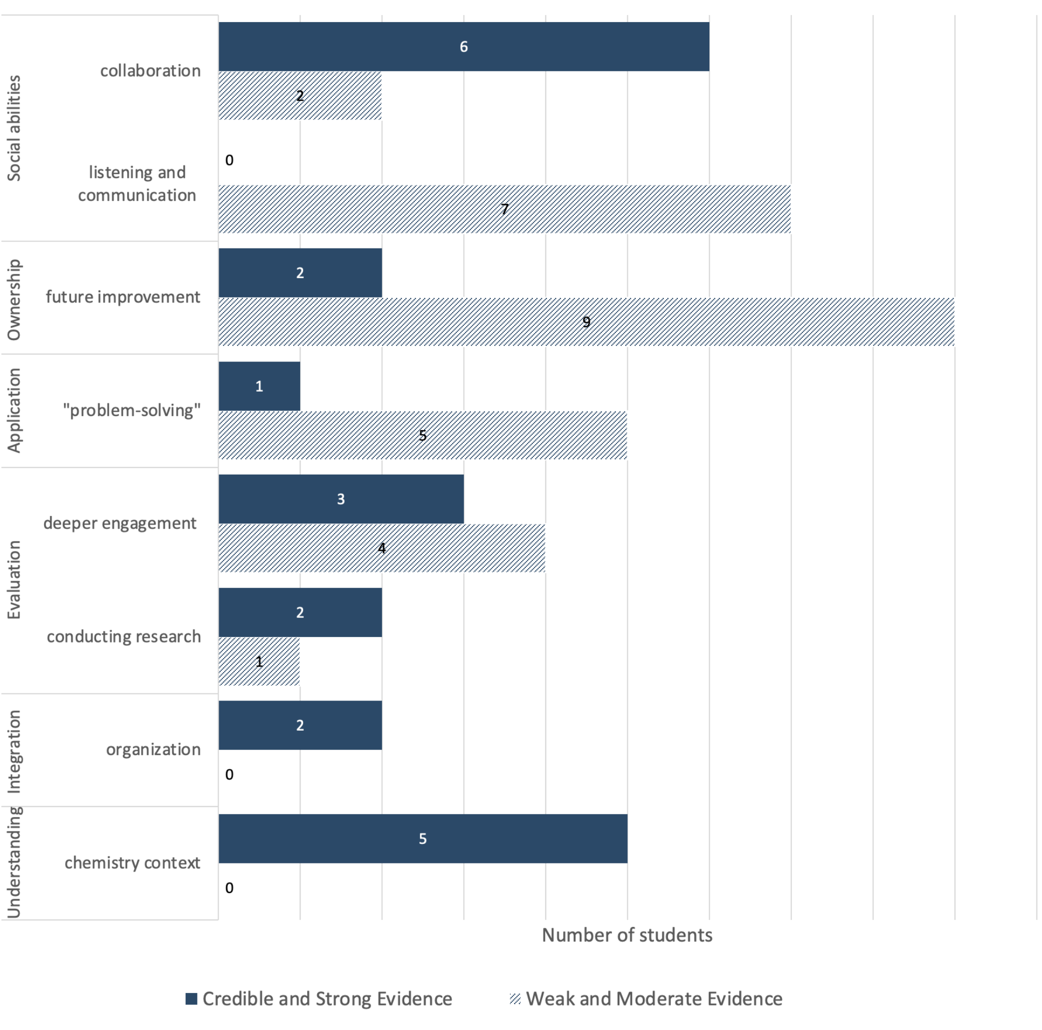


Figure 5.28. Number of students whose reflections present evidence of the developing systems thinking skills

After reviewing students' reflections, we found that students developed collaboration skills and an understanding of the chemistry context in the system the most based on the presence of credible and strong evidence. We can claim confidently that *evaluation: deeper engagement* developed in students. Based on the presence of weak and moderate evidence, we also found that the most progress was made in an attitude of taking ownership for future improvement, in *listening and communication* skills, in problem solving skills and in *integration: organization*. From the reported excerpts in students' reflections it was apparent that students were developing *analysis: elements* skills, *analysis: relationships* skills and an understanding of the chemistry context, even though not many students mentioned these skills in their reflections. It is inferred that more students were developing these skills, as these skills were promted the most during the intervention activities. From students; reflections, the *skills integration: dynamic interactions*, *application: predictions* and *application: "creativity"* developed to a lesser extent.

5.4. STUDENT'S DEMONSTRATION OF SYSTEMS THINKING SKILLS

In this section, the evaluation of SOCMEs based on the assessment rubric, rater feedback and content analysis will be presented and triangulated to make inferences about the systems thinking skills that were demonstrated during the intervention. The reliability of the SOCME scores will be presented first, which will be followed by the analysis of an example SOCME and the demonstrated and developed skills.

- SOCME rubric and reliability of scores
- Skills demonstrated on SOCMEs
- Summary of developed skills

Figure 5.29. Overview of the section on students; demonstration of systems thinking skills

5.4.1. RELIABILITY OF SCORES

To understand how reliably two independent raters and the researcher assessed the SOCMEs, the variance of total scores and the variance within the different SOLO levels of the rubric were compared. This will provide valuable information regarding the consistency between raters when the SOCME diagrams were graded, and a lack of consistency in grading would indicate poor reliability.

THE VARIANCE IN TOTAL SOCME SCORES

The variance between the final scores assigned by the two raters in comparison to the researcher was calculated for the six SOCMEs to understand whether scores were applied consistently for different SOCMEs. The variance in scores of all six SOCME diagrams is shown in Table 5.11. below.

Table 5.11. Variance in scores of all six SOCME diagrams out of 80

SOCME number	Rater 1	Rater 2	Researcher	Average out of 80	Variance
SOCME 1	72	60	68	67	37
SOCME 2	66	55	55	59	40
SOCME 3	63	66	64	64	2
SOCME 4	68	55	70	64	66
SOCME 5	75	78	70	74	16
SOCME 6	71	72	75	73	4

The variance of SOCME total scores for SOCME 3 and 6 was low, indicating a remarkably high consistency in grading by all the raters, as seen in Table 5.11. The variance for the scores assigned to the SOCME submitted by group 5 showed moderate consistency. Therefore, from the six SOCME diagrams, SOCME 3, 5 and 6 were marked more consistently between all three raters and indicated higher reliability than the other SOCME scores. The large variances in the SOCMEs 1, 2 and 4 indicates a lack of consistency between raters to score the same SOCME. It was also found that rater 2 marked the multistructural levels differently than the other raters, which could have influenced the SOCME scores. The lack of consistency was further investigated by looking at the variation of scores assigned by each rater for each SOLO level.

THE VARIANCE BETWEEN SOLO LEVEL SCORES

The details and discussion of this section are presented in the article under review (Appendix B). Therefore, only the main findings and considerations will be presented here. The inter-rater reliability was calculated as a measure of the consistency of the rating to better understand the reliability of the rubric. Since the data was numerical, the inter-rater reliability was calculated using the intraclass correlation coefficient (ICC) with a two-way mixed model, with a mean rating of k=3, to investigate the consistency amongst raters grading the SOLO levels of each SOCME. 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, it was difficult to make conclusions regarding the reliability of the rubric as the sample size was small and the confidence interval was large.

A scatterplot, shown in Figure 5.30, revealed the SOLO level scores assigned by two independent rates and the researcher for all six SOCMEs. The scatterplot revealed consistent grading for the lower SOLO levels from unistructural to relational low, and inconsistent grading was observed as evidenced by considerable variation in higher SOLO levels from relational medium to extended abstract. The correlation between variation in scores and the SOLO levels was found to be statistically significant, leading to the finding that variation increased with an increase in SOLO levels. Given the challenges associated with marking higher SOLO levels, it is possible that raters might not be competent in assessing high proficiency in systems thinking skills.

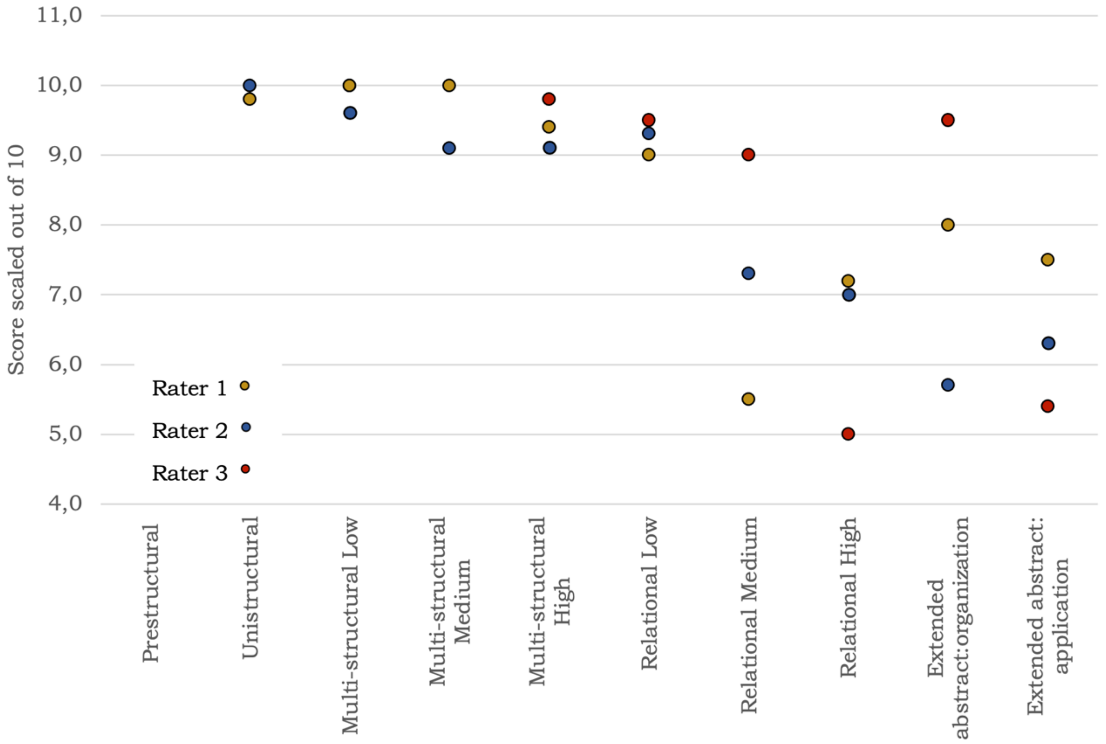
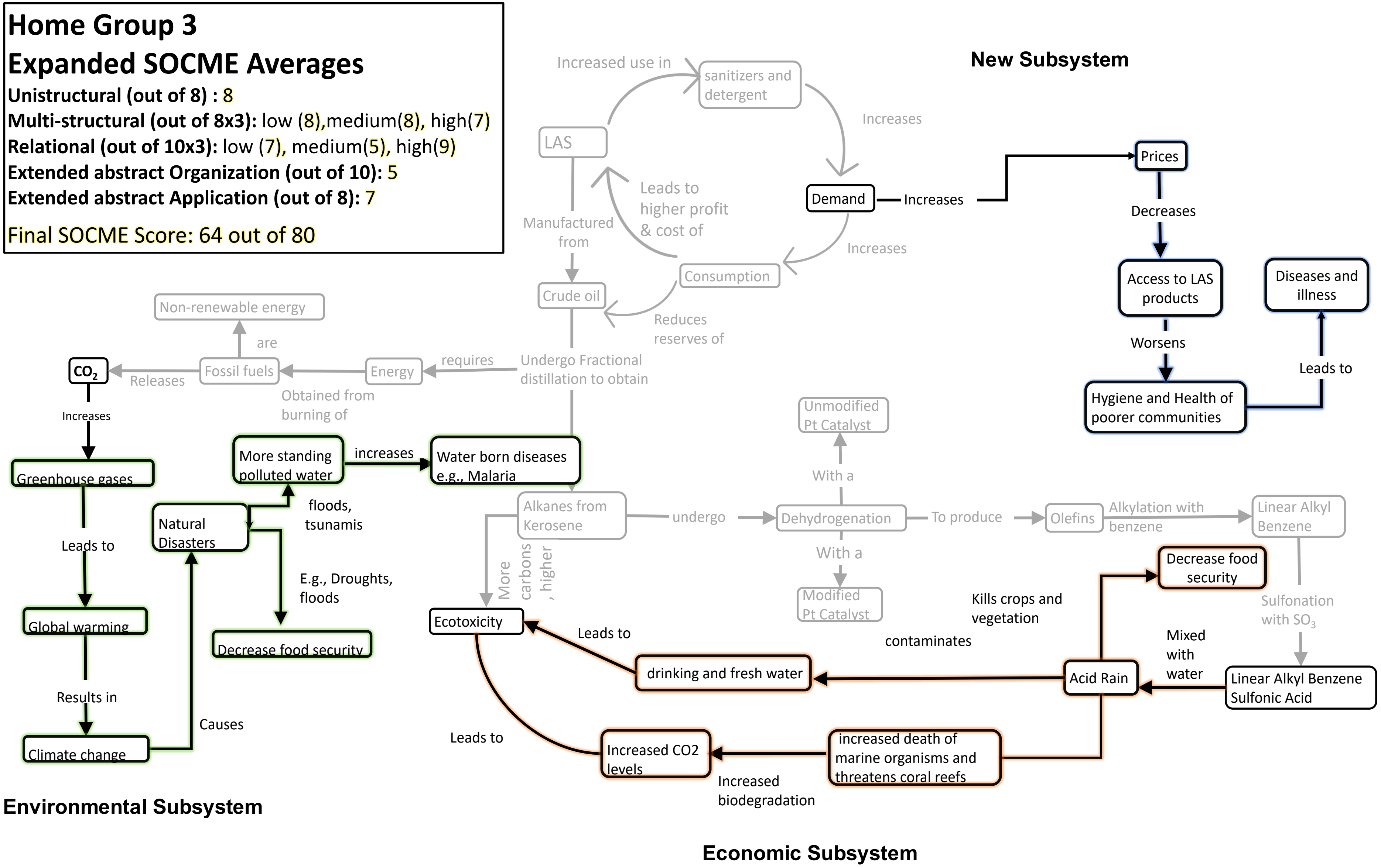


Figure 5.30. Average SOLO level scores from six SOCME diagrams assessed by three independent raters

As a result of the inconsistency in grading SOCME diagrams, the reliability of the scores was not convincing enough to make valid interpretations from the data. Therefore, content analysis and rater feedback were employed to validate the scores and to create a better understanding of the skills that were demonstrated. This further analysis will be demonstrated using SOCME 3 as an example.

5.4.2. ANALYSIS OF AN EXAMPLE SOCME

In this section, the interpretation of the scores for SOCME 3 will be triangulated with findings from content analysis and rater feedback to validate the findings and provide a better understanding of the systems thinking skills that students were developing. The SOCME presented (Figure 5.31.) has been modified to show the new concepts, connections, subsystems, and predictions that students added as they expanded the given partial SOCME. The other SOCME diagrams submitted by students can be seen in appendix D. The example SOCME will be used as a reference to provide evidence of what has been done generally throughout all the SOCMEs.



Home Group 3

Expanded SOCME Averages

Unistructural (out of 8) : 8

Multi-structural (out of 8x3): low (8),medium(8), high(7)

Relational (out of 10x3): low (7), medium(5), high(9)

Extended abstract Organization (out of 10): 5

Extended abstract Application (out of 8): 7

Final SOCME Score: 64 out of 80

Figure 5.31. SOCME submitted by home group 3.

ANALYSIS: ELEMENTS

The unistructural and one of the multistructural SOLO levels were assessed to analyse students; demonstration of *analysis: elements.* SOCME 3 had a total of 16 newly added concepts, where one of these concepts, *"drinking and freshwater",* was assessed in this unistructural SOLO level for its quality. This concept was considered relevant in the system of LAS as acid rain can potentially result from the sulfonation step and contaminate drinking and fresh water. The format was suitable as it was in a concept block with appropriate font and size. Overall, the SOCME was on a multistructural high level as it contained more than three concepts with appropriate linking words and connections between concepts. The 15 other concepts were assessed for their quality, and it was seen that propositions, for example, "*demand increases prices decrease access to LAS products*", were formed. The newly added concepts all seemed relevant to the system of LAS. However, the format is lacking as some concepts contained linking words, for example, "*decrease food security*", "*increased CO2 levels*", and "*increased death of marine organisms and threatens coral reefs*". Therefore even though many concepts were added, some concepts lacked quality. Overall, this SOCME scored an average of 98% for *analysis: elements,* which corroborated the content analysis findings and the rater feedback, where Rater 1 commented that *"some good ideas and concepts"* were added to the SOCME. Rater 2 agreed that *"a lot of the concepts were good"*. In summary, the content analysis and rater feedback corroborated the scores assigned to *analysis: elements,* revealing that this skill was demonstrated and was developing in students.

ANALYSIS: RELATIONSHIPS

The relational low and medium levels were assessed to analyse students' demonstration of *analysis: relationships* skills. On the SOCME, at least 1 or 2 good connections were added between concepts within one or two subsystems with a proposition. For example, "*Linear Alkylbenzene sulfonic acid (LABSA) mixed with water acid rain kills crops and vegetation decrease food security"* was chosen to assess its quality in the relational low SOLO level. This proposition, added in the economic subsystem, was relevant as sulfonation in the industrial manufacture of LAS could contribute to potential acid rain that can kill crops and vegetation. However, the linking words were not appropriate, as LABSA will not result in acid rain if mixed with water. The acid rain possibly resulted from the formation of sulfuric acid in the atmosphere. Therefore the quality of linking words used in this proposition was poorly chosen. For the relational medium level, connections were not demonstrated in all three subsystems. The connections were within the economic and environmental subsystems and the newly added subsystem. Within the new subsystem, a different proposition was chosen to assess its quality, "*demand increases prices decreases access to LAS products worsens hygiene and health of poorer communities leads to diseases and illness".* The connections in this proposition were relevant, the linking words were appropriate, it connected within the new subsystem, concepts, and connections had a good format, and it can be read as a proposition or feedback loop. Rater 1 agreed that inappropriate linking words were used as the implementation and connection" of the concepts "were lacking". This SOCME scored 82% for *analysis: relationships*, which were validated by the demonstration of this skill and with rater feedback, which indicated an overall good quality linking words. Nevertheless, the evidence suggested that the skill *analysis: relationships* were demonstrated on this SOCME.

INTEGRATION: DYNAMIC INTERACTIONS

The relational high SOLO level was assessed on the SOCME diagram to understand the demonstration of *integration: dynamic interactions.* The SOCME also showed 3 connections between subsystems together with the connections within subsystems. However, these connections between subsystems, which are called interactions, did not explicitly state possible dynamic change, even though it is implied to occur over time. The following interactions were identified between the economic and environmental subsystem *"acid rain increased death of marine organisms and threatens coral reefs increased biodegradation increased* CO_2 *levels leads to ecotoxicity"* together with *"acid rain contaminates drinking and freshwater leads to ecotoxicity"* and the economic subsystem with the new subsystem *"demand increases prices decreased access to LAS products worsens hygiene and health of poorer communities leads to diseases and illness".* All of these interactions seemed relevant, however, the linking words between subsystems in two of the three interactions lacked depth. However, the connections were well placed , had a good format and could be read as a proposition or feedback loop. *The* connections added between concepts within and between subsystems have been made, however, some linking words are not appropriate and rater 1 commented that *"some concepts were used multiple times in different subsystems and instead of connecting the subsystems via these concepts they were kept isolated"* (rater 1). These findings agreed with the lower score average of 57% that was assigned for *integration: dynamic interactions.* In summary, the skill *integration: dynamic interactions* was only partially demonstrated.

INTEGRATION: ORGANIZATION

The extended abstract SOLO level was assessed to understand students' demonstration *of integration: organization*. To assess this level, the organization of some concepts assessed for the lower levels should be revisited. The concept of *"drinking water and freshwater*", which was chosen to assess at the unistructural levels, did not fit well into the economic subsystem and related more to the environmental and societal subsystem. For that reason, it was also not organized well in the SOCME. For the 15 other concepts assessed in the multistructural levels, only about half of the concepts fit well into their subsystems, specifically referring to concepts related to future predictions. These concepts from the proposition "*CO2 increases greenhouse gasses leads to global warming results in climate change causes natural disasters eg floods, droughts decrease food security and floods, tsunamis more standing water increases water-borne diseases e.g. Malaria"* was organized well into the environmental subsystem. A new subsystem was added with relevant concepts. However, the subsystem was not given a name, and the concepts within the new subsystem fit better into existing subsystems. For example, *“prices”* fit well into the economic subsystem and *access to LAS products”, “hygiene of health of poorer communities”*, and *“diseases and illness”* fit better into the societal subsystem. Overall the concepts added for the predictions relating to scenario A or B fit well into the environmental subsystem. Other concepts, linking words and connections such as *“acid rain* and “crops and vegetation”, fitted better into the environmental subsystem and *“decreased food security”* fitted better into the societal subsystem. Therefore concepts could have been better organized into more appropriate subsystems. Rater 2 also agreed that the concepts did not fit into their correct subsystems and rater 1 stated that “*the SOCME was not very neat, which made it difficult to follow the propositions and flow of thoughts*”. The content analysis and rater feedback corroborated the low score of 47% that was given for *integration: organization.* Therefore this skill was only partially demonstrated on the SOCME.

APPLICATION

Application skills were also assessed at the extended abstract SOLO level. SOCME 3 added concepts that related to scenario A as stated in practical activity 2 shown in Figure 5.32.

Scenario A

In South Africa, coal-fired power stations depend on fossil fuels for the generation of electricity. SASOL uses the electricity for the fractional distillation to obtain the kerosene used in the manufacturing of linear alkylbenzene sulfonate. When coal is burned, carbon dioxide is emitted. The emitted carbon dioxide can be absorbed by aquatic systems, such as oceans. If excessive carbon dioxide is absorbed, ocean acidification can result, which threatens the life of coral reefs.

Predict how carbon dioxide emitted during the manufacturing of LAS, can contribute to global warming and expand on the impacts of global warming and its contribution to climate change. You can expand on any examples of your choice, these can include changes in global temperatures, the frequency of natural disasters, malaria and typhoid outbreaks, the impacts of ocean acidification and acid rain on terrestrial and aquatic life.

Figure 5.32. Practical activity 2 prediction for scenario A

The SOCME showed more than five concepts related to this prediction. It was assessed for its quality based on its clarity, relevance and format, which in this instance, was good. The SOCME was also assessed as a whole to judge whether the concepts, relationships, propositions, predictions and added subsystems described the system of LAS well. Overall, the interconnections and organization in the SOCME needed to be improved. However, the concepts and predictions were good overall, with some work needed to improve the quality of linking words. The average score of 79% for *application* agreed with the content analysis, and this SOCME had no rater feedback on this level.

Table 5.12. summarizes the average scores assigned to each SOLO level and findings from content analysis, which agreed with these scores. A general decrease in scores from *analysis* skills to *integration* skills was observed with an increase in scores for *application* skills. Content analysis also confirms these scores as this SOCME lacked overall organization, and the concepts added

to a new unlabelled subsystem fitted better into other subsystems. Also, the lack of interactions between subsystems resulted in a low score for *integration: dynamic interactions*. However, good concepts, relationships and predictions were added, resulting in higher scores for *analysis* and *application* skills.

Table 5.12. Systems thinking skills demonstrated on SOCME 3

SOLO levels	Sublevel	Skills	Content analysis	Average Score in % (3 raters)
Unistructural Multi-structural	All levels	*analysis: elements*	Skill demonstrated	98
Relational	Low Medium	*analysis: relationships*	Skill demonstrated	82
	High	*integration: dynamic interactions*	Partially demonstrated	57
Extended abstract	organization	*integration: organization*	Partially demonstrated	47
	Application	*application*	Partially demonstrated	79

In summary, we found that on SOCME 3 students demonstrated concepts and connections but were struggling to integrate and organize concepts and relationships in the SOCME, therefore students were developing *analysis* skills, but they were developing *integration* and *application* skills to a lesser extent.

5.4.3. DEMONSTRATED SYSTEMS THINKING SKILLS ON ALL THE SOCMEs

The other five SOCMEs were also analysed and evidence from content analysis, rater feedback and SOCME scores was triangulated to make judgements regarding the demonstration and development of skills. Content analysis revealed that *chemistry understanding, integration: cyclic behaviour* and *integration: emergence* were not demonstrated on SOCMEs. These were also not assessed in the SOCME rubric. The judgement of the development of skills based on what students have demonstrated, rater feedback and SOCME scores are summarized in Table 5.13 below.

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Table 5.13. Summary of findings from SOCME content analysis, rater feedback and SOCME scores assessed from the rubric

Systems thinking skills	Evidence from content analysis	Evidence from overall rater feedback	Evidence from SOCME scores	Triangulation of evidence	Judgement of development
Analysis: elements	Demonstrated on all 6 SOCMEs with mostly good quality concepts in high numbers added within subsystems	Raters indicated that students *"were able to add generalized concepts and ideas" rater 1*	6 SOCMEs ≥ 93%	Qualitative analysis validates the average high SOCME score	**Demonstrated and skills developed.**
Analysis: relationships	Demonstrated on 5 SOCMEs with mostly poor quality of linking words and propositions that aren't coherent	Rater 1 stated in general that students were able to add *"ideas and connect them to existing concepts" rater 1*	5 SOCMEs ≥ 82% 1 SOCME of 67%	Qualitative analysis validates the average high SOCME score	**Demonstrated and skills developed.**
Integration: dynamic interactions	Partially demonstrated on 5 SOCMEs with limited connections implying changing behaviour and not demonstrated on 1 SOCME	Both raters felt that this skill was too difficult for students to demonstrate	3 SOCMEs ≥77% 2 SOCMEs of 67, 57% 1 SOCME of 0%	Qualitative analysis of two SOCMEs did not validate the scores. Only qualitative evidence was considered due to inconsistent grading of higher SOLO levels.	**Partially demonstrated and skills developing to a lesser extent**
Integration: organization	Partially demonstrated on 5 where concepts did not fit well into subsystems and new subsystems were not added or fully appropriate and demonstrated on 1	Both raters felt that this skill was too difficult for students to demonstrate, whereas rater 1 stated that students struggled to organize mostly between subsystems. Rater1 stated that "*2-3 groups identified new subsystem boundaries includes new subsystems" rater 2 stated that "a lot of students did not add new subsystems" and was "quite disorganized"*	4 SOCMEs ≥ 77% 1 SOCME of 70% 1 SOCME of 47	Qualitative analysis of SOCMEs agreed with some scores. Only qualitative evidence was considered due to inconsistent grading of higher SOLO levels	**Partially demonstrated and skills developing to a lesser extent**
Application	Partially demonstrated on all 6 SOCMEs, lacking in integration to describe the interconnections within and between subsystems of LAS.	Rater 1 stated that *"most of the groups stuck to generalised concepts such as global warming. Raters'* 1 and 2 felt that students' achieved this skill.	3 SOCMEs ≥ 75% 2 SOCME of 58% 1 SOCME of 47%	Qualitative analysis of some SOCMEs agreed with scores, but only qualitative evidence was considered due to inconsistent grading of higher SOLO levels.	**Partially demonstrated and skills developing to a lesser extent**

We found that the average SOCME scores agreed with the demonstration of *analysis: elements* and *relationships* skills. However, making confident claims about the demonstration of *integration* and *application* skills was more challenging due to the large spread of scores and inconsistencies reported in grading higher SOLO levels, as discussed above. It was also observed that findings from the content analysis did not fit the scores assigned to two SOCME diagrams for the demonstration of *integration: dynamic interactions.* The SOCMEs submitted by Home groups 5 and 6 achieved high scores of 90% and 93% for *integration: dynamic interactions*. These scores were high, even though both SOCMEs lacked overall integration, where home group 5 only demonstrated one relationship between subsystems and home group 6 only demonstrated three. The high variation in scores also did not compare well with what was observed for the other SOCME diagrams. Findings revealed that raters assessed higher SOLO levels in the SOCME rubric with less consistency. Stewart (2012) also noted similar findings: a less consistent rating was observed in the SOLO taxonomy at the sub-category divisions, especially for the relational levels (Stewart, 2012). Biggs and Colls (1982) stated clearly in their book Evaluating the Quality of Learning: The SOLO taxonomy that *“quantifying SOLO analysis may lead to definite anomalies”* (Biggs, 1982). Therefore, a decision was made to use the evidence from qualitative analysis to make final interpretations of the developing skills. It was claimed that if the skill was demonstrated, students were developing it. If the skill was only partially demonstrated, students were developing it to a lesser extent, and if it was not demonstrated, then the skill was not developing.

In summary, we found that *analysis: elements* and *analysis: relationships* skills were developing as they were demonstrated and that *integration: dynamic interactions*, *integration: organization* and *application* skills were developing to a lesser extent as they were only partially demonstrated. Even though the scores were not considered for final judgements, the lower scores agreed with what raters identified as the most challenging skills to demonstrate, which were *integration: dynamic interactions* and *integration: organization*

5.5. CONCLUDING REMARKS

This chapter discussed snapshots of evidence from students' perceptions, reflections, and SOCME demonstrations to better understand the skills that students were developing during the systems thinking intervention. The following criteria, shown in Table 5.14., were used to indicate the extent of the evidence for concluding that skills were developing. Table 5.15 was created to provide an overview of the number of students developing each skill summarizing all the findings that were presented in this chapter.

In summary, findings from students' perceptions revealed that they perceived to have achieved a *chemistry understanding*, *analysis: elements*, *analysis: relationships*, *integration: organization* and *integration: dynamic interactions*. They also perceived that *integration: organization*, and *chemistry understandin*g were the most challenging systems thinking skills to demonstrate on the SOCME. Focus group interviews provided reasons for their perceptions, which were based on their unfamiliarity with systems thinking skills and the limited exposure that they have had to develop these skills. Findings from students' reflections provided credible and strong evidence that *collaboration*, *evaluation deeper engagement* skills developed and that progress was made in developing *ownership: future improvement*, *application: problem solving* and a *systems understanding: chemistry context*. Students also developed the ability to identify the elements and relationships within the system, even though not many students mentioned these skills in their reflections, they were prompted throughout the intervention to apply their *analysis* skills. Most students did not report learning about *integration* skills, indicating that only some of the students developed *integration* skills. Evidence showed that students were learning to make predictions, but the other *application* skills, such as *problem-solving*, and *creativity* only developed in some students. Evidence of what students have demonstrated, as evaluated from SOCME scores, content analysis and rater feedback, revealed that *analysis* skills were demonstrated on all the SOCME diagrams. However, the diagrams lacked demonstration of *integration a*nd *application* skills, where *integration* skills were demonstrated the least. The raters also identified it as the most challenging skill to demonstrate, which agreed with the trend in SOCME scores. The SOCME scores triangulated well with the qualitative findings in the example SOCME 3, which was graded with high consistency. However, the scores were not used to judge the development of skills due to the high variation resulting from inconsistent grading of higher SOLO levels. The trustworthiness of the findings was carefully considered and the limitations of these findings are further discussed in chapter 7.

Table 5.14. Criteria used to judge the systems thinking skills that were developed.

Symbol	Description	Perception	Reflection	Demonstration
●	Most students developed this skill	7 or more students	8 or more students with at least 3 students with credible/strong evidence	more than 3 SOCMEs
⭘	About half of the 11 students developed this skill	4 to 6 students	4 to 7 students with at least 1 student with credible/strong evidence	3 SOCMEs
○	Some students developed the skill	1 to 3 students	Less than 4 students with at least 1 student with credible/strong evidence or more than 3 students with weak evidence	1 or 2 SOCMEs
--	Assessment tool not suitable or unreliable findings (reflections)			

Table 5.15. Summary of findings from presented evidence

Systems thinking skill	Perceptions	Reflections	Demonstration
Understanding			
• Chemistry understanding	●	--	--
• Systems understanding	●	⭘	●
Analysis			
• Elements	●	--	●
• Relationships	●	--	●
Integration			
• Organization	●	○	⭘
• Dynamic interactions	●	--	○
Application			
• Predictions	⭘	--	⭘
• Problem solving	--	⭘	--
• Creativity	--	--	○
Evaluation			
• Deeper engagement	--	●	--
• Conducting research	--	○	--
Ownership			
• Future improvement	⭘	⭘	--
• Challenge recognition	--	--	--
Social abilities			
• Collaboration	--	●	--
• Listening and communication	--	○	--

CHAPTER 6: DISCUSSION OF FINDINGS

6.1. INTRODUCTION

In this chapter, the findings obtained from students' perceptions, reflections, and demonstrations will be triangulated to better understand which systems thinking skills were developing in first-year chemistry students and what evidence suggests that they were developing a sustainable action perspective. The findings will be considered in the context of the literature in seeking to answer the research questions.

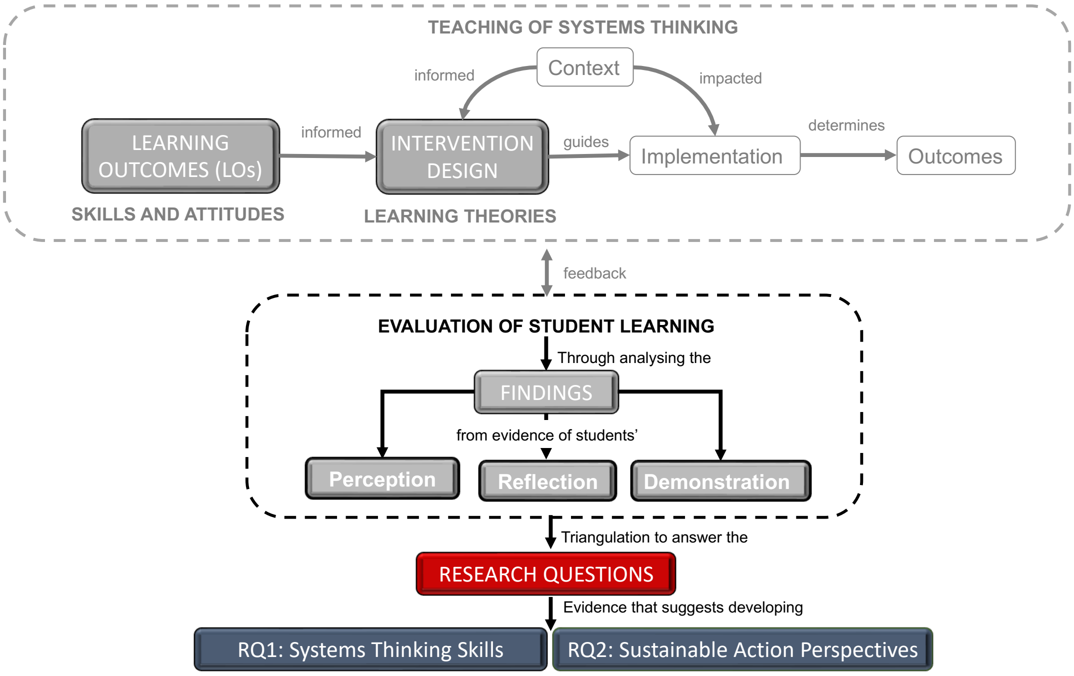


Figure 6.1. Overview of Chapter 6

The evidence obtained from students' perceptions, reflection and demonstration will be viewed together and compared to create a more complete picture of the systems thinking skills that first-year students were developing. Findings from students' perceptions provided rich insights regarding what systems thinking skills they perceived to have achieved and what skills they regarded as the most and least challenging during the expansion of a SOCME. Focus group interviews clarified why they experienced specific skills as most challenging. Findings from coding students' reflections provided insights regarding the understanding, skills, and attitudes that students were developing. Content analysis, rater feedback and SOCME scores provided insights about the skills that students could demonstrate as they expanded their SOCME diagrams. To triangulate the findings, students' perceptions analysed from the closed-ended questionnaire questions and thoughts from the focus group interviews will be compared with their reflections from the open-ended questionnaire questions and what students were able to demonstrate as they expanded their SOCMEs. The findings obtained will be used to answer the research questions. In the following section, the evidence that suggests systems thinking skills were developing in first-year chemistry students will be discussed as framed by the first research question of this study.

6.2. RESEARCH QUESTION 1: DEVELOPING SYSTEMS THINKING SKILLS

This section includes a discussion of the findings to answer the first research question that guided this study to investigate which systems thinking skills were developing in first-year chemistry students as they engaged in a systems thinking intervention. The findings from the evidence presented in Chapter 5 will be used to discuss the developing *analysis, integration, evaluation, application*, and *ownership* skills.

6.2.1. UNDERSTANDING

In the context of the intervention, *understanding* was defined as follows: If students understood the chemistry in this intervention, it meant that they could think about the physical and chemical properties of LAS on a molecular level and therefore developed the skill *chemistry understanding*. If students gained an understanding of the system, it meant that they were able to zoom out of the chemistry to visualize its context with a systems thinking lens. In other words, students could use their systems thinking skills to visualize chemistry's role and real-world implications in various subsystems. Students then developed a *systems understanding*. In this section findings will be discussed to determine whether students developed both understandings.

CHEMISTRY UNDERSTANDING

Eight of the eleven students perceived to have achieved an understanding of the chemistry. No evidence was obtained regarding student’s claims of learning chemistry, as they were not prompted to reflect on their chemistry understanding in question 5 and 7. Students’ high perception of achievement could be a result of their prolonged engagement with the chemistry content, which was explicitly taught and scaffolded throughout the activities. Students were also not prompted to reflect on their chemistry understanding in the questionnaire. It is, therefore, not surprising that they did not make any claims of gaining this skill. Even though most students felt they achieved this skill, six students felt it was the most challenging skill to demonstrate on their SOCMEs. This aligned with the evidence obtained from content analysis, which revealed that students did not demonstrate their chemistry understanding on their SOCMEs. Students expressed that it would be too overwhelming and complex to demonstrate their chemistry knowledge on their SOCMEs. Instead, they preferred to focus on subsystems to deal with the complexity using a reductionist approach.

Szozda et al. (2022) reported after conducting a systems thinking concept mapping intervention with chemistry students that students struggled to demonstrate more than one level of granularity on their concept maps. Similarly, students in this study could have experienced it as challenging to move between the submicroscopic and macroscopic levels of granularity, which is why they could have perceived it as challenging to demonstrate on their SOCMEs. Applying multi-level thinking in chemistry makes it a complex subject, and students struggle to move between the macroscopic and microscopic levels of chemistry (Szozda et al., 2022; Taber, 2013). Some students also perceived that the surfactant content was more challenging than demonstrating their systems thinking skills, revealing their difficulty in applying multi-level thinking. Defever et al. (2015) reported that chemistry students struggle to use chemical characteristics to describe chemical behaviour in organic chemistry due to a lack of system thinking, conceptual weakness and knowledge integration in unfamiliar contexts (Defever, 2015).

Even though the evidence from students’ reflections and demonstrations did not provide much insight into the development of this skill, students’ perceptions indicated that most students achieved a better understanding of the chemistry. This is a valuable finding, especially given the difficulty of the chemistry and that the learning was focused on systems thinking. Students maintained their focus on the chemistry even though they were engaged in systems thinking activities. Interestingly, some students expressed that they could understand the system's hidden dimensions better after visualizing the complex interactions on the SOCME. The intervention, therefore, enabled students' to move between the molecular level and systems level of granularity to foster the development of systems thinking understanding, skills and attitude. Students need to engage with the chemistry concepts on a molecular level to interconnect chemistry concepts to create relationships and make interpretations. This intervention fostered the growth of systems thinking skills but kept the chemistry core to the learning. The concepts maps and SOCME reduced the complexity associated with visualizing more than one level of granularity with chemistry as the “hidden dimensions”.

SYSTEMS UNDERSTANDING

Evidence from students’ reflections and demonstrations complemented each other well and indicated that students were developing a better understanding of the system of LAS. Five students claimed that they had gained an understanding of the chemistry context of the system, even though students perceived that it was challenging to demonstrate the chemistry context on the SOCME. Students experienced it as challenging as they were not used to thinking about the relevance of chemistry from a systems thinking perspective. Students acknowledged their familiarity with studying chemistry in isolated parts and were not used to integrating the parts to understand potential real-world implications of chemistry. This finding aligns with an observation made by Defever et al. (2015), who reported that students fragmented chemistry knowledge frameworks are the reason why they struggle to integrate isolated chemistry concepts (Defever, 2015). We also found that students could recognize the relevance but were not used to thinking about it and struggled to articulate it.

When students were asked to demonstrate their understanding of the system, they felt unsure about what was expected of them and struggled to think creatively. Szozda et al. (2022) reported that without scaffolding, students struggled to add connections to their concept maps linking the chemistry to its context (social, individual and nature). These findings indicate that students require more practise demonstrating their systems (chemistry in context) understanding to feel more confident in being creative. Students' ability to zoom out of chemistry is where they can acknowledge chemistry's real-world systems phenomena and implications (Sabelli, 2006; Tripto et al., 2013). The SOCME diagram was useful to facilitate the process of zooming out of the underlying chemistry so that students could visualize the real-world implications of chemistry in the system of LAS. About half of the students reported having gained systems thinking skills as they learnt how to deal with the interconnectedness and complexity of the system. They could also move between different granular levels to visualize the whole system without losing sight of the smaller details.

SUMMARY

Overall, evidence revealed that students were developing an understanding of chemistry and had achieved LO1 of the intervention. Students also developed an understanding of the system, with more evidence as they could demonstrate the context of the chemistry on their SOCMEs. As shown in Figure 6.2.

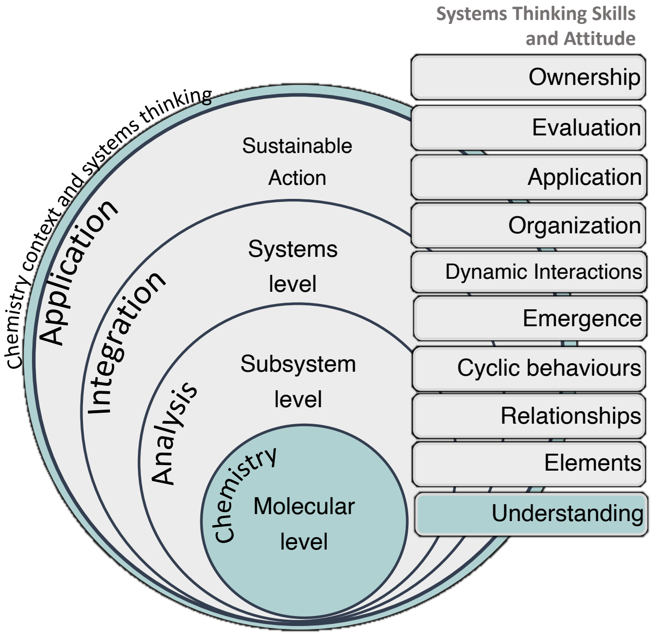


Figure 6.2. *Chemistry understanding* on a molecular level and *systems understanding* on a systems level

The scaffolding provided in this intervention allowed students to zoom out of the hidden dimensions on a molecular level, which enabled them to develop an understanding of the system as they visualise LAS's interconnections on a systems level. It is on this level where the chemistry context incorporates the human element to promote chemistry as the science for society, which can give rise to an eco-reflexive approach to chemistry education.

6.2.2. ANALYSIS

Students developed *analysis* skills (Figure 6.3) if they were able to zoom out of the chemistry to a systems level of granularity to identify the concepts that describe the role and implications of chemistry in various subsystems and the meaningful relationships between these concepts. Findings after comparing evidence from the three perspectives will be discussed to get a better understanding on the development of *analysis: elements* and *relationships.*

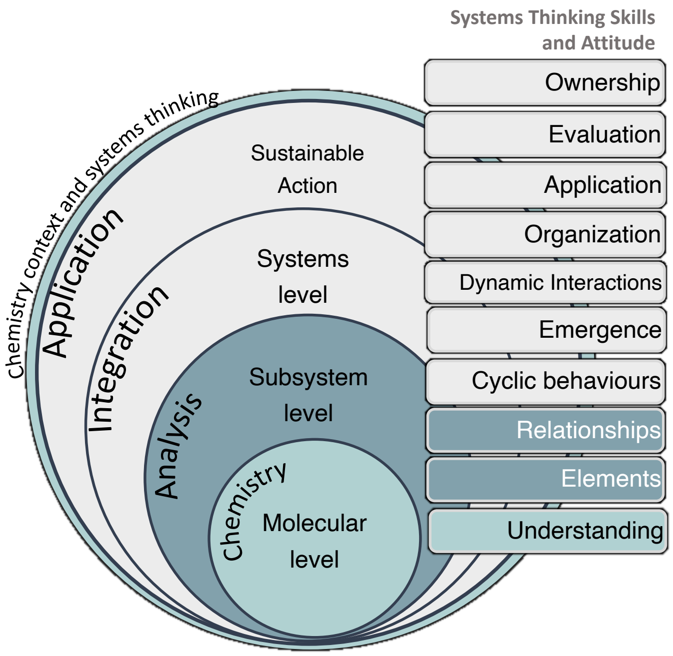


Figure 6.3. *Analysis: elements* and *analysis: relationships* is on a subsystem level

Triangulation revealed that students were developing both *analysis: elements* and *analysis: relationships* skills to a large extent in the intervention. Although students' high perception of achievement of *analysis: elements* was not supported by students' reflections they did demonstrate the skill in their SOCMEs. By contrast, students' high perception of achievement of *analysis: relationships* was corroborated by the quality of their reflections, revealing that students were able to identify and analyze the relationships, effects and links within a system. Even though more students referred to *analysis: relationships* in their self-reflections in comparison to analysis:

elements, the latter is a prerequisite for developing the ability to analyse relationships. Overall, the higher perception of achievement could have resulted from the prolonged engagement students had throughout the systems thinking activities, especially during the SOCME expansion, where students were prompted to add concepts and relationships. Students also perceived *that analysis: elements* and *analysis: relationships* were the easiest skills to demonstrate on their SOCME diagrams, as were demonstrated on almost all of the SOCMEs.

However, the quality of connections was judged to be poor indicating that adding appropriate linking words to describe the relationships between concepts represented a higher cognitive challenge than just adding concepts. Students could have also struggled to add good quality relationships due to a lack of concept mapping skills. After assessing concept maps with the SOLO taxonomy, Stewart reported that the concept maps created by students with no prior concept mapping experience scored lower in the relational and higher SOLO levels compared to the groups that were exposed to concept mapping skills (Stewart, 2012). After assessing SOCMEs with the rubric informed by the SOLO taxonomy, we found that the majority of SOCMEs were on a low level of unistructural, multistructural and relational. Overall, students were able to add concepts and relationships within one or two subsystems. However, they found it more challenging to demonstrate relationships between concepts in all three subsystems (relational medium level on the rubric). Thus, revealing a possible link between the poor quality of linking words and propositions and the students' lack of prior concept-mapping experience.

We found that students could demonstrate concepts and connections on their SOCMEs and achieved LO2 and LO3 of the intervention. This agreed with the findings that Szozda et al. (2022) reported that all participants demonstrated components and connections on their systems thinking concept maps, even though in their study, the quality of concepts and connections was not studied. Students' demonstration of connections revealed that they could identify the concepts in the system and demonstrate *analysis: elements,* even though they did not report on developing this skill to a large extent in their reflections. Student's ability to identify the components of a system is an essential foundation that should be present before other high-order systems thinking skills are developed (Assaraf & Orion, 2005; York & Orgill, 2020). Assaraf and Orion also reported that even though a growing number of components revealed a growing number of connections, students still struggled to create an overall coherent network of relationships. This points to students' lack of integration skills, which will be discussed in the following section

6.2.3. INTEGRATION

Students were said to have developed *integration* skills if they could use their understanding and *analysis* skills to organize the system components and to put together the parts to describe the emergent properties, the cyclic behaviours, and the dynamic interactions with the system. Figure

6.4. shows how the focus has now zoomed out to a systems-level granularity. Given the cognitive challenge (Jacobson & Wilensky, 2006) of envisaging potential cyclic and emergent behaviours of LAS, some cyclic and emergent behaviour was taught and not prompted for or required in the expansion of the SOCME. Therefore, this discussion will focus on only two of the *integration* skills. The skills *integration: dynamic interactions* involve students' ability to identify and describe interactions within and between subsystems that can change over time (LO6). The skill *integration: organization* involves their ability to organise new system-level concepts in the whole system and identify the new subsystem boundaries (LO7).

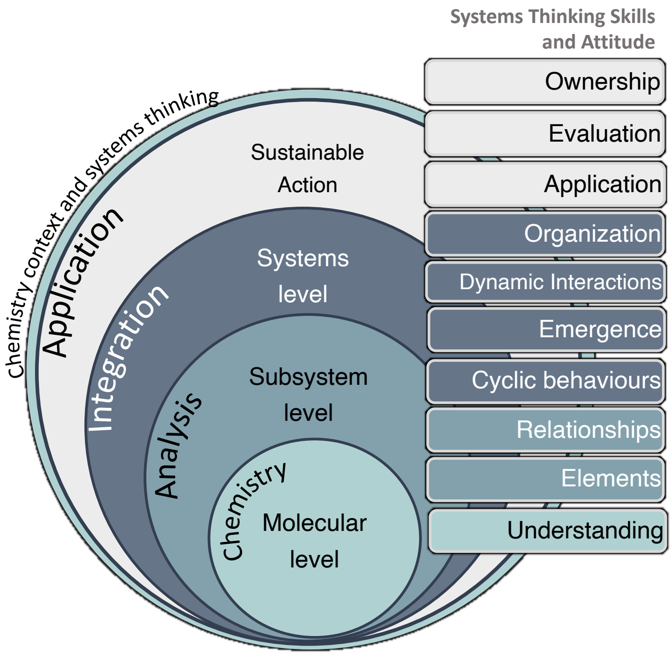


Figure 6.4. *Integration* on a systems level

DYNAMIC INTERACTIONS

Only one student reflected on learning about the complex interactions between subsystems from a broad perspective, which could have enabled them to recognize the dynamic interactions in the system. Few students reported learning about the time-dependent interactions within a subsystem or between subsystems in their reflections, indicating the skill developed to a lesser extent. Interestingly, coding the skill *dynamic: interactions* was challenging with a poor percent agreement of 11.2%, revealing that the independent coders interpreted this presence of the skill in students' reflections differently or did not code the skill in students' reflections. Not only was this difficult to analyse in students' self-reflections, but the interpretation of the skill contributed to disagreement during the analysis. If coders misinterpreted the terminology, then it is possible that students also found it challenging to understand. This could perhaps explain the unexpected high perception of achievement of this skill. Students' high perception of achievement was surprising as it has been identified in the literature as one of the most challenging systems thinking skills to develop, together with the ability to identify and examine cyclic and emerging behaviours (Jacobson & Wilensky, 2006). The high perception of achievement of *integration: dynamic interactions,* therefore, did not align with students' reflections, However, some students could have perceived to have achieved the skill as they engaged with variables that change over time during the first practical activity.

The lack of demonstration of dynamic interactions on the SOCMEs contradicted findings from students' perceptions. Most students indicated that they developed this skill and did not indicate it as the most or least challenging skill to demonstrate on the SOCME. This skill was partially demonstrated on SOCMEs as students added few connections between subsystems, with limited reference to change in time. These findings are not surprising as it is challenging to demonstrate "behaviour over time" skills as it requires an understanding of the system's nonlinearity that can influence system-level behaviour (Assaraf & Orion, 2005; Yoon et al., 2018; York & Orgill 2020). Most recently, it has been reported that students struggle to demonstrate patterns and factors that contribute to dynamic behaviour, potentially because students might not have sufficient prior experience working with complex dynamic systems (Szozda et al., 2022). Not only was it challenging for students to demonstrate the skill, but it was also challenging to analyse *integration: dynamic interactions* on SOCMEs from a researcher's perspective.

In summary, the systems thinking skill *integration: dynamic interactions* developed to a lesser extent in students, even though students perceived to have achieved the skill. Students' could have experienced it as challenging due to a lack of conceptual understanding, their inability to demonstrate the skill and their familiarity with thinking about linear cause-and-effect relationships between concepts without their dynamic interrelationships.

ORGANIZATION

Student reflections revealed that they understood the skill *integration: organization* required an understanding of the components and relationships that make up the system's structure. Most students perceived to have achieved *integration: organization*, even though they indicated that it was one of the most challenging skills to demonstrate on their SOCMEs. However, students' reflections showed that only two were developing this skill. Findings from rater feedback and content analysis of SOCMEs corroborated those from student reflections, revealing the lack of demonstration of *integration: organization.* This skill was only demonstrated on one SOCME, which had well-organized concepts and a creative new subsystem. The other SOCMEs indicated that students were developing this skill, but to a lesser extent, as concepts did not fit well into subsystems and new subsystems were not added or those added were not appropriate.

We found that students needed help to deal with the complexity of organizing concepts and relationships into existing and new subsystems. This finding seems to agree with Pazicni and

Flynn's prediction that students' ability to organize system components and processes will diminish as the number of concepts within the system increases (Pazicni & Flynn, 2019). Assaraf and Orion (2010) also reported a similar finding where learners struggled to process complex relationships and organize components within a system during a concept mapping intervention (Assaraf & Orion, 2010). During the focus group interviews, students reported that they found it easier to focus on isolated parts or subsystems to organize concepts and relationships into new and existing boundaries. This reveals that students preferred a reductionist approach to deal with the system's complexity and had to use their analysis skills to demonstrate *integration: organization.* This shows the value of scaffolding analysis skills so students can use them to organize the concepts and relationships within various subsystems. Students should also be explicitly taught how to demonstrate *integration: organization* skills. Students mentioned during the focus group interview that they could demonstrate the skill but need more practise as they have not had any exposure to systems thinking skills.

The findings from this study agree with Szozda's (2022) statement that it is essential to prompt and explicitly teach systems thinking terminology and skills to students so that they can demonstrate the breadth of connections and identify boundaries. It is also important to set system boundaries that limit cognitive load while ensuring the system boundaries are not too narrow to reduce the true complexity of the system under study (Pazicni & Flynn, 2019). If students receive adequate practise and become more familiar with examining the complex interconnections within a system, it could enhance their confidence in expressing their unique perspectives as they think outside the box to expand their SOCMEs.

In summary, we found that students were progressing in organizing system-level concepts within existing and new subsystem boundaries. The existing subsystem boundaries represented areas of focus in the societal, environmental, and economic contexts. Students experienced this skill as cognitively challenging and unfamiliar. However, progress has been made in developing this skill in such a short timeframe.

SUMMARY

Integrating concepts to understand the whole meaningfully is complicated by nature (Defever, 2015). Students struggled to demonstrate *integration: dynamic interactions* on their SOCMEs and *integration: organization*; however, both skills were developing in a few students. Evidence suggested that more students were developing *integration: organization* compared to *integration: dynamic interactions*. Even though it was challenging for students to deal with the discomfort, uncertainty, and complexity of demonstrating these *integration* skills, they perceived to have achieved them despite the challenges. However, from the lack of demonstration of these skills in the reflections or on the SOCMEs, their perceptions appear misguided.

6.2.4. APPLICATION

It was found that students developed *application* skills if they were able to evaluate the whole SOCME and use their *understanding*, *analysis* and *integration* systems thinking skills to make future predictions about the system (Figure 6.5).

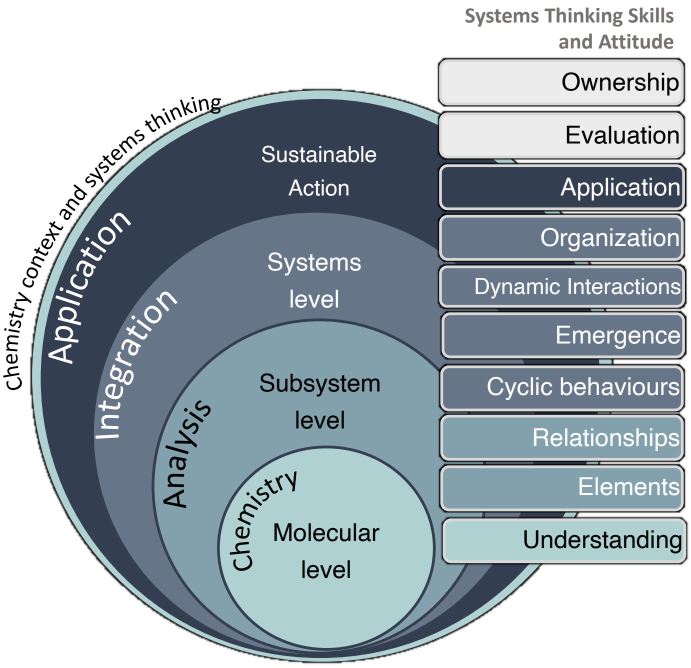


Figure 6.5. Understanding, analysis and integration required for developing the *application* skills

Overall, students perceived to have achieved *application: predictions* and indicated that the skill was neither the most nor least challenging to demonstrate on their SOCMEs. Findings from students' reflections revealed that they recognized LAS's potential positive and negative impacts on the system, which corroborates their perception of achievement. The limited mention of learning about making predictions agreed with evidence from SOCME content analysis, showing that none of the SOCME diagrams fully demonstrated *application: predictions*. Most of the students could add predictions to their SOCMEs, but they struggled to integrate concepts and connections across the whole SOCME. Rater feedback confirmed that students struggled to think creatively to make future predictions with their future prediction restricted answering discussion prompts. About half of the students, based on the strength of evidence, were developing a*pplication: problem-solving* skills. The development of *application: problem solving* skills were only observed in students' reflections as evidence from their perceptions and what they have demonstrated weren't prompted.

The lack of demonstration of *application* skills on students' SOCMEs was expected, as it can be a very challenging task to make predictions about future behaviours of a system under different conditions (Penner, 2000). York and Orgill et al. (2020) proposed that an attempt to predict future system-level behaviour could contribute to a better understanding of the system. This was observed in this study, even though students did not fully demonstrate their competence in making predictions. In this intervention, students learned about changing behaviours over time, the complex interconnectedness of the system, and how to problem-solve and think creatively. In such a short timeframe, meaningful progress was made in developing students' *application* skills and their understanding of systems thinking.

In summary, we found that students were making progress in developing *application* skills as they were able to make future predictions about the system of LAS. Students struggled to integrate their predictions across all the subsystems fully. Only a few students reported on developing *application: creativity* skills in their reflections, which complements the evidence that it was only demonstrated on one SOCME diagram, with the addition of a new subsystem. Since we did not expect this skill to emerge from the data, no perceptions from students about it were available for comparison.

6.2.5. EVALUATION AND OWNERSHIP

The systems thinking skills *evaluation* and the attitude *ownership* appeared mostly as students reflected on their learning during the intervention. The evidence suggested that students were gaining a deeper understanding of the topic of surfactants and were developing an attitude of *ownership* as they recognized the real-world implications of chemistry and the role of chemistry in future sustainability as well as their role. Therefore, students were said to have developed an attitude of ownership if they were able to use their understanding of the chemistry on a molecular level and of the chemistry context on a systems level together with their systems thinking skills to take sustainable action as shown in Figure 6.6.

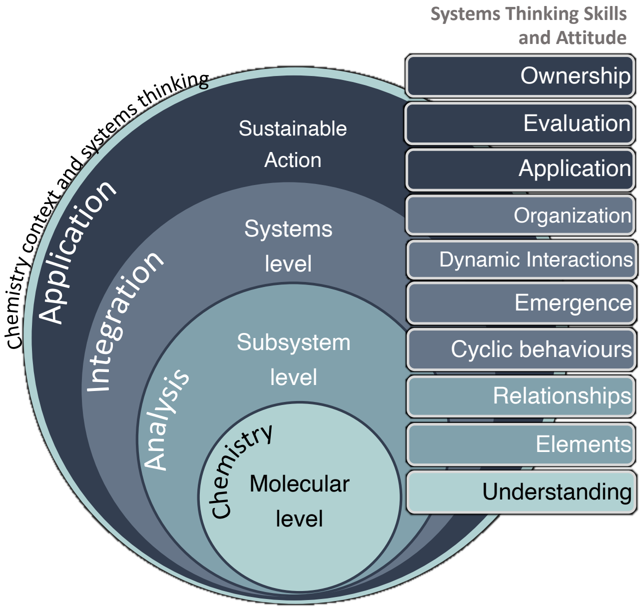


Figure 6.6. Systems thinking skill *evaluation* and attitude of *ownership* for sustainable action

Evaluation: deeper engagement skills include “critical thinking” characteristics identified by students. *Evaluation: conducting research* includes students’ ability to source information to make judgments and informed decisions. Students claimed to have developed both *evaluation* skills in their reflections, where *evaluation: deeper engagement* developed to a larger extent. These findings cannot be triangulated as students’ perceptions of *evaluation* skills and their demonstration thereof were not assessed due to the unsuitability of the analysis methods. Since it emerged from students’ reflections, we found that the skill *evaluation: deeper engagement* co-occurred with many other systems thinking skills that students also reported developing in the intervention. A network diagram was created on Atlas.ti, shown in Figure 6.7., to reveal the reflections providing evidence of developing *evaluation: deeper engagement* and its co-occurrence with other systems thinking skills.

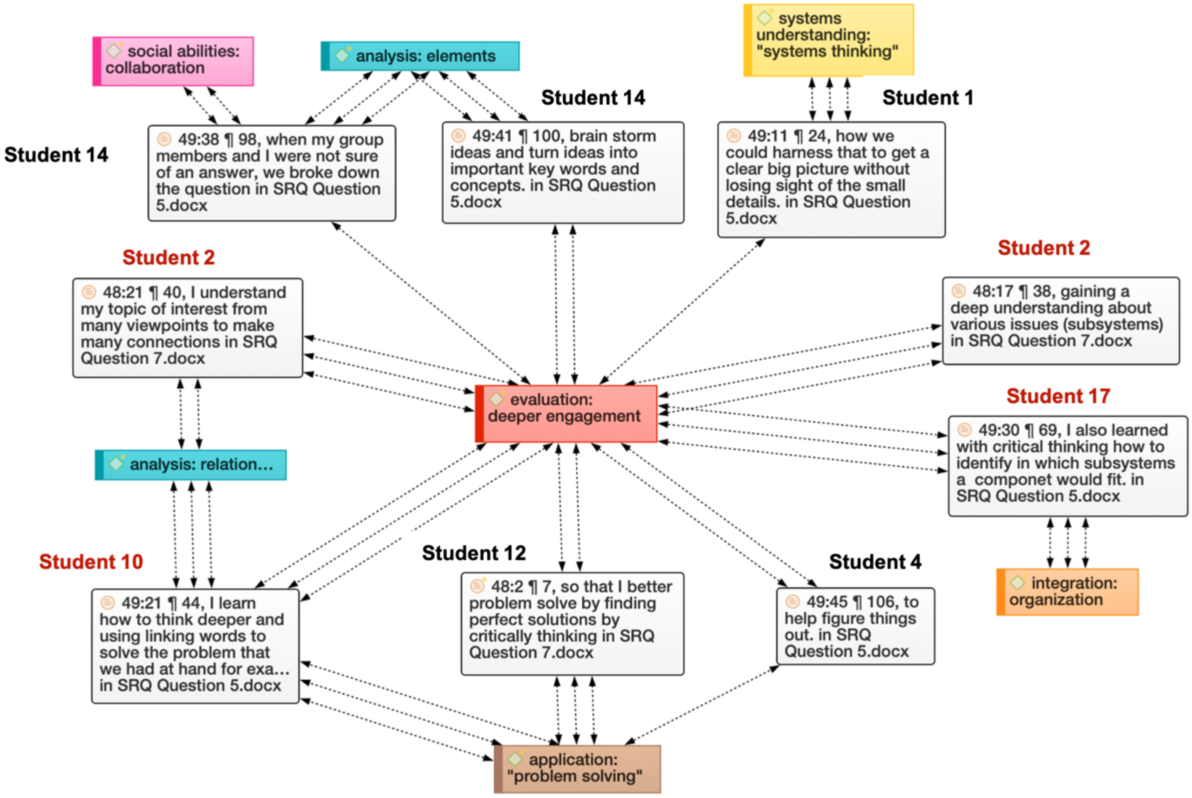


Figure 6.7. Atlas.ti network showing code co-occurred with *evaluation: deeper engagement*

The skill *evaluation: deeper engagement* co-occurred with students’ *systems understanding* of *“systems thinking”, analysis, integration, application skills and social abilities.* Students’ reflections revealed that three students, students 2, 17 and 10, were developing *evaluation: deeper engagement* skills. These students also reflected on learning about the system's elements and relationships, organizing components within subsystems and problem-solving skills.

Taking ownership encompasses changing one's thinking and making informed decisions that could contribute towards addressing future sustainability challenges. This attitude was not expected to develop in such a short time frame. Nevertheless, students perceived to have developed an attitude of *ownership: future improvement* and reflections revealed their intentions to take sustainable action. Their reflections and perceptions revealed that about half of the students developed this attitude, whereas only some developed *ownership: challenge recognition*. We found that students who claimed to have gained an attitude of *ownership: future improvement* also developed other systems thinking skills based on credible and strong evidence, including *evaluation: conducting research,* as well as an understanding of the system, specifically the chemistry context, For *ownership: challenge recognition* students recognized how difficult it is to find a balance between the complex relationships between subsystems, how one component could influence other components in the system and how as humans we tend to focus more on the benefits of chemistry and less on its consequences. Students' reflections revealed that *ownership: challenge recognition* developed with a systems understanding.

Students did not reflect on what they could do to make the chemistry of surfactants more sustainable, even after being taught about the way forward in the take home message video. Perhaps students' needed to be prompted more in this regard. Szozda et al. (2022) also found that the students who constructed a systems thinking concept map in chemistry could indicate connections between chemistry and other contexts but did not include human connections to the underlying chemistry. Therefore, students must be asked to reflect on how they can take ownership to alter chemistry for sustainability.

In summary, students made progress in developing *evaluation: deeper engagement and ownership: future improvement,* as they evaluated the system on a deeper level to understand better the role and implications of chemistry in various subsystems and their role to take sustainable action. Even though students did not reflect on their role in the underlying chemistry, the evidence revealed that some students could have developed a sustainable action perspective. This will be discussed further to answer the second research question of this study.

6.3. RESEARCH QUESTION 2: SUSTAINABLE ACTION PERSPECTIVE

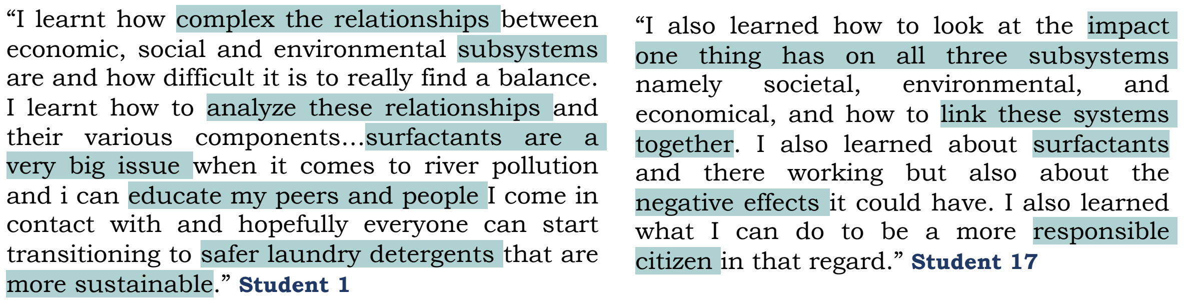
This section will discuss the second research question, which asked what evidence suggested that students were developing a sustainable action perspective. Talanquer (2019) described a sustainable action perspective as the ability to analyse complex interactions between human and earth systems critically and to engage in responsible action toward global sustainability. In this study, students' intentions to take sustainable action were analysed to understand whether they were developing a sustainable action perspective. Students were considered to be developing a sustainable action perspective if they:

i) reported on learning about the complex interactions or interconnections in a system, which relates to a *systems understanding: "systems thinking"* ,

ii) developed a *systems understanding* of the real-world implications of chemistry or surfactants based on credible and strong evidence for *systems understanding: chemistry context, and*

iii) indicated a willingness adjust their behaviour i.e. developed an attitude of taking ownership, based on credible and strong evidence, indicating *ownership: future improvement.*

We found that two students out of eleven developed a sustainable action perspective. These students gained a deeper understanding of the complex interconnections within the system and the implications of surfactants or chemistry. They also reported on what they would do to make better-informed decisions to take sustainable action. These responses, unprompted in question 5, are shown in Figure 6.8. below.

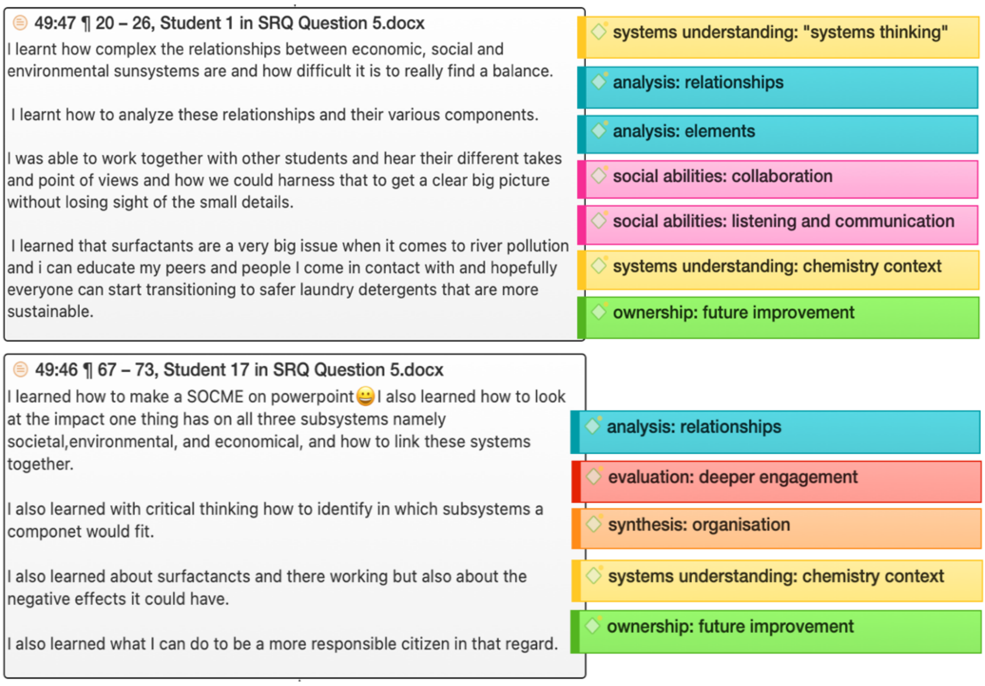


"I learnt how complex the relationships between economic, social and environmental subsystems are and how difficult it is to really find a balance. I learnt how to analyze these relationships and their various components…surfactants are a very big issue when it comes to river pollution and i can educate my peers and people I come in contact with and hopefully everyone can start transitioning to safer laundry detergents that are more sustainable." **Student 1**

"I also learned how to look at the impact one thing has on all three subsystems namely societal, environmental, and economical, and how to link these systems together. I also learned about surfactants and there working but also about the negative effects it could have. I also learned what I can do to be a more responsible citizen in that regard." **Student 17**

Figure 6.8. Students' responses revealing the development of a sustainable action perspective

As shown in Figure 6.8. student 1 gained an understanding of the *"complex relationships between the economic, societal and environmental subsystems"* whilst acknowledging the real-world implications of chemistry. They reported that *"surfactants are a very big issue"* and were inspired to take sustainable action by educating others to use more sustainable laundry detergents. Student 17 gained an understanding of the *"impact of one thing" on "all three subsystems"* and how they are connected, as well as about the "*negative effects"* of surfactants and what they can do going forward to "*be a more responsible citizen"*. Both students gave these reflections in question 5, hence they were not prompted to reflect on taking sustainable action. We also found that these two students developed other systems thinking skills. Figure 6.9. shows the reflection excerpts and the skills that were coded on Atlas.ti with strong and credible strength of evidence.



49:47 ¶ 20 – 26, Student 1 in SRQ Question 5.docx

I learnt how complex the relationships between economic, social and environmental sunsystems are and how difficult it is to really find a balance.

I learnt how to analyze these relationships and their various components.

I was able to work together with other students and hear their different takes and point of views and how we could harness that to get a clear big picture without losing sight of the small details.

I learned that surfactants are a very big issue when it comes to river pollution and i can educate my peers and people I come in contact with and hopefully everyone can start transitioning to safer laundry detergents that are more sustainable.

systems understanding: "systems thinking"
analysis: relationships
analysis: elements
social abilities: collaboration
social abilities: listening and communication
systems understanding: chemistry context
ownership: future improvement

49:46 ¶ 67 – 73, Student 17 in SRQ Question 5.docx

I learned how to make a SOCME on powerpoint😀I also learned how to look at the impact one thing has on all three subsystems namely societal,environmental, and economical, and how to link these systems together.

I also learned with critical thinking how to identify in which subsystems a componet would fit.

I also learned about surfactancts and there working but also about the negative effects it could have.

I also learned what I can do to be a more responsible citizen in that regard.

analysis: relationships
evaluation: deeper engagement
synthesis: organisation
systems understanding: chemistry context
ownership: future improvement

Figure 6.9. Students' responses revealing the development of a sustainable action perspective

Both students developed a *systems understanding: chemistry context*, demonstrated *analysis: relationships* skills and developed an attitude of *ownership: future improvement*. Student 1 also developed *social abilities* and reported learning *analysis: elements* skills, whereas student 17 developed *integration: organization* and *evaluation: deeper engagement* skills. Students did not reflect on learning about LAS's physical and chemical properties. However, they developed an understanding of systems thinking and the chemistry context that enabled them to see the system's interconnectedness that could have motivated an attitude of ownership. These students, together with many others that reflected on taking ownership, are likely to act responsibly for a sustainable future as they reflected on the chemistry context and interconnectedness of chemistry. Wheeler and Bijur (2012) stated that students are more likely to appreciate and act responsibly to ensure a sustainable future if they develop a deeper understanding of the interconnectedness of systems through chemistry (Wheeler & Bijur, 2012). The process of developing systems thinking skills in students can contribute significantly to improving their deeper understanding of chemistry concepts (Vachliotis, Salta, & Tzougraki, 2021).

This study showed, from the implementation of the intervention, that there were four levels of students' development towards taking sustainable action. These levels included an understanding of chemistry and its context, *analysis* skills to take the complex system apart, *integration* skills to put the parts back together in an organized manner to visualize the whole system with all its interconnections and an attitude of taking ownership. Ownership is a prerequisite for taking sustainable action. It is the highest level of development towards a sustainable action perspective, as Talanquer calls it, that we hoped to achieve in this intervention. Other skills, such as *evaluation*, allowed students to engage on a deeper level with the content and to conduct research. The skill s*ocial abilities: collaboration* developed the most in students. Students' ability to apply their understanding allowed them to move between different granularity levels and develop a systems thinking perspective to make predictions and solve complex problems. These skills make up the foundation for taking sustainable action. Taking action has been said to require a foundation of building knowledge, cognitive skills and social abilities (Taimur & Sattar, 2019). Together with systems thinking, collaboration, critical thinking and problem-solving skills are key competencies for ESD (Taimur & Sattar, 2019; Wiek et al., 2011; Zoller, 2012).

Critical reflection in this intervention allowed students to create meaning and conceptualize their experiences, which enhanced their learning experience about systems thinking. Mezirow (1990) stated that reflection is not about simply stopping to think, plan or problem-solve for future action based on what you have learned, but it is about critically questioning the learning experience for better meaning-making (Mezirow, 1990). Students' ability to reflect on their learning allowed them to take a step back, visualize the system of LAS with its complex interconnections, and think critically about its implications and role in society, the environment, and the economy. This reflective attitude and questioning norms and practices puts critical thinkers in a position to take sustainable action (Taimur & Sattar, 2019). This aligns with the advocated critical reflexive approach to chemical thinking and action which includes a critical consciousness, critical literacy, and critical agency (Sjöström & Talanquer, 2018). Therefore, the scaffolding provided during this intervention helped guide students' critical reflections, which could have contributed to developing sustainable action perspectives in first-year chemistry students.

6.4. CONCLUDING REMARKS

To understand the a fuller picture of the system thinking understanding, skills and attitude that were developing throughout the intervention, only pieces of each perspective that provided trustworthy findings could have been put together. Figure 6.10 illustrates the summarized findings in an attempt to answer the first research question. The circles and skills that are coloured in darker shades indicate that more students developed these skills during the intervention. The lighter or white shaded areas indicate that these skills developed to a lesser extent, however might indicate progress made. The evidence taken from different snapshots suggested, especially in such a short timeframe, that meaningful progress was made in students' ability to develop systems thinking skills and a sustainable action perspective.

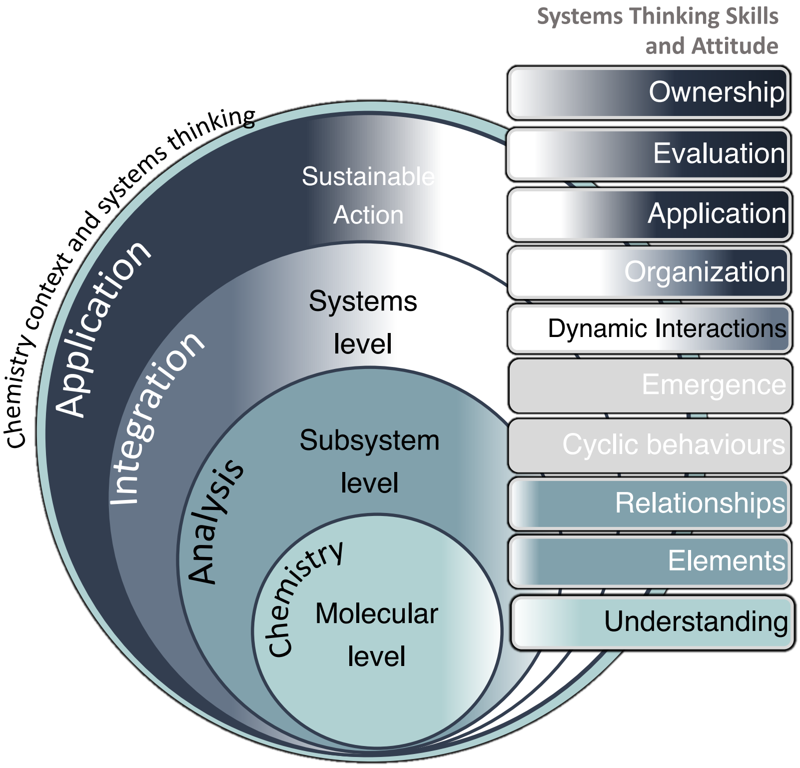


Figure 6.10. Summary of the systems thinking skills that were developing in first-year chemistry students

Although this study did not actively assess students' understanding of the chemistry, it was inferred that students understood the chemistry content presented in the absence of any evidence to the contrary. It was evident that most students developed a *systems understanding*, which allowed them to view the chemistry in context. Most students also developed *analysis* skills, which enabled them to identify concepts and connections that were relevant to the system. Fewer students developed *integration* and *application* skills, where more evidence was collected from students perceptions, reflections and demonstrations for *integration* skills in comparison to *application* skills. Students made progress in developing *integration: organization*, *application: predictions and application: problem solving skills, where integration: dynamic interactions* were developing the least if at all. Integration skills are cognitively challenging skills as seen from students' perception, reflection and demonstration due to students' lack of familiarity and practise with these systems thinking skills. Since *integration* skills are embedded into *application* skills, the lack thereof can limit students' ability to apply their understanding and systems thinking skills to visualize the complex interconnections and real-world implications of chemistry and recognize their role in sustainable action. Nevertheless, students reported that they have gained a deeper understanding of the system (*evaluation: deeper engagement*) and reported on what they would do going forward to take sustainable action. Two students out of eleven developed a sustainable action perspective, which encouraged some students to learn chemistry more deeply as they recognized the real-world implications of the system of LAS and their role in sustainable action.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1. INTRODUCTION

This chapter will provide an overview of the study and a summary of the findings that contributed to answering research questions 1 and 2 regarding the evidence that suggested that systems thinking skills and a sustainable action perspective were developing in first-year chemistry students. After that, the implications of this study on future research in Systems Thinking in Chemistry will be discussed, with a summary of the study's validity, reliability and rigour and possible areas for further research. This chapter will then provide recommendations for teaching and assessing systems thinking based on findings from this intervention. This will be followed by the contributions and significance of this study and concluded with an overall reflection of the researcher.

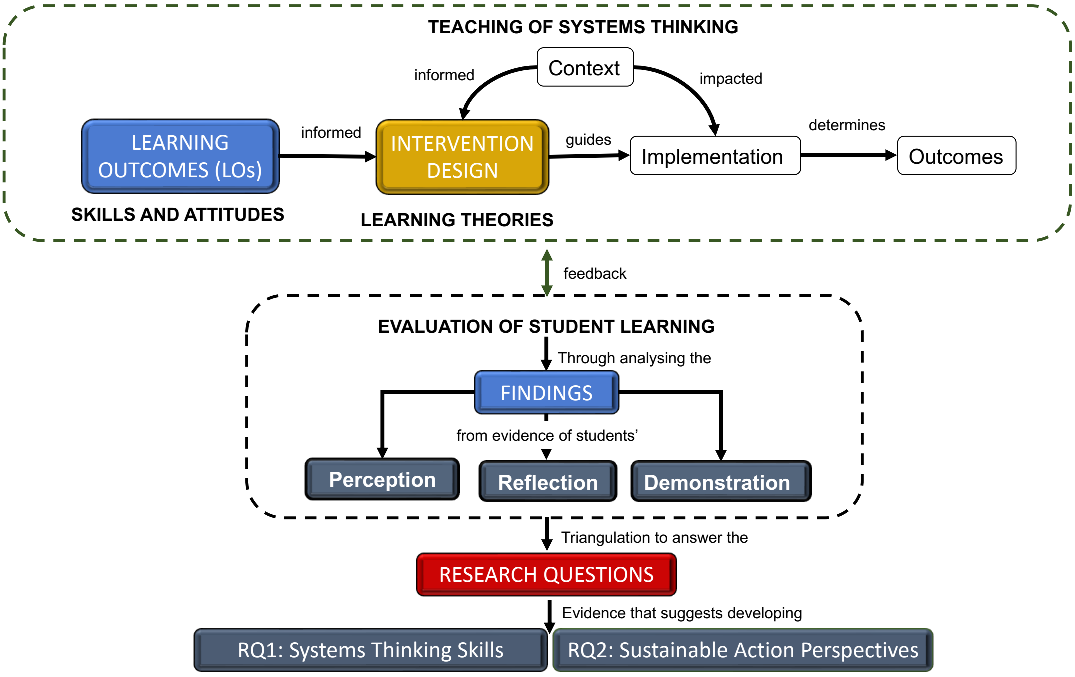


Figure 7.1. Overview of Chapter 7

7.2. OVERVIEW OF THE STUDY

To address the emerging global sustainability challenges, scientists framed an action plan prompting a call for integrating a systems thinking approach in chemistry education to prepare systems thinkers who can significantly contribute to sustainability. However, the systems thinking teaching and assessment resources to facilitate the development of systems thinking skills are limited. Therefore, this project developed useful teaching and assessment resources to stimulate the growth of systems thinking in first-year chemistry. These resources included activities that scaffolded the development of systems thinking with visualization tools. Concept maps, expanded concept maps, and System-Oriented Concept Map Extension (SOCME) diagrams were used to enable students to visualize the hidden dimensions of the system and the real-world implications of chemistry in society, economy and environment. The system under consideration included interacting subsystems influenced by the molecule Linear Alkylbenzene Sulfonate, an anionic surfactant used commonly in laundry detergents. The research questions probed for evidence that students developed systems thinking skills and a sustainable action perspective. A mixed-methods research design was used to collect data from students' perceptions, reflections, and demonstrations to create a complete picture of the understanding, skills, and attitudes that students were developing throughout the systems thinking intervention. Students' perceptions were analysed from questionnaire data and focus group interviews to understand their achievement of systems thinking skills and what skills were most challenging to demonstrate as they expanded their SOCMEs and why. Students' reflections from a questionnaire were analysed to understand what students have learned during the intervention. Lastly, students' systems thinking skills on their SOCMEs were analysed quantitatively from rubric scores and qualitatively from content analysis and rater feedback. Findings from these three perspectives were compared in a concurrent triangulation design to enrich and validate the findings. We concluded from this study that the intervention facilitated the development of systems thinking skills and inspired a sustainable action perspective as students engaged deeply with the relevant topic of surfactants.

7.3. SUMMARY OF FINDINGS

In this section, the findings that emerged from the study to answer the two research questions will be presented below.

7.3.1. RESEARCH QUESTION 1

The first research question asked which systems thinking skills were developing in first-year chemistry students as they engaged in a systems thinking intervention. We found that most students developed a *systems understanding* and *analysis* skills from the designed intervention in this study. The majority of the students' claimed to have gained an understanding of the context of the chemistry with its role and real-world implications in various subsystems and gained *analysis: elements* and *analysis: relationships* skills as they identified and elicited the relevant concepts and connections within the system. Students were developing *integration* and *application* skills to a lesser extent. Students made progress in developing *evaluation: deeper engagement* and an attitude of *ownership: future improvement.* These findings are promising given the cognitive complexity associated with systems thinking and the short timeframe in which the intervention was implemented to develop systems thinking understanding, skills and attitudes.

7.3.2. RESEARCH QUESTION 2

The second research question probed for evidence that suggests a sustainable action perspective was developing in first-year chemistry students. The systems thinking skills that were developing in students, as reported to answer research question one, were used as part of the evidence to answer this research question. To claim that a student was developing a sustainable action perspective, they must have gained some systems thinking skills and an attitude of taking ownership. Developing a *systems understanding* to recognize the complex interconnections in the system and the real-world implications of chemistry and *ownership: future improvement* can help students recognize their role in sustainable action. Students' reflections were the only evidence that revealed the co-occurrence of these skills and their development from a holistic perspective. Evidence from perceptions and demonstrations could not be used to get a complete picture of the development of a sustainable action perspective. The evidence obtained from students' reflections revealed that two students were developing this perspective and also developed other skills identified as key competencies of education for sustainable development. Therefore, evidence from students' reflections provided a more complete picture to understand the growth of a sustainable action perspective.

7.4. LIMITATIONS OF THE STUDY

It is challenging to investigate the reality of students systems thinking learning within a limited time frame. The evidence presented in this study is limited in that it only presents parts of the complete picture of the understanding, skills and attitudes that students were developing during this study. Critical decisions had to be taken during the planning of the study to contain its scope. The research questions informed these decisions, and they, in turn, informed the types and extent of data that would be collected to answer the research questions. The limited scope of the study would inevitably limit the comprehensiveness of the findings that can be obtained. The pragmatic approach adopted in this study, allowed for the use of multiple different perspectives, however it has limited the depth of findings one would obtain from a particular lens. Drawing onto many different frameworks made it more challenging to make confident claims about the evidence of systems thinking understanding, skill and attitude development.

The systems thinking learning could have been limited as a result of the short timeframe in which the intervention was implemented, Indeed, developing systems thinking skills is a gradual process that cannot be fully demonstrated in a short timeframe. Also, as a result, boundaries had to be drawn to minimize cognitive overload and the complexity of some systems thinking skills as students participated in the intervention. We acknowledge that narrow boundaries were drawn around the systems thinking skills *chemistry understanding*, *integration: dynamic interactions*, *integration: emergent behaviours* and *integration: cyclic behaviours*. For this reason, these skills were explicitly taught, where the hidden dimensions of the system adopted a Johnstone's triangle interpretation and the emergent behaviours arose from chemical phenomena. It is also, for this reason that this study was considered a pilot to understand the zone of proximal development of first-year chemistry students.

The limitations associated with the conclusions drawn from this study include the inability to make confident claims based on the strength of evidence of all the developing systems thinking skills, as all the skills were not present in students' reflections, perceptions and demonstrations. Therefore, comparing skills development from each perspective was challenging as some skills emerged from reflections that were not present in students' perceptions or demonstration of skills. Findings from students' reflections regarding the strength of evidence, should also be considered with care as the same coders used to verify the trustworthiness of the codebook, was used to determine the strength of evidence. Therefore, the disagreement of coders for skills discussed in the section on the trustworthiness of the codebook has made triangulation of findings challenging. There might also be shortcoming in students' perceptions as their conceptual understanding of each systems thinking skill asked in question 2, 3 and 4 in the self-reflection questionnaire weren't adequately probed for. It is possible that students' demonstration of skills were influenced by their technical competence in SOCME construction, their unfamiliarity with the visualization tool and possible cognitive load. It was also challenging to make confident claims about the skills developing from SOCME scores derived from the rubric due to the need for more consistency in grading the higher SOLO levels for each SOCME. It was challenging to make conclusions regarding the reliability of the rubric due to the limited number of SOCMEs that were assessed, the limited number of raters and the limited time raters were exposed to developing systems thinking skills themselves.

7.5. IMPLICATIONS FOR FUTURE RESEARCH

This study incorporated the STH model to sequentially scaffold the development of systems thinking skills based on level of challenge. However, the use of this model and the scaffolding of skills step-wise does not necessarily mean that the order in which the skills were scaffolded was from least challenging to most challenging. This study acknowledges that even though the learning was scaffolded in Piagetian-like stages, it does not mean that students' systems thinking skills also developed in such a linear and hierarchical manner. The skill development of first-year chemistry students could have been fragmented, web-like, and dynamic (Schenck & Cruickshank, 2015). Students could have also developed analytical and holistic systems thinking skills simultaneously as on an analytical-holistic continuum. Therefore, future research can explore how students develop systems thinking skills in more depth.

Future research can explore evidence in depth from one perspective or lens to reduce the complexity of analysis and to avoid implicit gaps and overlaps in theoretical underpinning. Future research in terms of students' demonstration of systems thinking skills can explore using the reliability of the rubric with more adequately equipped raters who assess many different SOCMEs. Efforts must be made to reduce the influence of possible confounding factors, which include students familiarization with systems thinking visualization tools, explicit probing for their understanding of systems thinking skills and their expectancy to obtain the right answer. Other existing frameworks, methods and visualization tools can be used to investigate systems thinking skill development. Some of these can include investigating students reasoning abilities, using network motifs, a granularity scale and an environmental and sustainability triangular model (Szozda et al., 2022). Future research could also explore methods of data analysis that are in line with a systems thinking approach to better understand the evidence of students' systems thinking development.

Further research can explore different systems thinking assessment and or analysis tools. The SOLO taxonomy could be used to analyse the learning quality based on the complexity level present in students' self-reflections. Analysing students' critical reflections can more profoundly explore the development of a sustainable action perspective. The research question could ask:

i) What is the value of assessing students' critical reflections with the SOLO taxonomy to understand the development of a sustainable action perspective?

Another area of research could be focused on exploring the development of creativity in chemistry using systems thinking visualization tools. One can explore whether students' creativity was constrained with a partial SOCME and how creative thinking in chemistry can be encouraged. This research question could ask:

ii) How can systems thinking visualization tools be used to enhance creative thinking in chemistry?

Lastly, future research could explore whether similar findings were attained regarding the development of systems thinking skills and a sustainable action perspective after the intervention has been implemented on a large scale in a face-to-face setting. This research question could ask:

iii) What systems thinking learning gain was achieved when the intervention was implemented face-to-face on a large scale?

7.6. RECOMMENDATIONS

The following section aims to share valuable insights that have been gained during this study from a teacher's perspective. The implications and recommendations for teaching and assessing future systems thinking interventions will be discussed.

7.6.1. TEACHING SYSTEMS THINKING

SOCMEs are useful visualization tools that can facilitate the development of systems thinking skills in first-year chemistry students from a molecular-level foundation to sustainable action. The visualization tools used in this intervention can be used by students to move between different levels of granularity. We recommend that lecturers explicitly prompt students to revisit the molecular level of granularity so that students can evaluate the role of chemistry in various subsystems and their role in becoming responsible citizens for future sustainability. Self-reflection should be an essential part of the learning process as it can allow students to take control of their learning and develop a sense of ownership.

SOCMEs can also be used as a tool to provide formative feedback to students to teach them how to apply systems thinking skills and thereby reduce expectation uncertainties. Even though, SOCMEs can be used as pedagogical tools with appropriate facilitation, not all the systems thinking learning can be elicited on a SOCME diagram or assessed by the SOCME rubric. Therefore, analysis of the SOCME as an "end-product" of the learning will not provide a complete picture of all the understanding, skills and attitudes students were developing. We suggest that the sustained integration of systems thinking concepts and scaffolding systems thinking skills would benefit from more tools than only SOCMEs. We also propose that these tools should be used over a longer timeframe to expose students to systems thinking throughout a module or undergraduate year.

SOCMEs can also teach students how to deal with the complexity of systems using a zoom-in and-out approach. We recommend that lecturers prompt students to zoom into a particular subsystem at a time to view the relevant concepts, connections and relationships before considering other subsystems. This could contribute to reducing cognitive overload experienced by students as they engage with unfamiliar systems thinking skills and visualization tools. Students' lack of quality in connections, linking words and propositions demonstrated in this study revealed students' lack of concept mapping skills. We suggest exposing students' to concept mapping skills before embarking on this intervention. The zoom-in and out strategy and concept mapping experience could reduce the cognitive overload and challenge associated with demonstrating systems thinking skills, enhancing students' confidence and creative thinking abilities.

Since students experienced *integration* skills as the most challenging systems thinking skills to demonstrate, we recommended that lecturers teach these skills explicitly so that students become more familiar with applying these skills. We also recommend that lectures expose students to the two-dimensional character of systems thinking. This can enable students’ to use both their *analysis* and *integration* skills to evaluate a system as a whole and not just as a collection of parts. Students can experience developing systems thinking skills as challenging, so lecturers should be aware that developing these skills is a process that takes time. We recommend that lecturers adapt the teaching materials and their scaffolding based on the needs of their students and their zones of proximal development.

7.6.2. ASSESSING SYSTEMS THINKING

It was evident from this study that raters needed to be more competent in assessing systems thinking skills demonstrated on SOCMEs, perhaps as they have not had much exposure to systems thinking themselves. Therefore, raters should be adequately trained to develop systems thinking skills and to assess these skills demonstrated on SOCMEs. We recommend that raters should assess several SOCMEs and then engage in discussions about scores to enhance the consistency in grading amongst all the raters before continuing with the grading process for large groups. As a first attempt at assessing systems thinking from SOCME diagrams, the rubric was useful in driving systems thinking learning. The rubric also enabled the formative assessment of SOCME diagrams and identifying areas that require future attention in teaching and assessment systems thinking. Even though the SOCME rubric, informed by the SOLO taxonomy, included aspects to assess the quality of demonstrated skills, we suggest that raters provide summaries of their observations to lecturers so that a better understanding can be gained regarding the quality of what students have demonstrated and the skills they were developing.

7.7. CONTRIBUTIONS AND SIGNIFICANCE OF THE STUDY

The lack of systems thinking teaching and assessment resources has contributed to the lack of its implementation in chemistry education. This study has contributed towards developing useful teaching and assessment resources to stimulate the growth of systems thinking in first-year chemistry students. These activities were designed to show students the role and real-world implications of laundry detergents in South Africa. Teaching students about LAS's role and real-world implications have encouraged them to learn chemistry more meaningfully. The material created aligned with the first-year organic chemistry curriculum and was adapted for curriculum transformation towards relevant chemistry education. The purpose of the teaching materials was to move away from a reductionist approach to chemistry education and towards a more holistic approach where the real-world implications of chemistry are embedded into the curriculum to prepare a generation of systems thinkers that can potentially contribute to the future of sustainability in science. Students’ willingness to embrace the complexity of learning about systems thinking revealed eagerness to move away from a fragmented approach to chemistry education.

This study provided evidence that using scaffolding with visualization tools, such as concept maps and SOCMEs can be useful in developing students' systems thinking understanding, skills and attitude. Using concept maps and SOCMEs to scaffold the learning allowed students to move between different levels of granularity, which enabled a balance of the systems thinking learning with learning about chemistry. Evidence revealed that students engaged on a deeper level on the topic of surfactants and were eager to revisit the chemistry after visualizing the context of the chemistry on a SOCME diagram. Thus, the intervention fostered the development of systems thinking in chemistry, which revealed that significant progress was made to develop systems thinking given the limited exposure students had to the topic.

The scaffolding from a molecular-level foundation to ownership has contributed to developing a sustainable action perspective in at least two first-year chemistry students, which revealed that progress was made in preparing students to deal with local and global sustainability challenges. Apart from developing systems thinking skills, students also gained *evaluation*, *problem-solving* and *collaboration* skills from this study, which revealed their progress in developing some of the key competencies identified in Education for Sustainable Development. Therefore, this study has shown that introducing STICE can prepare citizens with sustainable action perspectives that are willing to engage in problem-solving for global sustainability after evaluating the impacts and interrelationships between humans, chemistry and the environment.

This study also contributed to addressing the gap in the evaluation of systems thinking. An assessment tool that can be used to assess SOCME diagrams and to drive the learning of systems thinking in chemistry was developed, which has never been reported before. Also, this study has contributed to possible analysis techniques that the chemistry education research community can use to analyse thinking development from multiple sources of evidence, including reflections, perceptions and demonstrations on SOCMEs.

7.8. REFLECTION OF THE RESEARCHER

As a researcher, my desire to investigate pieces of evidence to create a picture of the truth has always been embedded in my character. On my research journey throughout this study, I realised that I had to learn how to become comfortable dealing with complexity. Embarking on systems thinking research required hours of just thinking, working through the challenges to tell a story about developing and evaluating systems thinking in first-year organic chemistry. I realised that I required systems thinking skills to integrate the evidence collected in this study and analyse it from multiple perspectives to get a snapshot of students' experiences and systems thinking development. Investigating possible answers to the research questions that guided this study required analysis skills to break the complex reality of students' learning into smaller digestible pieces. It then required integration skills to organize these pieces to formulate a more complete picture. After that, I engaged deeply with the findings to communicate this research's value in preparing systems thinkers for local and global sustainability.

As a teacher, I also had to adopt a systems thinking perspective to understand how we can prepare a generation of systems thinkers in chemistry in the best possible way. This approach has dominated most of my thinking and writing as I constantly reflected on how this research can be used in my journey as a teacher. I believe that I am a teacher at heart and therefore found it challenging to switch between a researcher's and teacher's perspective, especially because a large component of this research was focused on teaching systems thinking. This research study has completely changed my teaching approach and inspired me to develop more systems thinking teaching materials like the ones used in this intervention. This project enabled me to enrich my teaching approach, to follow my passion and to inspire students to consider careers in chemistry as responsible citizens of society.

A quote from Marcus Honeysett described my whole experience as a researcher and teacher during this study. He said that "the quest for authenticity demonstrates a desire to invest in things that are true and worthwhile." (Honeysett, 2002, p. 60). It was a challenging journey, but it was worthwhile as the pieces of evidence of students' experiences were used to tell a story with integrity that revealed valuable truths that has changed my teaching approach and can potentially redirect the future of chemistry for the benefit of our society.

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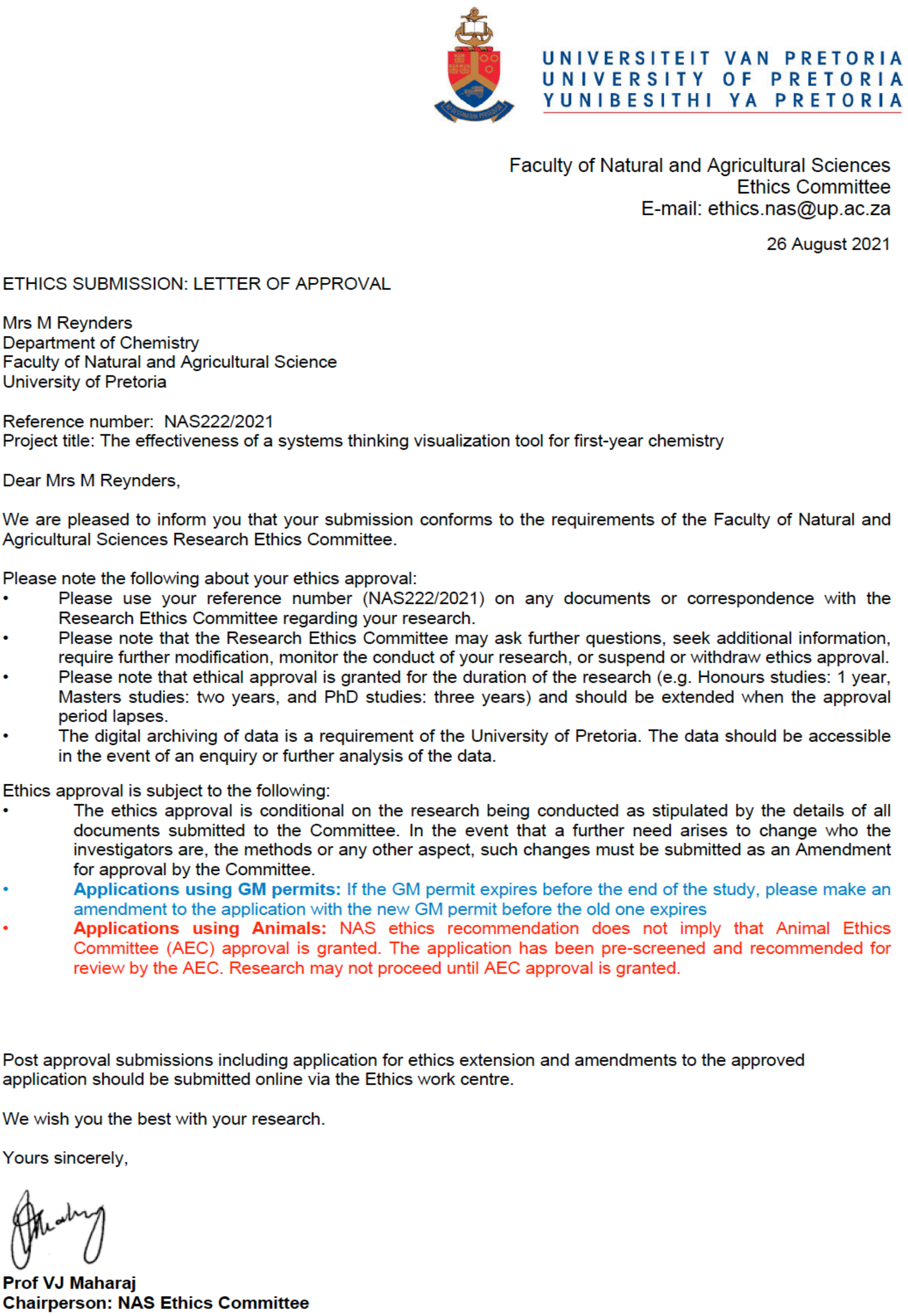
APPENDIX A: ETHICAL CLEARANCE

A1. ACCEPTANCE OF ETHICS COMMITTEE



UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Natural and Agricultural Sciences
Ethics Committee
E-mail: ethics.nas@up.ac.za

26 August 2021

ETHICS SUBMISSION: LETTER OF APPROVAL

Mrs M Reynders
Department of Chemistry
Faculty of Natural and Agricultural Science
University of Pretoria

Reference number: NAS222/2021
Project title: The effectiveness of a systems thinking visualization tool for first-year chemistry

Dear Mrs M Reynders,

We are pleased to inform you that your submission conforms to the requirements of the Faculty of Natural and Agricultural Sciences Research Ethics Committee.

Please note the following about your ethics approval:

- Please use your reference number (NAS222/2021) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, monitor the conduct of your research, or suspend or withdraw ethics approval.
- Please note that ethical approval is granted for the duration of the research (e.g. Honours studies: 1 year, Masters studies: two years, and PhD studies: three years) and should be extended when the approval period lapses.
- The digital archiving of data is a requirement of the University of Pretoria. The data should be accessible in the event of an enquiry or further analysis of the data.

Ethics approval is subject to the following:

- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.
- **Applications using GM permits:** If the GM permit expires before the end of the study, please make an amendment to the application with the new GM permit before the old one expires
- **Applications using Animals:** NAS ethics recommendation does not imply that Animal Ethics Committee (AEC) approval is granted. The application has been pre-screened and recommended for review by the AEC. Research may not proceed until AEC approval is granted.

Post approval submissions including application for ethics extension and amendments to the approved application should be submitted online via the Ethics work centre.

We wish you the best with your research.

Yours sincerely,

Prof VJ Maharaj
Chairperson: NAS Ethics Committee

APPENDIX B: ARTICLE UNDER REVIEW

Teaching and assessing systems thinking in first-year chemistry

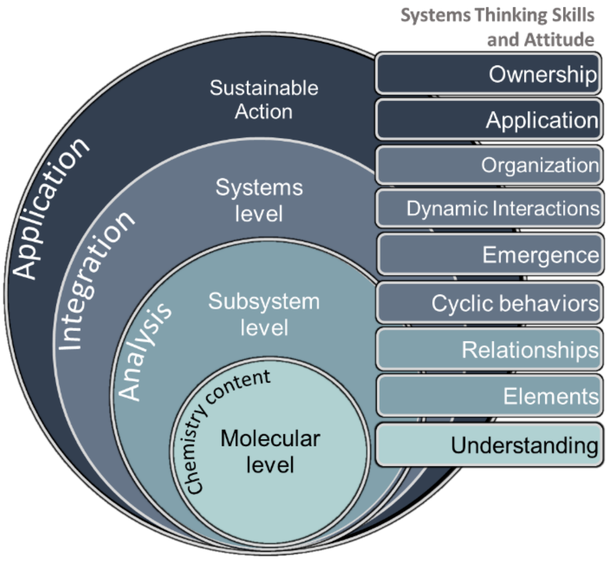
Micke Reynders, Lynne A Pilcher*, and Marietjie Potgieter

Department of Chemistry, University of Pretoria, Pretoria, Gauteng, South Africa

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 of 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 (Mahaffy, Matlin, et al., 2019b). 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) (York et al., 2019). Recent IUPAC-funded projects have sought to promote the introduction of STICE,(IUPAC, 2020) the first of which culminated in a special issue of this journal in 2019 showcasing such initiatives in the field (Mahaffy, Brush, et al., 2019). 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 (Mahaffy, Matlin, et al., 2019b). Concept mapping is an effective tool to develop and assess students' ability to organize concepts and identify interrelationships (Ruiz-Primo & Shavelson, 1996; Stewart, 2012). Concept maps can reveal the knowledge and skills that students gained as their construction promotes the engagement and processing of content (Hall & O'Donnell, 1996; Wheeldon & Faubert, 2009).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 (Aubrecht et al., 2019). SOCMEs aid in visualizing the complexity of increasing interconnectedness between concepts, which is a key feature of systems thinking (Aubrecht et al., 2019). 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 (Brandstädter et al., 2012; Stewart, 2012; Tripto et al., 2013; York et al., 2019). 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” (Novak, 1990). 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 (Biggs, 1982). 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 (Biggs, 1982).This taxonomy, called the Structure of the Observed Learning Outcomes (SOLO), characterizes learning according to the "quality of assimilation in terms of progressive structural complexity" (Biggs, 1982). The SOLO taxonomy can assess learning quality from surface learning to deep learning in five stages based on the level of complexity demonstrated. These stages are known as SOLO levels and each SOLO level has sub-levels. The SOLO levels assess learning quality from structural (pre-structural, unistructural, multistructural) to relational and then extended abstract (Biggs, 1982).

Martyn 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 (Stewart, 2012). Vogelzang et al.(Vogelzang et al., 2020) 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 (Stewart, 2012) and Biggs et al. (Biggs, 1982) 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

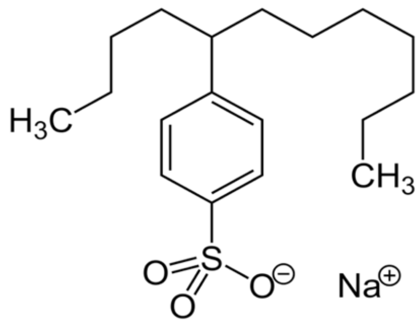
Visualizing the complexity within a system requires the ability to "understand the multi-level structure" of various components and processes (Hmelo-Silver & Azevedo, 2006). However, the multi-level structure of a system can be viewed on several scales of granularity ranging from a molecular to a macroscopic, 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 (Orgill et al., 2019). 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 et al.(Pazicni & Flynn, 2019). 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 expand 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 (Novak & Cañas, 2008).

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.(Mahaffy, Matlin, et al., 2019b; Pazicni & Flynn, 2019).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 et al.(Assaraf & Orion, 2005), and York et al.'s ChEMIST table of systems thinking characteristics.(York & Orgill, 2020)

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 the system-level concepts and processes relevant to a system
3	Identify and illustrate the relationships between system level 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, 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” (Talanquer, 2019). 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.

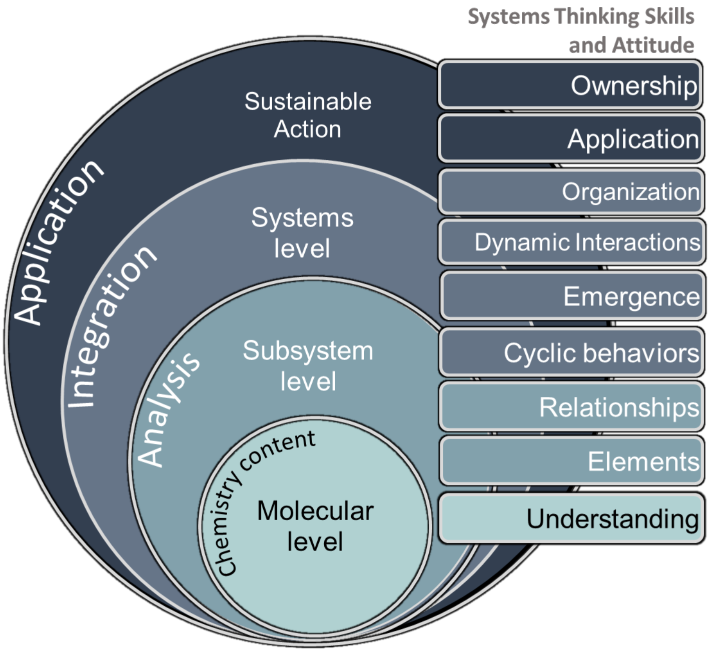


Figure 2. Hierarchical scaffolding of systems thinking skills from a molecular level foundation to sustainable action

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, but 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 1500 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 introductory activities to enhance group dynamics.

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 they can take sustainable action and a self-reflection questionnaire. Figure 3 provides a schematic representation of the sequence of events during the two sessions.

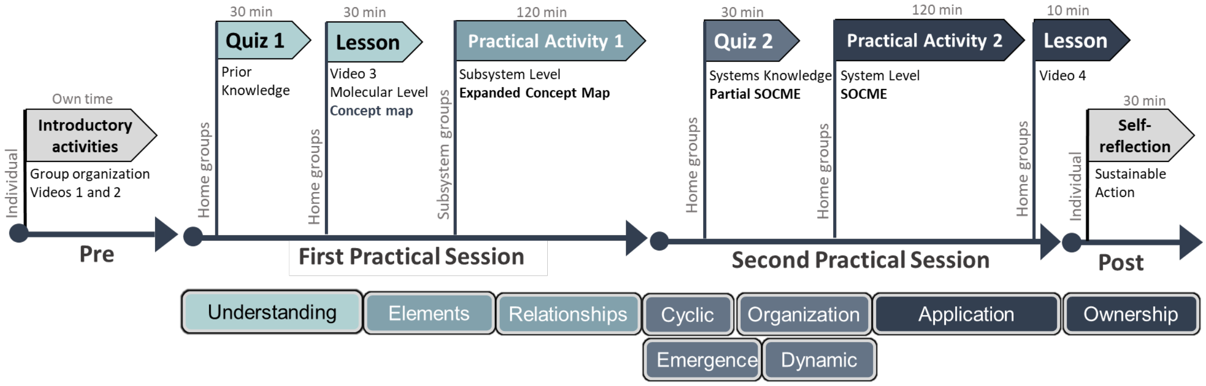


Figure 3. Sequence of activities during the intervention with the ST skills targeted and scaffolded in each activity

Design for cooperative learning

The activity used a jigsaw cooperative learning approach, (Aronson, Blaney, Stephan, Sikes, & Snapp, 1978) 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 et al.(Assaraf & Orion, 2005) and Yoon et al.(Yoon et al., 2018) 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.

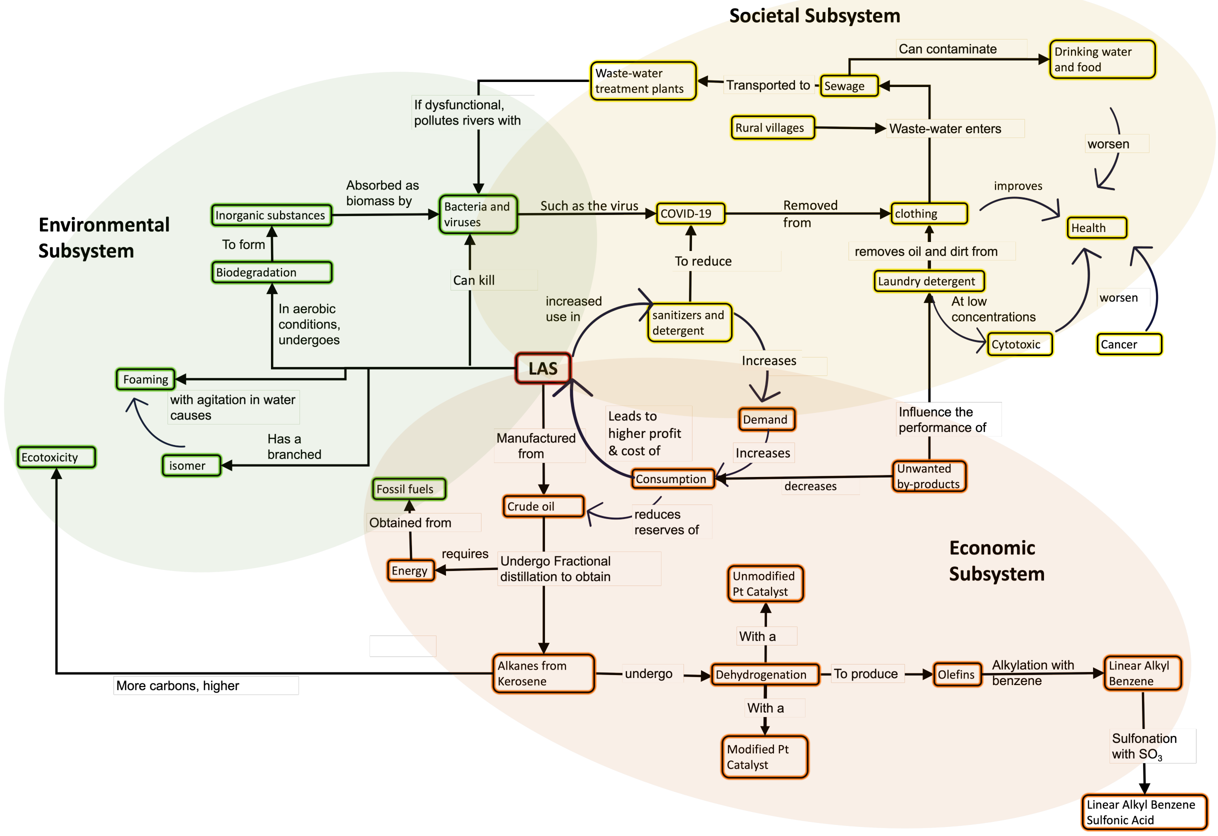


Figure 4. Partial SOCME concerning Linear Alkylbenzene Sulfonate.

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.” (Biggs, 1982). 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 (Biggs, 1982).

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	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	Analysis: relationships
	Medium	Connections between concepts within all three subsystems	10	
	High	Connections within AND between subsystems	10	Integration: dynamic interactions
Extended abstract		Organize concepts into subsystems and add new subsystems	10	Integration: organization
		Apply knowledge holistically to make future predictions	8	Application

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, demonstrating analysis and integration skills to understand the interactions of LAS within and between various subsystems. 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. 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).

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 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 practical sessions that spanned two weeks and that took approximately 6 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. The final mark for 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: relationships* 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.

The average score assigned to this SOCME by three independent raters is 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.

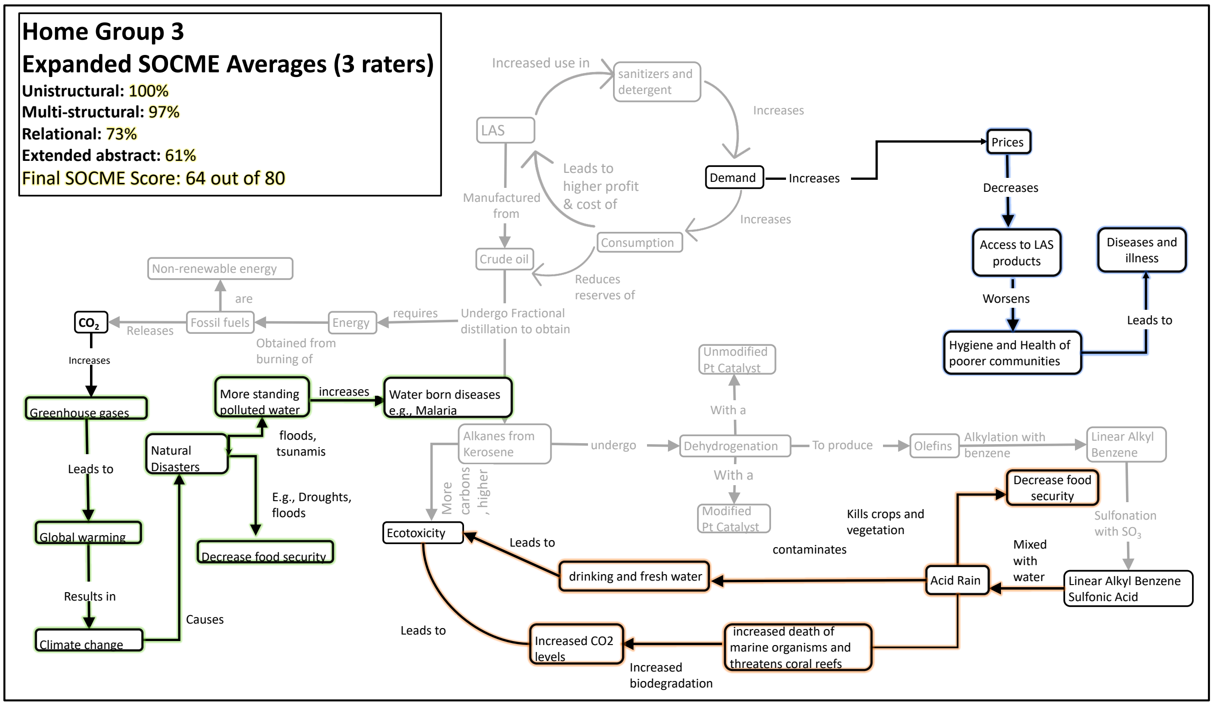


Figure 5. Evidence of an expanded partial SOCME submitted by home group 3. This figure includes a component of the partial concept map that students received as the shaded part (Figure)

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, and demonstrating *integration: dynamic interactions*, *integration: application,* and *integration: organization* skills on the SOCME were 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 (İlhan & Gezer, 2017). 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.(İlhan & Gezer, 2017) For the SOLO taxonomy the inter-rater reliability is the most important measure to understand the consistency of grading amongst raters (Biggs, 1982). 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, with 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 5) 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.

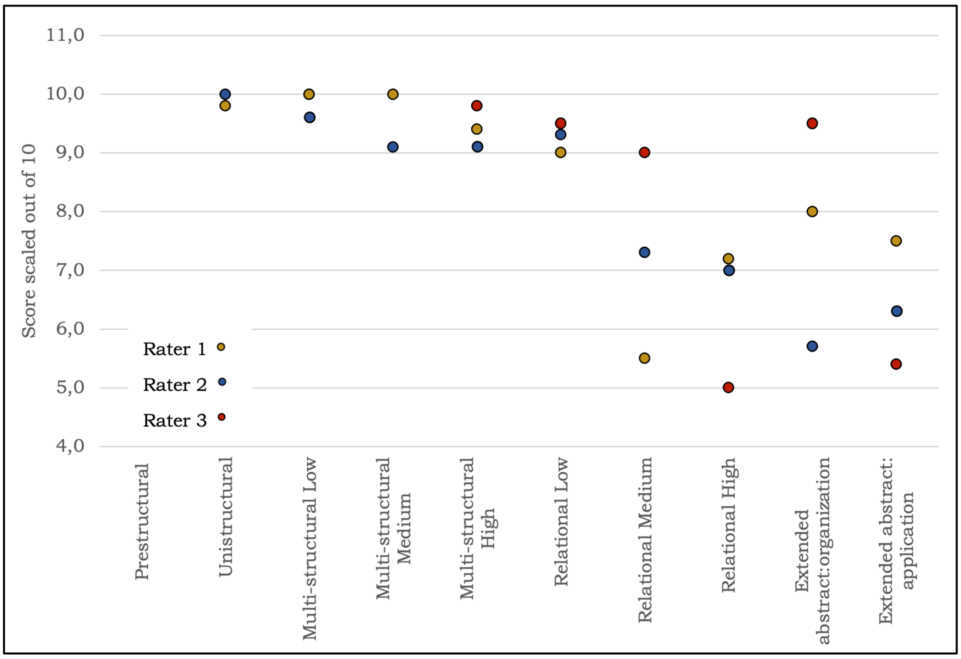


Figure 5. Average SOLO level scores from six SOCME diagrams assessed by three independent raters

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 (Stellmack, Konheim-Kalkstein, Manor, Massey, & Schmitz, 2009). Teachers' unfamiliarity with SOLO based rubrics can result in lower inter-rater reliability (Chan et al., 2002; Leung, 2000). This could be addressed by making the rubric more explicit and by providing better systems thinking training to the raters to ensure they are familiar with using 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 or 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 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

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX. [ACS will fill this in.]

Chemistry Themes and Design principles (.docx)

Rater Training Manual and SOCME Assessment Rubric (.docx)

Proof of Ethical Clearance (.pdf)

Activity Resources

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)

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)
- Practical Activity 2 Expansion of SOCME(.pptx)
- Self-reflection Questionnaire (.docx)

Additional Resources

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

Concept maps and SOCME diagrams

- Core Chemistry Concept Map (.pptx)
- Expanded Concept Maps (.pptx)
- Partial SOCME (.pptx)

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APPENDIX C: SYSTEMS THINKING ACTIVITIES

C1. ALIGNMENT WITH PHYSICAL AND ORGANIC CHEMISTRY THEMES

Table C1. Physical and Organic Chemistry themes aligned with the surfactant (LAS) systems thinking activities

Chemistry Theme	Chemistry Knowledge	Systems knowledge
Homogenous and Heterogeneous Mixtures	The polarity of oil, water, and LAS The density of oil and water	• How surfactants work in laundry detergents to remove oil and dirt particles from clothing in the presence of water (emergent behavior)
Physical properties of substances	Amphiphilic structure of LAS	• Use of LAS in sanitizers and its ability to destroy the lipid-bilayer of Covid -19
	Surface tension	• How surfactants cause foaming
	Concentration	• LAS at non-cytotoxic concentrations and colon cancer • Critical Micelle Concentration and Foaming • Lethal concentration (LC_{50}) and Ecotoxicity • LAS concentration and Biodegradation
	Solubility of LAS and long chain hydrocarbons	• LAS in wastewater absorbed by crops and in the drinking water of rural areas • Bioavailability and sorption into organic matter
Chemical properties of substances	Acidity and basicity (pH) of LAS	• Ecotoxicity of LAS
Intermolecular Forces	London dispersion forces Dipole-dipole IM forces	• The energy required in fractional distillation
Ionic salts and solubility	Inorganic salts (phosphates, sulfates)	• Biodegradation • Eutrophication
Acid-base chemistry	Neutralization with NaOH	• Industrial manufacture of LAS
	Conjugate acid-base pairs	• Biosurfactants
Rates of reaction	Modified Platinum Catalysts	• Platinum reserves in South Africa • Hazards of Heavy metals
	Selectivity	• Waste • Detergency Performance • Market demand and consumption
	Yield	• Large-scale production of LAS
Hybridization and bonding	Saturation of hydrocarbons Bond rotation and energy barriers	•
Skeletal structures	IUPAC naming	•
Isomers	Branched alkyl benzene sulfonates (BAS)	• Foaming • Detergency power
Hydrocarbons	Alkane chain length	• Cytotoxicity
Fractional distillation	The boiling point of crude oil fractions Intermolecular forces Volatility	• Fossil fuels • Non-renewable energy • CO2 emissions and global warming

	The molar mass of LAS	
Functional groups	Alkanes Alkenes Aromatics Sulfonic acid	
Organic reactions	Dehydrogenation	• Industrial manufacture • Modified and unmodified Platinum Catalysts
	Alkylation with benzene	• Carcinogenic reagents
	Sulfonation	• Acid rain • Acid spill • Corrosive reagents
	Synthesis	• Principles of green chemistry • Atom economy • Waste reduction • Renewable feedstock • Safer solvents • Pollution prevention • Biodegradability • Energy efficiency

C2. SELF-REFLECTION QUESTIONNAIRE

Dear students,

Thank you for participating in this research project! Your time and effort are greatly appreciated! I truly hope that you have enjoyed the learning experience about systems thinking in chemistry. This questionnaire is only a reflection on what you have learned and aligns with the fifth learning outcome of practicals 4 and 5, which is as follows:**Describe** what you can do to ensure you apply your systems thinking skills and take sustainable action as a responsible citizen and future scientist. After watching the take-home message video, please take 20 minutes of your time to answer the following questions as you reflect on your participation in the surfactant project. **Take Note**: Your response to this questionnaire will remain anonymous if reported and demographic and institutional data are kept confidential. The information won't be shared with anyone outside of the project. This questionnaire is voluntary, and you are free to opt-out without being penalized.

Question 1:

Identify the most important chemical properties and behaviour of linear alkylbenzene sulfonate that contribute to its value in our economy, its health impacts in our society, and environmental consequences throughout its life cycle from crude oil to ultimate biodegradation.

Question 2

Which of the systems thinking skills do you feel you have successfully achieved during practicals 4 and 5? (tick the applicable boxes)

- ○ The ability to identify the components of a system and processes within the system

○ The ability to identify relationships among the system’s components
○ The ability to identify dynamic relationships within a system
○ The ability to organize the system’s components and processes within a framework of relationships
○ The ability to understand the cyclic nature of systems
○ The ability to make generalizations
○ The ability to identify the hidden dimensions of the system (intermolecular forces, surface tension, molecular geometry, acidity, and basicity, nucleophilicity, solubility, polarity)
○ Thinking temporally: retrospection and prediction

<u>Question 3</u>

Which of these skills did you find the most challenging during the construction of your SOCME diagram? (tick the applicable boxes)

○ The ability to identify the components of a system and processes within the system
○ The ability to identify relationships among the system’s components
○ The ability to identify dynamic relationships within a system
○ The ability to organize the system’s components and processes within framework of relationships
○ The ability to understand the cyclic nature of systems
○ The ability to make generalizations
○ The ability to identify the hidden dimensions of the system (intermolecular forces, surface tension, molecular geometry, acidity, and basicity, nucleophilicity, solubility, polarity)
○ Thinking temporally: retrospection and prediction

<u>Question 4</u>

Which of these skills did you find the least challenging during the construction of your SOCME diagram? (tick the applicable boxes)

○ The ability to identify the components of a system and processes within the system
○ The ability to identify relationships among the system’s components
○ The ability to identify dynamic relationships within a system
○ The ability to organize the system’s components and processes within a framework of relationships
○ The ability to understand the cyclic nature of systems
○ The ability to make generalizations
○ The ability to identify the hidden dimensions of the system (intermolecular forces, surface tension, molecular geometry, acidity, and basicity, nucleophilicity, solubility, polarity)
○ Thinking temporally: retrospection and prediction

Question 5

A student that did the aspirin practicals, asks you to briefly explain what skills (systems thinking, communication, technological, problem solving, creativity, etc.) and understanding you have gained in these practicals. What would you tell the student to answer their question?

Question 6

How can the chemistry and engineering of alkylbenzene sulfonate be altered to ensure sustainable manufacturing, minimal environmental consequences, and safe but effective detergents for household use?

Question 7

What would you do as a responsible citizen and an upcoming scientist from here on forward to ensure you apply systems thinking in your daily life and take sustainable action after participating in these practicals?

Question 8

Which of the following components did not work well for you during practicals 4 and 5? (tick the boxes)

○ The pre-recorded videos
○ The introductory home group activities
○ The group work (home groups and subsystem groups)
○ The group roles
○ The live practical sessions
○ The quizzes
○ The practical activities
○ Constructing a SOCME diagram on PowerPoint
○ Communication with tutors or instructors
○ Other

Question 9

For the ticked boxes in question 6 and the “other” option, please explain in your opinion why these components did not work well?

Question 10

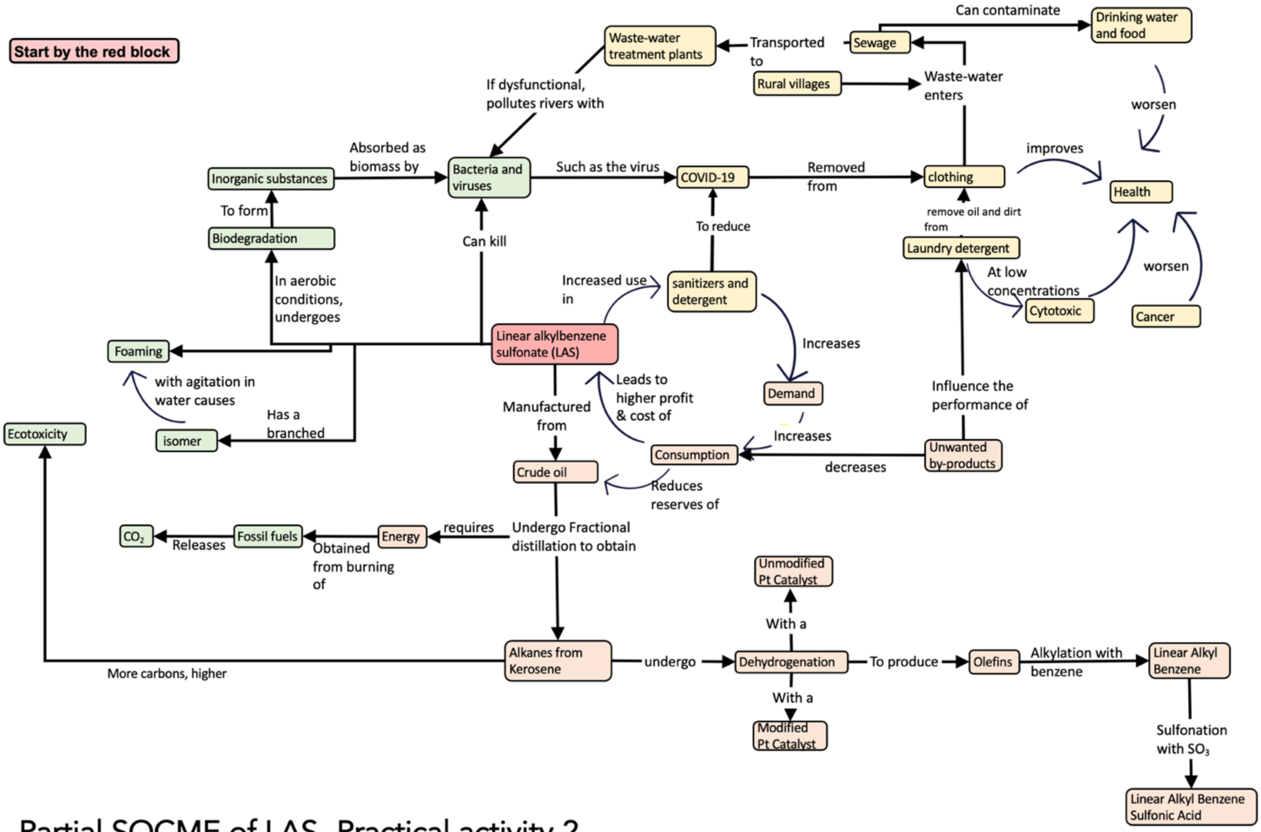
Provide any suggestions for practicals 4 and 5, that might improve the effectiveness of learning about systems thinking in chemistry?

C3. RATER TRAINING MANUAL AND SOCME RUBRIC

Dear tutors,

Before you can use the rubric, please read the terminology below for a better understanding of certain concepts:

Term	Description
Concept	An idea in the form of one or two words placed in a block
Connection	Represented by an arrow and indicates a relationship between two concepts
Linking word	Words written on arrows to describe a connection or relationship
Proposition	Are units of meaning when two concepts are linked to create a meaningful sentence
SOCME	System Oriented Concept Mapping extension, which is an extended concept map focused on systems knowledge
SOLO Taxonomy	The structure of observed learning outcomes taxonomy is a model that describes levels of increasing complexity in students understanding
Level of a SOLO rubric	Can either be pre-structural, unistructural, multi-structural, relational, or extended abstract
Sublevel of a SOLO rubric	Can either be low, medium, or high



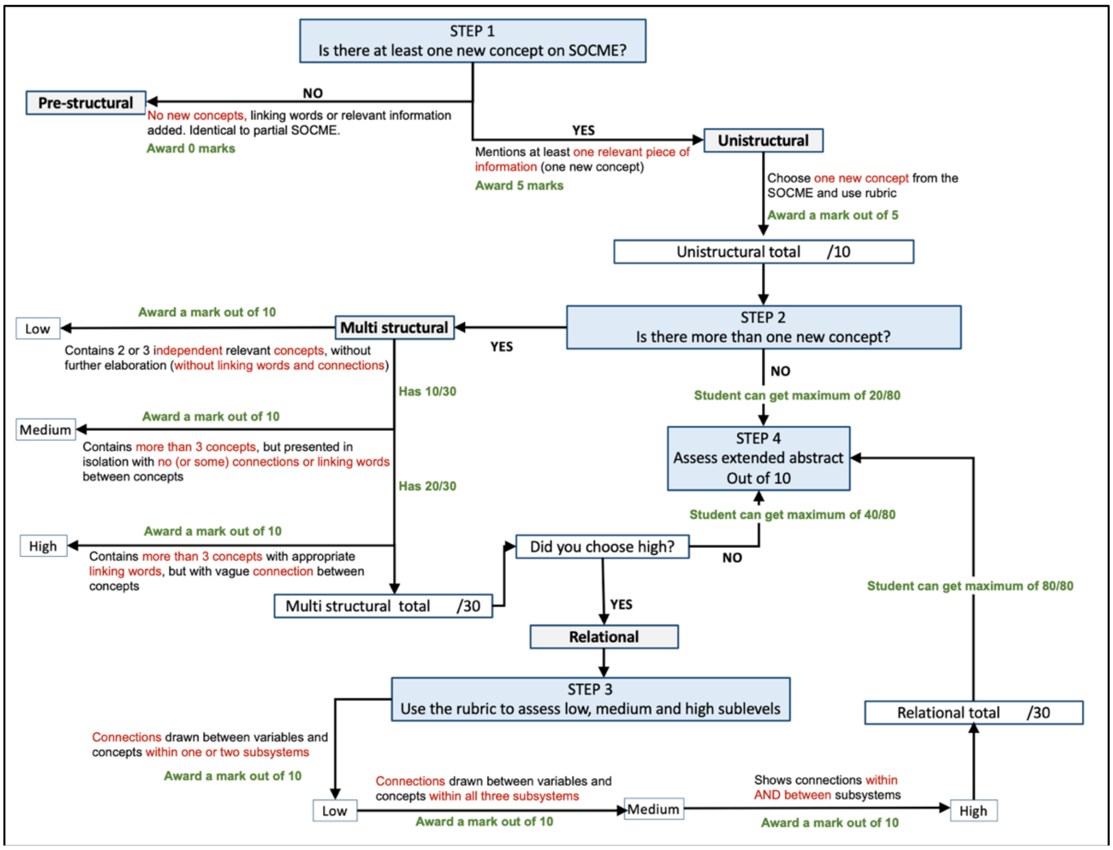
Partial SOCME of LAS- Practical activity 2

You will assess new concepts and linking words added to this partial SOCME:

SOLO TAXONOMY RUBRIC (SHORT VERSION)

SOLO level	Sub-level	Description of student responses	Score	Examples of verbs students illustrate
Pre-structural		No new concepts, linking words, or relevant information were added and SOCME looks like the original provided partial SOCME.	0	
Unistructural		Mentions at least one relevant piece of information (one new concept)	10	Identify, name, recall, state
Multi-structural	Low	Contains only 2 or 3 new independent relevant concepts, without further elaboration (without linking words and connections)	10	Combine, describe, classify
	Medium	Contains more than 3 new concepts, but is presented in isolation with no (or some) connections or linking words between concepts	10	
	High	Contains more than 3 concepts with appropriate linking words and connections between concepts	10	
Relational	Low	Connections are drawn between variables and concepts within one or two subsystems	10	Analyse, apply, argue, compare, relate, contrast
	Medium	Connections are drawn between variables and concepts within all three subsystems	10	
	High	Shows connections within AND between subsystems	10	
Extended abstract		At the extended abstract level, students can generalise, make predictions, and organize systems components to understand the whole system	10	Create, formulate, reflect, generalise, predict, evaluate

SOLO RUBRIC CHART



Sub Level	**Description of Level**	**Description of mark**	**Mark**	**Tick**	**Total**
	No new concepts, linking words, or relevant information were added and SOCME looks like the original provided partial SOCME.	Give 0 if no new concepts are shown and SOCME looks like the provided SOCME (see appendix A)	0		0
	Mentions at least one relevant piece of information (one new concept)	You can give 5 marks if one new concept is shown on the ma	5		/5
		Assess **one new concept** on the SOCME and give a score out of 5 for the following:			
		The word added is a concept and not a linking word	1		
		The new concept added is relevant (relates to surfactants and linear alkylbenzene sulfonate)	1		
		The concept fits into the subsystem	1		
		The concept is in the correct format (in a block, appropriate font, size, colour)	1		
		It is organized well in the SOCME	1		
				Total	/10
Low	Contains only 2 or 3 new independent relevant concepts, without further elaboration (without linking words and connections)	You can give 5 marks for showing only 2-3 new independent relevant concepts	5		/5
		Assess **all the newly added concepts** and give a score out of 5 for the following:			
		The words added are concepts and not linking words	1		/5
		The new concepts added are relevant (relates to surfactants and linear alkylbenzene sulfonate)	1		
		The concepts fit into the particular subsystem	1		
		The concepts are in the correct format (in a block, appropriate font, size, colour)	1		
		Concepts are organized well in the SOCME	1		
Medium	Contains more than 3 new concepts, but is presented in isolation with no (or some) connections or linking words between concepts	You can give 5 marks for showing more than 3 new concepts with no (or some) connections	5		/5
		Assess **all the newly added concepts** and give a score out of 5 for the following:			
		The words added are concepts and not linking words	1		/5
		The new concepts added are relevant (relates to surfactants and linear alkylbenzene sulfonate)	1		
		The concepts fit into the particular subsystem	1		
		The concepts are in the correct format (in a block, appropriate font, size, colour)	1		
		Concepts are organized well in the SOCME	1		

High	Contains more than 3 concepts with appropriate linking words and connections between concepts	You can give 5 marks for showing more than 3 new concepts with connections	5		/5
		Assess **all the newly added concepts** and give a score out of 5 for the following:			
		3 new concepts are linked to given concepts or new concepts with linking words to form a proposition	1		/5
		The new concepts added are relevant (relates to surfactants and linear alkylbenzene sulfonate)	1		
		The concepts fit within the particular subsystem	1		
		The concepts are in the correct format (in a block, appropriate font, size, colour)	1		
		Concepts are organized well in the SOCME	1		
				Total	/30
Low	Connections are drawn between variables and concepts within one or two subsystems	You can give 5 marks for showing at least 1-2 valid connections between concepts with one or two subsystems	5		/5
		Assess **a proposition within one subsystem and give a** score out of 5 for the following:			
		Relevant connection	1		/5
		Appropriate linking words	1		
		Connects within the subsystems	1		
		Good format (font, size, colour)	1		
		Can be read as a proposition or a feedback loop	1		
Medium	Connections are drawn between variables and concepts within all three subsystems	You can give 5 marks for showing connections and concepts within all three subsystems.	5		/ 5
		Assess **a different proposition within one subsystem and give a** score out of 5 for the following:			
		Relevant connection	1		/5
		Appropriate linking words	1		
		Connects within subsystems	1		
		Good format (font, size, colour)	1		
		Can be read as a proposition or feedback loop	1		
High	Shows connections within AND between subsystems	You can give 5 marks if connections are shown within and between subsystems	5		/5
		Assess **all proposition between subsystems and give a** score out of 5 for the following:			
		Relevant connection	1		/5
		Appropriate linking words	1		
		Connects between subsystems	1		
		Good format (font, size, colour)	1		
		Can be read as a proposition or feedback loop	1		

				Total	/ 30
	At the extended abstract level, students can generalise, make predictions and organize systems components to understand the whole system	If students chose option A: you can give 5 marks if concepts about fossil fuels, carbon dioxide, global warming, climate change, ocean acidification, acid rain, aquatic life, malaria etc. are shown on SOCME. If students chose option B: you can give 5 marks if concepts about bad water quality, high concentration, washing in rivers, excessive foaming, blocking of sunlight, aquatic life, water pollution, etc. are shown on SOCME.	5		/5
		Look at the **whole SOCME** give a score out of 5 for the following:			
		Good propositions overall that tell a story of the whole system	1		/ 5
		The new concepts AND subsystems (other than economic, societal, and environmental) added are relevant (relates to surfactants and linear alkylbenzene sulfonate)	1		
		The concepts fit within or between subsystems	1		
		The concepts are in the correct format (in a block, appropriate font, size, colour)	1		
		Future prediction is made that shows clear connection and relevance to LAS	1		
				Total	/10

Level	**Score**	**FINAL SCORE**
Unistructural	**/10**	**/ 80**
Multi-structural	**/30**	
Relational	**/30**	
Extended abstract	**/10**	

Feedback to the group

Possible New Concepts and linking words

Environmental subsystem	Societal subsystem	Economic Subsystem
• Chemical Waste • Oil spills • Fossil fuels • Greenhouse gasses • Heavy metals • Wastewater Treatment Plants • Sewage • River quality • Anaerobic conditions • Oxygen • Sunlight (foaming blocks sunlight- decreases oxygen in river) • Eutrophication	• Health risks • Carcinogenic • Covid-19 • Rural villages • Health problems • Household use • Drinking water • Food • Cytotoxic • Population	• Platinum Exports • Job creation • Demand • Supply • Profits • Platinum reserves • Job creation improves economic status • Detergent performance • Manufacture .

anaerobic conditions caused by extensive **foaming** reduces the **biodegradability** of LAS due to the **decreased biological oxygen demand** of the river, because of the **blocking of sunlight**- limited oxygen is available for biodegradation and hence LAS **concentration** will persist for longer in river systems, thereby increasing the **ecotoxicity.**

South Africa produces the majority of its energy from **fossil fuels** in coal-fired power stations. High temperatures in fractional distillation require **more energy**- which results in increased burning of fossil fuels. This emits more **CO_2** into the atmosphere and can contribute to **global warming** and **ocean acidification.**

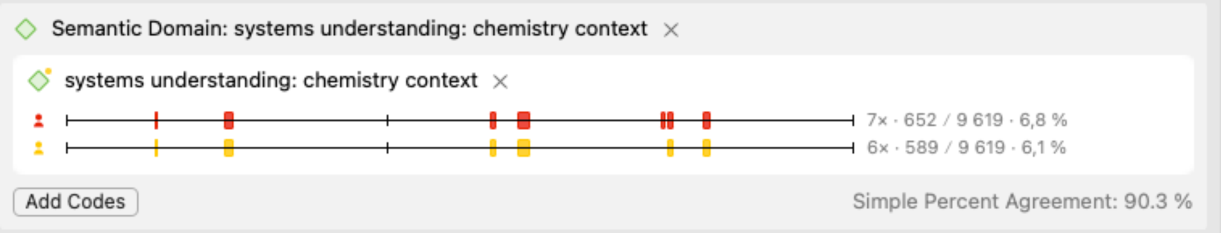
Sulfonation uses SO_3 and sulfuric acid which would lead to **acid rain** (SO_3) and **acid spills** into groundwater.

SA has abundant platinum reserves, **jobs are created**, more **exports,** and thus good economic growth, however, **heavy metals** are required to modify catalysts, which can result in environmental **pollution** and **health risks** together with the **carcinogenic** effects of benzene that laboratory scientists and workers in production plants have to work with. On the other hand, modified catalysts increase **olefin yields**, produce **high-performance** detergents as it is selective and therefore **reduces waste**

APPENDIX D: COLLECTED AND ANALYSED DATA

D1-3. SELF-REFLECTION QUESTIONNAIRE CODING, FINDINGS AND AGREEEMNT

Systems understanding:chemistry context					
Question	**Student ID**	**Self-reflection questionnaire excerpts**	**Agreement amongst 2 independent coders**	**Applied by**	**Strength of evidence**
5	*1*	*“I learned that surfactants are a very big issue when it comes to river pollution”*	Yes	3 coders	Strong
	10	*“I learned that you have to think about chemistry in a wider range for example how does it affect : people's health, biodiversity, economy etc.”*	Yes	3 coders	Credible
	2	*“I mastered the skills of the intersectional nature of chemistry”*	No	2 coders	Credible
		“I learnt how to take a step back and look at the real-world implications of chemistry.”	Yes	3 coders	
	17	*“I also learned about surfactancts and there working but also about the negative effects it could have. “*	Yes	3 coders	Credible
7	*1*	*“about the impact of surfactants on the environment.”*	Yes	3 coders	Strong
	8	*“Now that I know the impacts of LAS, I can choose to use less detergent, choose products wisely and wash my clothes less often.”*	Yes	2 coders	Credible



Semantic Domain: systems understanding: chemistry context

systems understanding: chemistry context

7× · 652 / 9 619 · 6,8 %

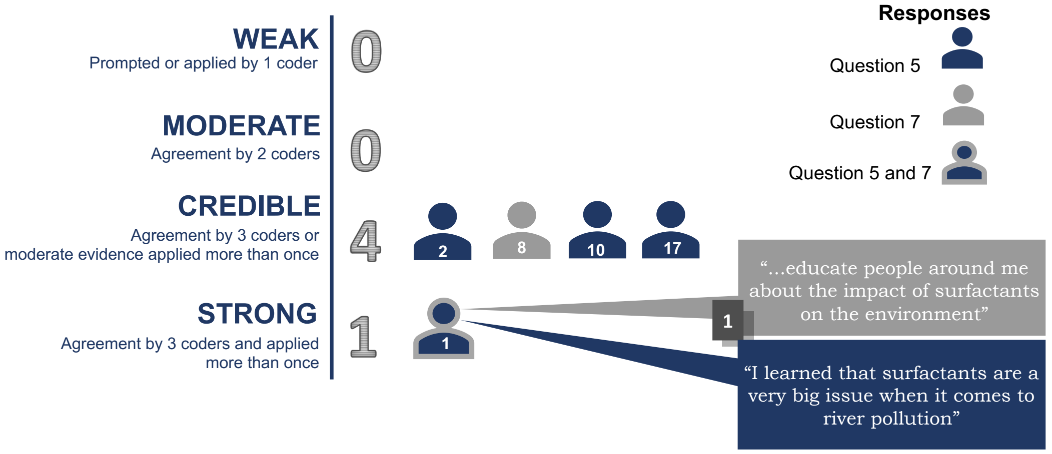
6× · 589 / 9 619 · 6,1 %

Add Codes

Simple Percent Agreement: 90.3 %

The codebook was applied consistenly for this code with simple percentage agreement of 90.3% as shown by the Atlas. ti diagram above, therefore the strength of evidence can be used for the interpretation of findings.

STRENGTH OF EVIDENCE
SYSTEMS UNDERSTANDING: CHEMISTRY CONTEXT

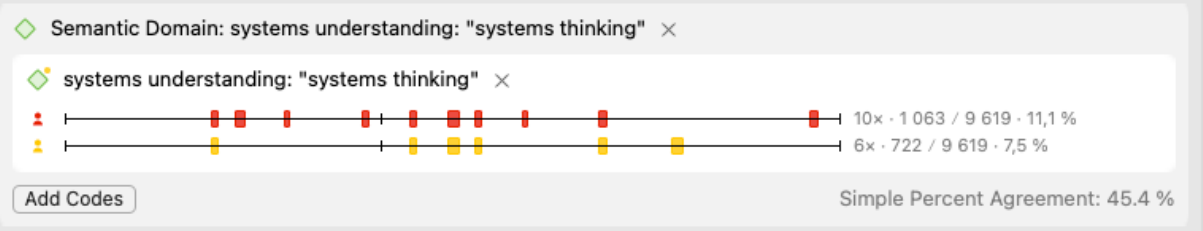


“...educate people around me about the impact of surfactants on the environment”

“I learned that surfactants are a very big issue when it comes to river pollution”

Systems understanding:”systems thinking”

Question	Student ID	Self-reflection questionnaire excerpts	Agreement amongst 2 independent coders	Applied by	Strength of evidence
5 Prompted	*12*	*“Systems thinking is a holistic way of approaching a problem in order to find a possible outcome.”*	Yes	3 coders	Weak
	1	*“I learnt how complex the relationships between economic, social and environmental sunsystems are and how difficult it is to really find a balance.”*	Yes	3 coders	Weak
		“how we could harness that to get a clear big picture without losing sight of the small details.”	Yes	3 coders	Weak
	10	*“One thing can influence a lot of other thing and we don;t normally think about that.”*	No	1 coder	Weak
	8	*“I learnt more about systematical thinking and how the economical, environmental and social spheres are all related.”*	Yes	3 coders	Strong
	17	*“I also learned how to look at the impact one thing has on all three subsystems namely societal,environmental, and economical, and how to link these systems together.”*	No	2 coders	Moderate
	14	*“also learnt systems thinking because we had to see information in concept and key word form and make sense of it”*	No	2 coders	Moderate
7	*13*	*“I whould think about things in my daily life in a more systamatic manner”*	No	1 coder	weak
	8	*“I have learnt from the systematic thinking of these practicals to look at the bigger picture of things.”*	Yes	3 coders	strong
	2	*“the most important thing about systems thinking is 'doing your homework' and gaining a deep understanding about various issues (subsystems).”*	No	2 coders	Moderate
	17	*“I would think about how something affects not only me in my specofoc surroundings but the other systems as well before using something that has more negatives in the big picture.”*	No	1 coder	Moderate
		“I have realised that stuff influence each other and the subsystems “	No	1 coder	
	14	*“as well as educating those around to start thinking systematically would improve the earth bit by bit”*	No	1 coder	Moderate


Semantic Domain: systems understanding: "systems thinking"

systems understanding: "systems thinking"

10× · 1 063 / 9 619 · 11,1 %

6× · 722 / 9 619 · 7,5 %

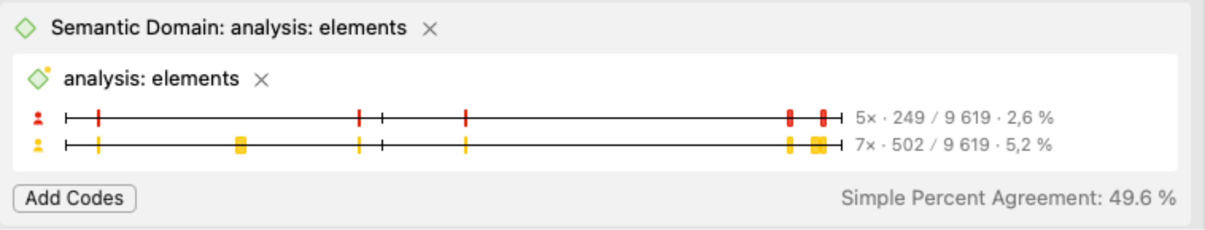
Add Codes

Simple Percent Agreement: 45.4 %

The codebook was not applied consistently for this code with simple percentage agreement of 45.4% as shown by the Atlas. ti diagram above, therefore the strength of evidence was not used for the interpretation of findings, but rather the content of students reflections.

Analysis: elements

Question	Student ID	Self-reflection questionnaire excerpts	Agreement amongst 2 independent coders	Applied by	Strength of evidence
5	*1*	*“their various components”*	yes	3 coders	Credible
	14	*“when my group members and I were not sure of an answer, we broke down the question”*	yes	3 coders	Moderate
		“constructed ideas until we came up with ideas that had been checked through research, reading notes provided and as well as sharing prior knowledge that seemed relevant to answering the question”	No	1 coder	Moderate
		“also learnt system thinking because we had to see information in concept and key word form and make sense of it”	No	2 coders	Moderate
		“brain storm ideas and turn ideas into important key words and concepts”	yes	3 coders	Moderate
7	*12*	*“all the other factors that are involved”*	yes	3 coders	Credible
	14	*“concepts and how other things in”*	yes	3 coders	Strong
	2	*“the most important thing about systems thinking is 'doing your homework' and gaining a deep understanding about various issues (subsystems).”*	No	1 coder	Weak

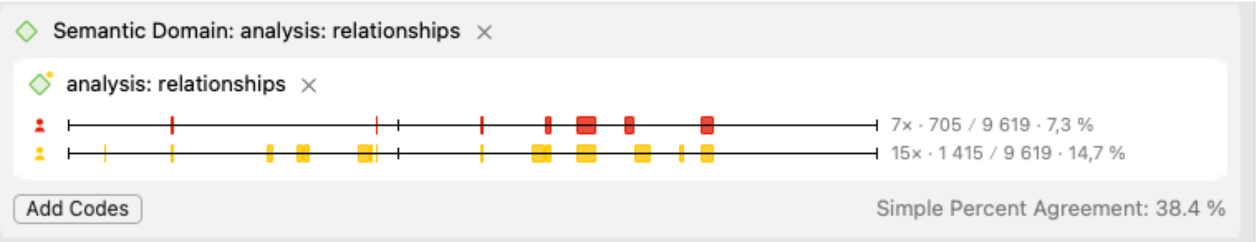


The codebook was not applied consistently for this code with simple percentage agreement of 49.6% as shown by the Atlas. ti diagram above, therefore the strength of evidence was not used for the interpretation of findings, but rather the content of students reflections.

Analysis: relationships

Question	Student ID	Self-reflection questionnaire excerpts	Agreement amongst 2 independent coders	Applied by	Strength of evidence (overall)
5	1	*“I learnt how to analyse these relationships”*	Yes	3 coders	Strong
	10	*“I learned that you have to think about chemistry in a wider range for example, how does it affect: people’s health, biodiversity, economy ect”*	No	1 coder	Weak
	10	*“one thing can influence a lot of other thing[s] and we don’t normally think about that”*	Yes	3 coders	Credible
	10	*“I learn how to think deeper and using linking words to solve the problems that we had at hand for example, ecotoxicity and biodiversity what does it have in common now you have to think deeper and say ecotoxicity decrease biodiversity ect”*	Yes	3 coders	Credible
	8	*“I learnt more about systematically thinking and how the economical, environmental and social spheres are all related”*	Yes	2 coders	Moderate

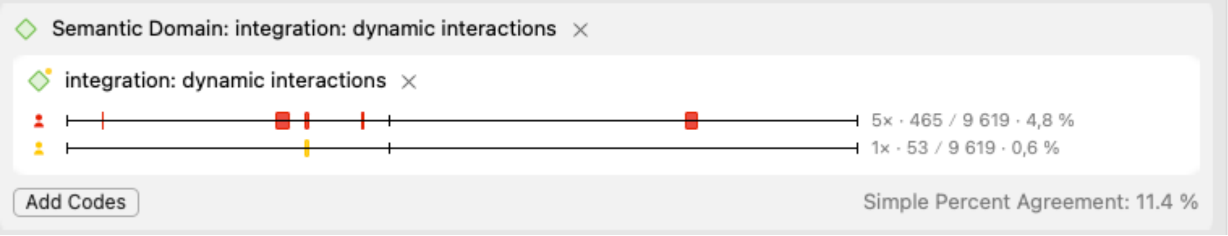
	8	*"I learnt that a product can be beneficial to one sphere but deterimental[detrimental] to another and we as a population often tend to focus on the advantages instead of the consequences of the disadvantages"*	No	1 coder	Weak
	2	*"I mastered the skills of the intersectional nature of chemistry"*	No	2 coders	Moderate
	17	*"I also learned how to look at the impact one thing has on all three subsystems namely societal, environmental, and[delete and] economical, and[delete comma and keep and] how to link these systems together"*	Yes	3 coders	Strong
7	12	*"influence the problems"*	No	2 coders	Moderate
	13	*"think about how things link to one another"*		3 coders	Credible
	2	*"I understand my topic of interest from many viewpoints to make many connections"*	No	2 coders	Moderate
	17	*"I have realised that stuff influence each other and the subsystems"*	No	2 coders	Credible
		"something I might think has[had] a small effect might actually have a big negative effect"	No	1 coder	
	14	*"thinking about my own day to dy[day] activities, big and small, as well as the ways in which my activities affect the space around me"*	No	1 coder	Strong
		"connecting my day to day with other subsystems"	No	1 coder	
		"could be affected"	Yes	3 coders	



The codebook was not applied consistently for this code with simple percentage agreement of 38.4% as shown by the Atlas. ti diagram above, therefore the strength of evidence was not used for the interpretation of findings, but rather the content of students reflections.

Integration: dynamic interactions					
Question	**Student ID**	**Self-reflection questionnaire excerpts**	**Agreement amongst 2 independent coders**	**Applied by**	**Strength of evidence (overall)**
5	1	*"I learnt how complex the relationships between economic, social and environmental sunsystems are and how difficult it is to really find a balance."*	Yes	1 coder	Weak
	17	*"I also learned how to look at the impact one thing has on all three subsystems namely societal,environmental, and economical, and how to link these systems together."*	No	1 coder	Credible
7	12	*"influence the problems"*	No	1 coder	Weak
	17	*"I would think about how something affects not only me in my specofoc surroundings but the other systems as well before using something that has more negatives in the big picture."*	No	2 coder	Credible

		“looked at all the interactions between the subsystems”	Yes	3 coders	
	14	*“connecting my day to day with other subsystems “*	No	2 coders	Moderate



Semantic Domain: integration: dynamic interactions ×

integration: dynamic interactions ×

5x · 465 / 9 619 · 4,8 %

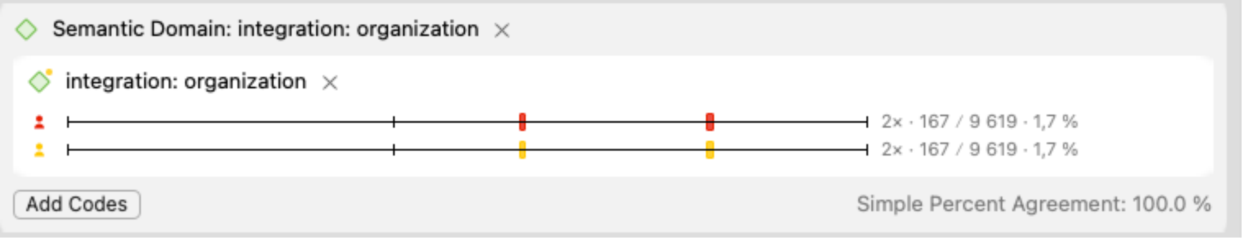
1x · 53 / 9 619 · 0,6 %

Simple Percent Agreement: 11.4 %

The codebook was not applied consistently for this code with simple percentage agreement of 11.4% as shown by the Atlas. ti diagram above, therefore the strength of evidence was not used for the interpretation of findings, but rather the content of students reflections.

Integration: organization

Question	Student ID	Self-reflection questionnaire excerpts	Agreement amongst 2 independent coders	Applied by	Strength of evidence (overall)
5	13	“I learned how to organise my thoughts into a universal diagram or idea. “	Yes	3 coder	Credible
	17	“I also learned with critical thinking how to identify in which subsystems a componet would fit.”	Yes	3 coders	Credible



Semantic Domain: integration: organization ×

integration: organization ×

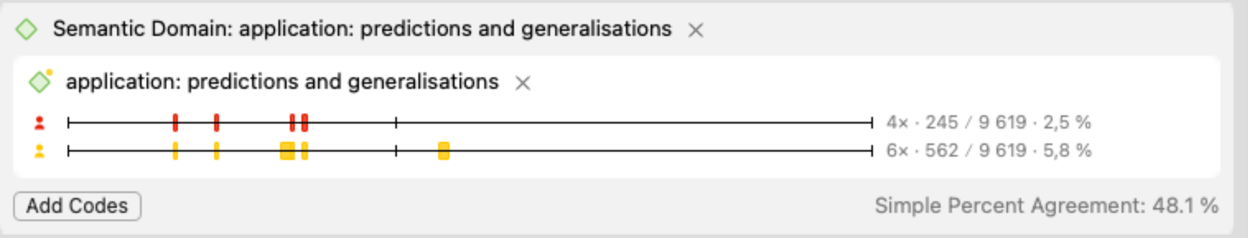
2x · 167 / 9 619 · 1,7 %

2x · 167 / 9 619 · 1,7 %

Simple Percent Agreement: 100.0 %

The codebook was applied consistently for this code with a perfect simple percentage agreement of 100% as shown by the Atlas. ti diagram above, therefore the strength of evidence can be used for the interpretation of findings.

Application: predictions					
Question	**Student ID**	**Self-reflection questionnaire excerpts**	**Agreement amongst 2 independent coders**	**Applied by**	**Strength of evidence**
5	12	“create new technologies, and with these techological advancements, better predictability for the future sustainability of our environment”	No	1 coder	Weak
7	13	“what the environmental and economic consequences are”	Yes	3 coders	Credible
	8	“the effects and consequences of me using such products”	Yes	3 coders	Credible
	17	“I would think twice before using anything that could be harmful to a subsystem”	No	1 coder	Strong
		“I would think about how something effects not only me in my specofoc surroundings but the other systems as well before using something that has more negatives in the big picture”	Yes	3 coders	
		“Something that has more negatives in the big picture”	Yes	3 coders	
		“something I might think has a small effect might actually have a big negative effect”	Yes	3 coders	
	14	“as well as educating those around to start thinking systematically would improve the earth bit by bit”	No	1 coder	Weak


Semantic Domain: application: predictions and generalisations ×

application: predictions and generalisations ×

4x · 245 / 9 619 · 2,5 %

6x · 562 / 9 619 · 5,8 %

Add Codes

Simple Percent Agreement: 48.1 %

The codebook was not applied consistently for this code with simple percentage agreement of 48.1% as shown by the Atlas. ti diagram above, therefore the strength of evidence was not used for the interpretation of findings, but rather the content of students reflections.

Application: problem solving					
Question	**Student ID**	**Self-reflection questionnaire excerpts**	**Agreement amongst 2 independent coders**	**Applied by**	**Strength of evidence (overall)**
5 **Prompted**	12	“system thinking is a holistic way of approaching a problem in order to find a possible outcome”	No	2 coders	Credible
		“excellent communication is needed to problem solve”	No	2 coders	
	10	“I learn[ed] how to think deeper and using linking words to solve the problem that we had at hand for example, ecotoxicity and biodiversity [and] what does it have in common now you have to think deeper and say ecotoxicity decrease biodiversity etc”	Yes	3 coders	Weak

	8	“I learnt about problem solving as a group of like[-]minded people studying degrees in science as this opportunity allowed me to work in a group”	Yes	3 coders	Weak
	11	“problem solving improves when more than one brain tackles a challenge”	Yes	3 coders	Weak
	14	“I learnt problem solving skills”	Yes	3 coders	Weak
	4	“to help figure things out”	No	1 coder	Weak
7	12	“so that I better problem solve by finding perfect solutions by critically thinking”	Yes	3 coders	Credible


Semantic Domain: application: "problem solving" ×

application: "problem solving" ×

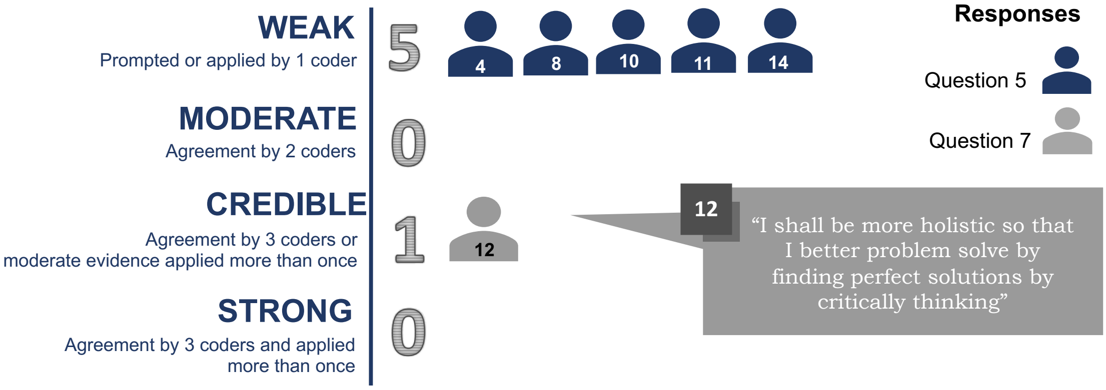
8× · 733 / 9 619 · 7,6 %

5× · 561 / 9 619 · 5,8 %

Simple Percent Agreement: 76.5 %

The codebook was applied consistenly for this code with a simple percentage agreement of 76.5% as shown by the Atlas. ti diagram above, therefore the strength of evidence can be used for the interpretation of findings.

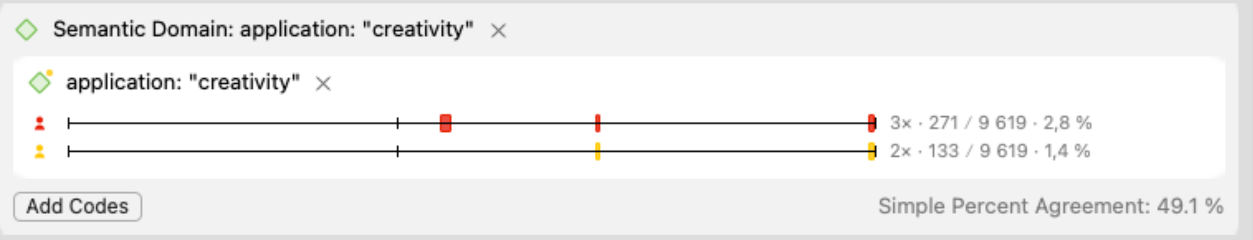
STRENGHT OF EVIDENCE
APPLICATION: “PROBLEM SOLVING”



“I shall be more holistic so that I better problem solve by finding perfect solutions by critically thinking”

Application: creativity

Question	**Student ID**	**Self-reflection questionnaire excerpts**	**Agreement amongst 2 independent coders**	**Applied by**	**Strength of evidence**
5	12	“create new technologies, and with the technological advancements, better predictability for the future sustainability of our environment”	No	1 coder	Weak
	10	“learned to be creative in my think process by means of the SOCME diagram”	Yes	3 coders	Weak
	4	“I have learnt to to become creative and think out of the box”	Yes	3 coders	Weak



Semantic Domain: application: "creativity"

application: "creativity"

3× · 271 / 9 619 · 2,8 %

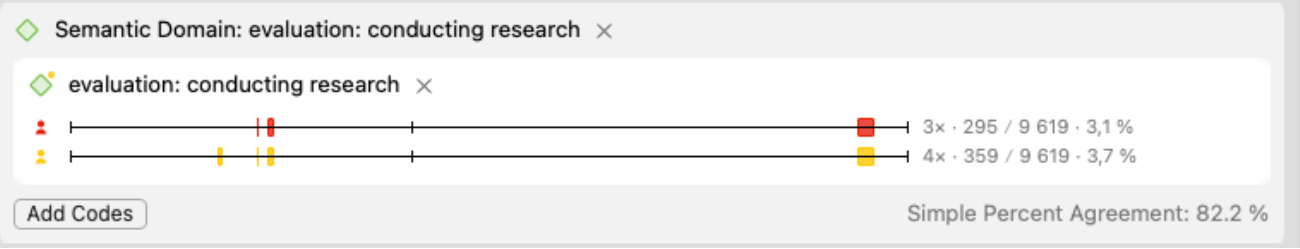
2× · 133 / 9 619 · 1,4 %

Simple Percent Agreement: 49.1 %

The codebook was not applied consistently for this code with simple percentage agreement of 49.1% as shown by the Atlas. ti diagram above, therefore the strength of evidence was not used for the interpretation of findings, but rather the content of students reflections.

Evaluation: conducting research

Question	Student ID	Self-reflection questionnaire excerpts	Agreement amongst 2 independent coders	Applied by	Strength of evidence
Question 5	14	*“constructed ideas until we came up with ideas that had been checked through research, reading notes provided and as well as sharing prior knowledge that seemed relevant to answering the question”*	Yes	3 coders	Credible
Question 7	8	“I would make sure I am well informed on what products I am using “	No	2 coders	Moderate
	2	“‘doing your homework’”	Yes	3 coders	Strong
		“I will be taking a more open-minded approach to the research that I undertake”	Yes	3 coders	



Semantic Domain: evaluation: conducting research

evaluation: conducting research

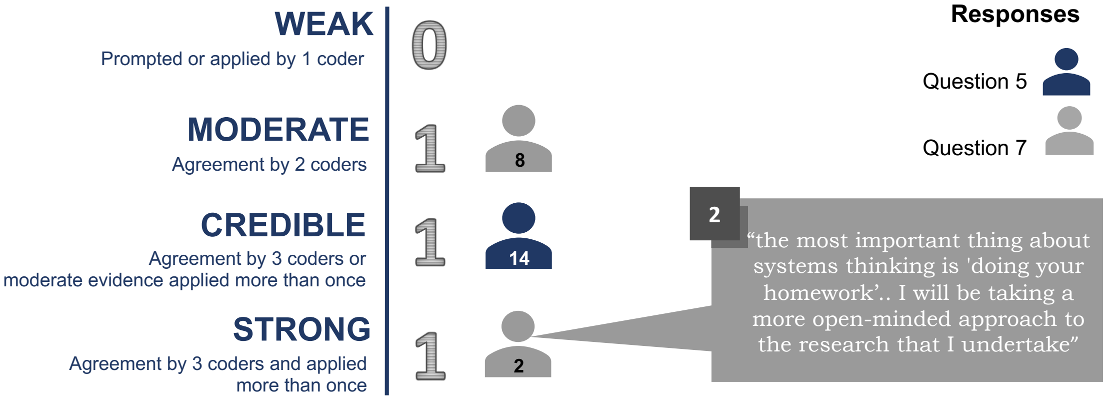
3× · 295 / 9 619 · 3,1 %

4× · 359 / 9 619 · 3,7 %

Simple Percent Agreement: 82.2 %

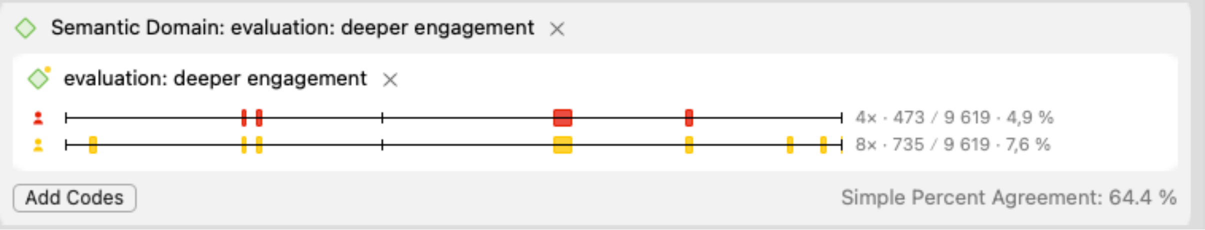
The codebook was applied consistenly for this code with a simple percentage agreement of 82.2% as shown by the Atlas. ti diagram above, therefore the strength of evidence can be used for the interpretation of findings.

STRENGTH OF EVIDENCE
EVALUATION:CONDUCTING RESEARCH



Evaluation: deeper engagement

Question	Student ID	Self-reflection questionnaire excerpts	Agreement amongst 2 independent coders	Applied by	Strength of evidence
5	1	*"how we could harness that to get a clear big picture without losing sight of the small details. "*	No	1 coder	Weak
	10	*"I learn how to think deeper and using linking words to solve the problem that we had at hand for example ecotoxicity and biodiversity what does it have in common now you have to think deeper and say ecotoxicity decrease biodiversity etc"*	Yes	3 coders	Credible
	17	*"I also learned with critical thinking how to identify in which subsystems a componet would fit."*	Yes	3 coders	Credible
	14	*"when my group members and I were not sure of an answer, we broke down the question"*	No	1 coder	Moderate
		"brain storm ideas and turn ideas into important key words and concepts."	No	3 coders	
	4	*"to help figure things out."*	No	2 coders	Moderate
7	12	"so that I better problem solve by finding perfect solutions by critically thinking"	No	2 coders	Moderate
	2	"gaining a deep understanding about various issues (subsystems)"	Yes	3 coders	Strong
		"I understand my topic of interest from many viewpoints to make many connections"	Yes	3 coders	



Semantic Domain: evaluation: deeper engagement ×

evaluation: deeper engagement ×

4x · 473 / 9 619 · 4,9 %

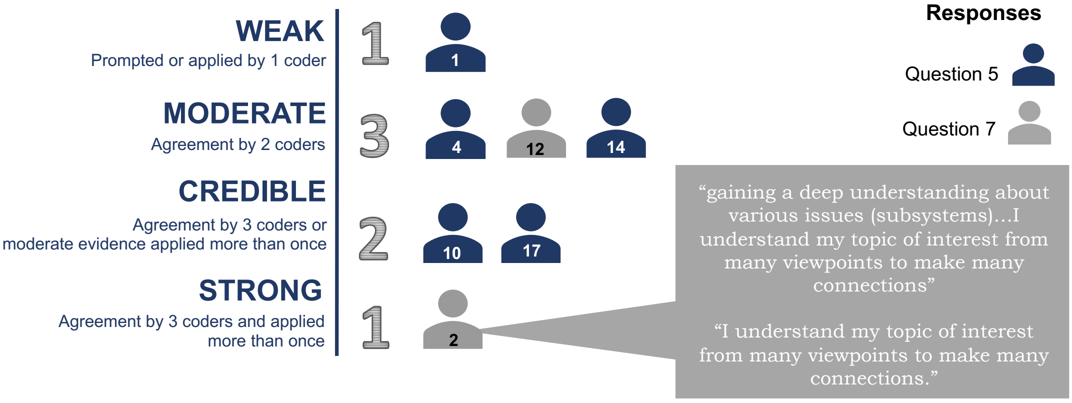
8x · 735 / 9 619 · 7,6 %

Add Codes

Simple Percent Agreement: 64.4 %

The codebook was applied consistenly for this code with a fair simple percentage agreement of 64.4% as shown by the Atlas. ti diagram above, therefore the strength of evidence can be used for the interpretation of findings.

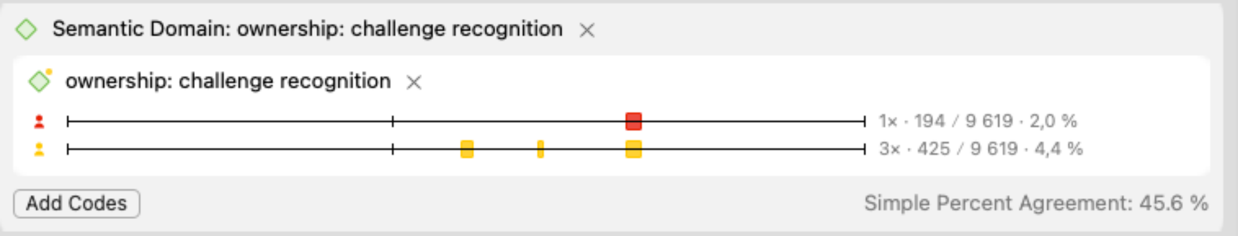
STRENGTH OF EVIDENCE
EVALUATION:DEEPER ENGAGEMENT



"gaining a deep understanding about various issues (subsystems)…I understand my topic of interest from many viewpoints to make many connections"

"I understand my topic of interest from many viewpoints to make many connections."

Ownership: challenge recognition					
Question	**Student ID**	**Self-reflection questionnaire excerpts**	**Agreement amongst 2 independent coders**	**Applied by**	**Strength of evidence**
5	1	*"I learnt how complex the relationships between economic, social and environmental sunsystems are and how difficult it is to really find a balance."*	No	2 coders	Moderate
	10	*"One thing can influence a lot of other thing and we don;t normally think about that. "*	No	2 coders	Moderate
	8	*"I learnt that a product can be beneficial to one sphere but deterimental to another and we as a population often tend to focus on the advantages instead of the consequences of the disadvantages."*	Yes	3 coders	Credible


Semantic Domain: ownership: challenge recognition

ownership: challenge recognition

1x · 194 / 9 619 · 2,0 %

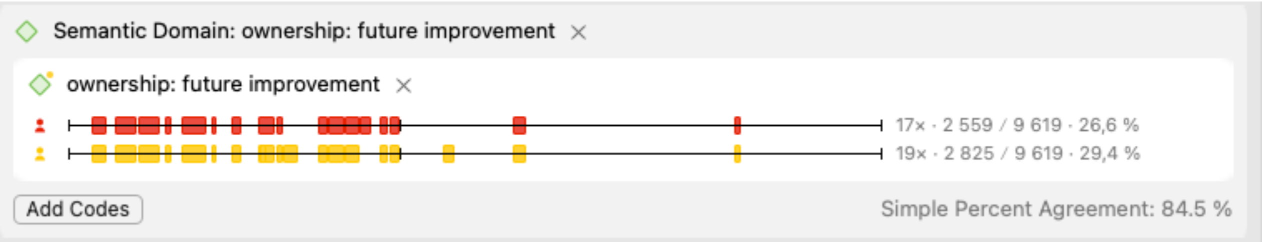
3x · 425 / 9 619 · 4,4 %

Simple Percent Agreement: 45.6 %

The codebook was not applied consistently for this code with simple percentage agreement of 45.6% as shown by the Atlas. ti diagram above, therefore the strength of evidence was not used for the interpretation of findings, but rather the content of students reflections.

	Ownership: future improvement				
Question	**Student ID**	**Self-reflection questionnaire excerpts**	**Agreement amongst 2 independent coders**	**Applied by**	**Strength of evidence**
5	12	*"create new technologies, and with these technological advancements, better predictability for the future sustainability of our environment"*	No	2 coders	Moderate
	1	*"i can educate my peers and people I come in contact with and hopefully everyone can start transitioning to safer laundry detergents that are more sustainable."*	Yes	2 coders	Credible
	17	*"I also learned what I can do to be a more responsible citizen in that regard."*	Yes	3 coders	Credible
7 **Prompted**	12	*"I shall be more holistic so that I better problem solve by finding perfect solutions by critically thinking about all the other factors that are involved and influence the problems."*	Yes	3 coders	Weak
	16	*"When buying detergents, take note of the ingredients and the use of palm oil which is not sustainable. Take note on whether the packaging is recyclable.When doing washing, use cold water and water less frequently to reduce energy and water consumption."*	Yes	3 coders	Weak
	1	*"I will also make sure to create minimal waste and get rid of it in a way that is as safe as possible.I will continue to shop mindfully and choose sustainable options. I will also continue*	Yes	3 coders	Weak

		to not wash my clothes too often and educate people around me”			
	13	*“I whould think about things in my daily life in a more systamatic manner “*	Yes	3 coders	Weak
	10	*“i will make sure that I buy biodegradable products instead of lots op plastic bottles. will use cold water to wash my cloths to save energy. i will make sure to buy eco-friendly detergents. will wash my cloths less often to safe water and energy.i will use less detergents when I wash my cloths”*	Yes	3 coders	Weak
	8	*“I would make sure I am well informed on what products I am using”*	Yes	3 coders	Weak
		“Now that I know the impacts of LAS, I can choose to use less detergent, choose products wisely and wash my clothes less often.”	Yes	3 coders	
	2	*“As an upcoming scientist, I will be taking a more open-minded approach to the research that I undertake to ensure that I understand my topic of interest from many viewpoints to make many connections.”*	Yes	3 coders	Weak
	17	*“I would think twice before using anything that could be harmfull to a subsystem. “*	Yes	3 coders	Weak
		“I would think about how something affects not only me in my specofoc surroundings but the other systems as well before using something that has more negatives in the big picture.”	No	2 coders	
	7	*“I would use less laundry detergent, every bit will help the enviroment, no matterhow small the action is.”*	Yes	3 coders	Weak
	11	*“support sustainable surfactants and help people around me do the same and also contribute the the health of our society and making it a safer place where it is easy to apply these actions.”*	Yes	3 coders	Weak
	3	*“I would make sure that after using the detergents i do not get ride of them to where it would damage our environment.Use less degetergents Not wahs frequently “*	Yes	3 coders	Weak
	14	*“Thinking about my own day to dy activities , big and small, as well as the ways in which my activities affect the space around me”*	No	2 coders	Weak
		“as well as educating those around to start thinking systematically would improve the earth bit by bit”	Yes	3 coders	Weak
	4	*“I would make sure to use eco friendly detergents and avoid wasting energy by washing more often and with warm or hot water.”*	Yes	3 coders	Weak


Semantic Domain: ownership: future improvement

ownership: future improvement

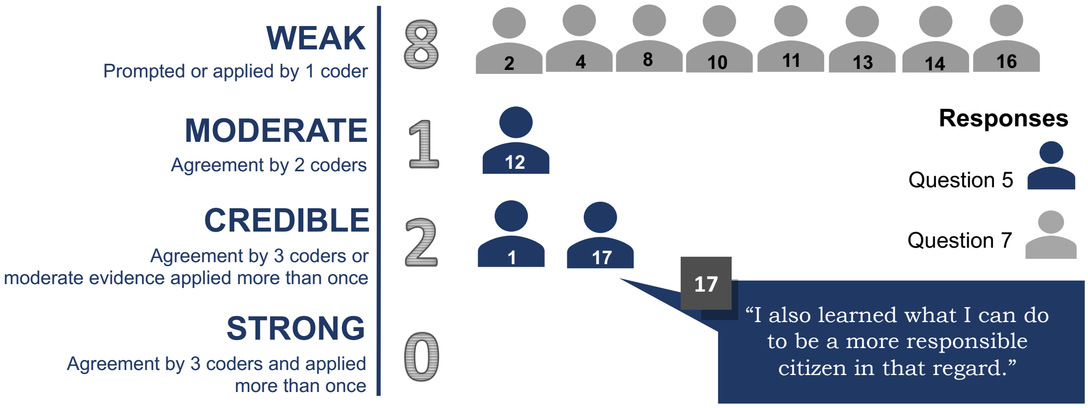
17× · 2 559 / 9 619 · 26,6 %

19× · 2 825 / 9 619 · 29,4 %

Simple Percent Agreement: 84.5 %

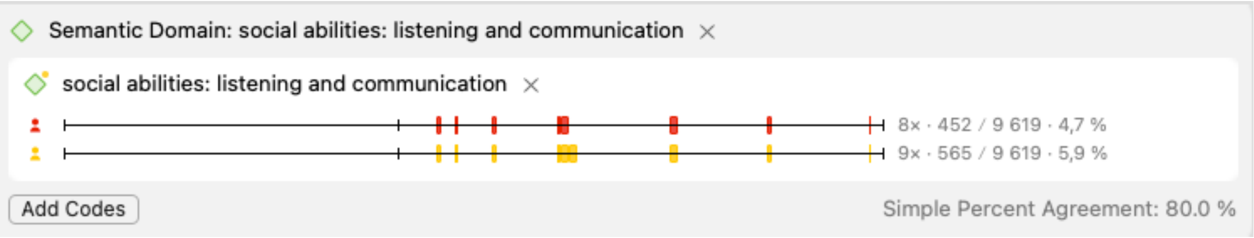
The codebook was applied consistenly for this code with a good simple percentage agreement of 84.5% as shown by the Atlas. ti diagram above, therefore the strength of evidence can be used for the interpretation of findings.

STRENGHT OF EVIDENCE
OWNERSHIP:FUTURE IMPROVEMENT



“I also learned what I can do to be a more responsible citizen in that regard.”

Social abilities: listening and communication					
Question	**Student ID**	**Self-reflection questionnaire excerpts**	**Agreement amongst 2 independent coders**	**Applied by**	**Strength of evidence**
5 **prompted**	12	*“Excellent communication is needed to problem solve”*	Yes	3 coders	Weak
	16	*“My communication skills were greatly improved”*	Yes	3 coders	Weak
	1	*“hear their different takes and point of views”*	Yes	3 coders	Weak
	10	*“I loved how we communicated about the practical.”*	Yes	3 coders	Weak
		“You are listening to the people's perspective of the practical and their ideas.”	Yes	3 coders	
		“It was fun to talk to my group member through the collaborate sessions because we can't see each other on campus.”	No	2 coders	
	8	*“It was also eye opening how we were studying similar degrees but took a different approach to every idea.”*	Yes	3 coders	Weak
	11	*“learned to thinking patterns of other students.”*	Yes	3 coders	Weak
	4	*“I have gained communication skill”*	Yes	3 coders	Weak


Semantic Domain: social abilities: listening and communication

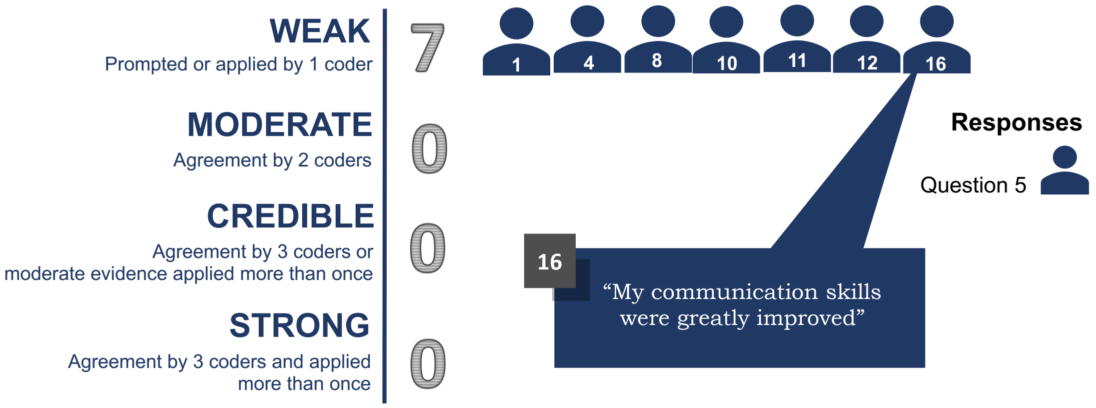
social abilities: listening and communication

8x · 452 / 9 619 · 4,7 %
9x · 565 / 9 619 · 5,9 %

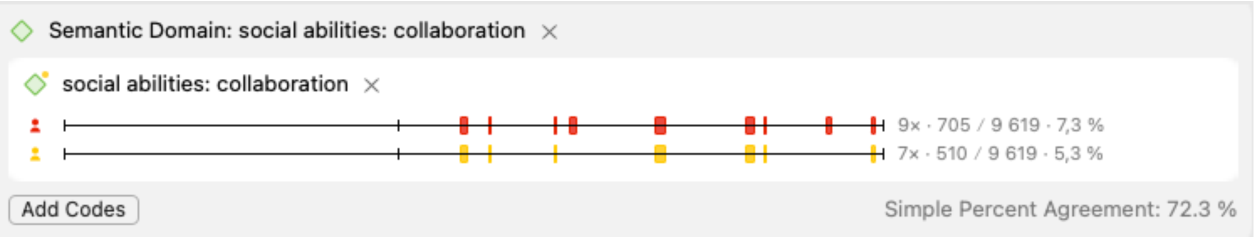
Simple Percent Agreement: 80.0 %

The codebook was applied consistenly for this code with a good simple percentage agreement of 80.0% as shown by the Atlas. ti diagram above, therefore the strength of evidence can be used for the interpretation of findings.

STRENGHT OF EVIDENCE
SOCIAL ABILITIES: LISTENING AND COMMUNICATION

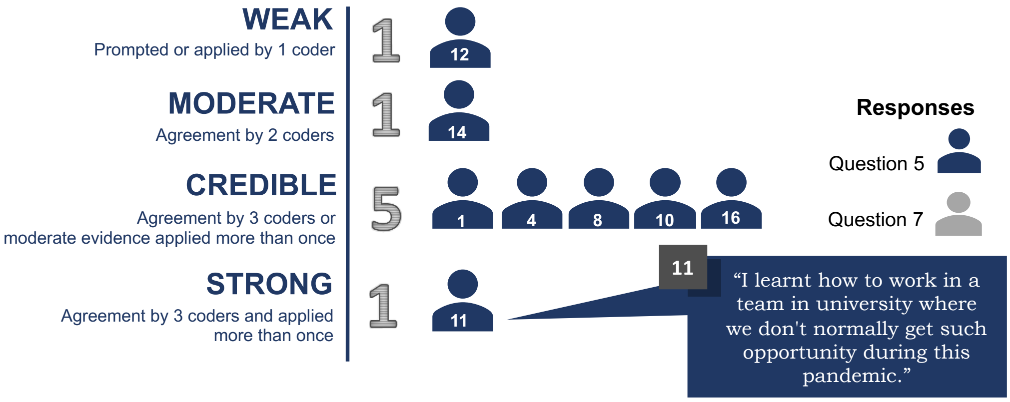


Social abilities: collaboration					
Question	**Student ID**	**Self-reflection questionnaire excerpts**	**Agreement amongst 2 independent coders**	**Applied by**	**Strength of evidence**
5	12	*“Excellent communication is needed to problem solve”*	No	1 coders	Weak
	16	*“the team members to perform a role and collaborate effectively to complete activities”*	Yes	3 coders	Moderate
	1	“I was able to work together with other students”	Yes	3 coders	Moderate
	10	“I loved working in this group”	Yes	3 coders	Moderate
		“It was fun to talk to my group member through the collaborate sessions because we can't see each other on campus.”	No	1 coders	
	8	*“I learnt about problem solving as a group of like minded people studying degrees in science as this opportunity allowed me to work in a group”*	Yes	3 coders	Moderate
	11	*“I learnt how to work in a team in university where we don't normally get such opportunity during this pandemic.”*	Yes	3 coders	Strong
		“Team work was definitely and bonus skill”	Yes	3 coders	
	4	*“I have gained communication skill”*	Yes	3 coders	Moderate
		“I learnt how to work in a team in university where we don't normally get such opportunity during this pandemic.	Yes	3 coders	
	14	*“when my group members and I were not sure of an answer, we broke down the question”*	No	2 coders	Moderate



The codebook was applied consistenly for this code with a simple percentage agreement of 72.3 % as shown by the Atlas. ti diagram above, therefore the strength of evidence can be used for the interpretation of findings.

STRENGHT OF EVIDENCE
SOCIAL ABILITIES: COLLABORATION



“I learnt how to work in a team in university where we don't normally get such opportunity during this pandemic.”

D4. FOCUS GROUP QUESTIONS

You are invited to attend **session 1** of our focus group discussion on **14 December at 11:00-12:00** online on Microsoft teams by clicking on this link Focus Group Session 1 Discussion. After clicking on the link, a invite.ics file will be downloaded, open the file and the meeting will be added to your calendar. From here on, you can click on the calendar link and open Microsoft Teams in your browser. The discussion session will last 40 minutes, however, I have booked out an hour timeslot for a quick introduction and conclusion after our focus group interview.

Instructions

As far as possible please:

- Find a quiet space with a good internet connection.
- Read through the questions before the start of the discussion
- Have your microphone unmuted so we that we can talk rather than typing out answers
- Have a pen and paper to make notes that you would like to discuss as the other students are participating

Focus Group Interview Program	
Time	**Activity**
10 minutes	Introduction - Interview facilitator - Purpose of interview - Collected data - Confidentiality - Consent - Permission to record - Agreements
40 minutes	Open-ended Focus group questions are asked. - Terminology - Systems Thinking Skills - Learning Outcomes
10 minutes	Conclusion and thank you

Focus Group Interview Questions

1. **Terminology (5 min)**

1.1. Systems thinking on its own is a term that you might have not been familiar with, before the start of practicals 4 and 5. However, throughout the intervention, there might have been other terminology and constructs or ideas that were new and not easy to understand. Can you recall any of these challenging terms?

1.2. Why did you find these terms challenging?

1.3. Suggest how we could define these terms to make it easier for future students?

2. Systems Thinking Skills (30 min)

2.1. Systems thinking skill 4: the ability to organize the system's components and processes within a framework of relationships.

2.1.1. What is your understanding of systems thinking skill 4?

2.1.2. This skill was indicated by most of you as one of the most challenging skills to demonstrate on your SOCME. What made it so challenging?

2.1.3. Most groups did not indicate any new subsystems (other than economic, social, and environmental) in the SOCMEs. How could we support groups so that they are better placed to identify other subsystems?"

2.2. Systems thinking skill 7: the ability to recognize the hidden dimensions of the system (intermolecular forces, surface tension, molecular geometry, acidity, and basicity, nucleophilicity, solubility, and polarity)

2.2.1. What is your understanding of systems thinking skill 7?

2.2.2. This skill was indicated by most of you as one of the most challenging skills to demonstrate on your SOCME? What made it so challenging?

2.2.3. In practical 4 you were given a core chemistry concept map from which you had to work to interpret an expanded concept map. In practical 5 you were given a partial SOCME and had to construct a final SOCME. During which part of this gradual process were you able to demonstrate the hidden dimensions of the system of Linear Alkylbenzene Sulfonate? Please explain.

D5. CODING OF FOCUS GROUP TRANSCRIPTS

Code Category: Perceptions of terminology		
Codes	**Quotations**	**Student ID**
"easy"	*"I found it really, really interesting and pretty easy to find connections, and to do that I just found the whole surfactant part difficult but the actual building and linking of ideas was not too difficult for me. I enjoyed that part"* *"most terms I think, were quite self-explanatory"*	*2*
	"I think the terms were not challenging. It's just new concepts and once you have introduced them, it is easy."	*6*
	"the more you discuss it, the easier you know you can understand it. So I can't think back on anything that was specifically challenging for me to understand because at the end of everything I was able to understand most of the terminology"	*5*
"familiar"	*"I found a lot of the terms were somewhat familiar, but then I remembered in the practical I would look at some of the terms I didn't have a complete understanding, so an example was biodegradation like I had a general idea, but what would in terms of the context of the project and like the research work that we were provided"*	*16*
	"your introductory video really helps as you would just straight out define them for us and get making us familiar with them instead of only really seeing them when we are getting tested on them"	
	"Most of the terms were words I had encountered before but didn't have a full round understanding of the terms. "	*15*

	"I find it easier to understand terms when we have an example we can relate to"	
	"it's also much easier to learn from examples you know and things that you already know. If I can make it relevant to that then it's much easier to get an idea of what it is"	*5*
"more difficult"	*"I found the actual content more difficult than the construction of systems thinking if that makes sense."*	*2*
	"I found the surfactants more difficult than actually having to assemble the diagram and the linking things"	
	"I found it really, really interesting and pretty easy to find connections, and to do that I just found the whole surfactant part difficult but the actual building and linking of ideas was not too difficult for me. I enjoyed that part"	
Code Category: Perceptions of challenging terminology		
"context"	*"I found a lot of the terms were somewhat familiar, but then I remembered in the practical I would look at some of the terms I didn't have a complete understanding, so an example was biodegradation like I had a general idea, but what would in terms of the context of the project and like the research work that we were provided"*	*16*
	"I wasn't entirely sure what counted as biodegradation, also ecotoxicity. I could genuinely tell that it's like harming the environment somehow, but like what? Just a bit more background of what exactly would it count as that? "	
	"I think it was just being unsure about the context. Like you did contextualize surfactants and LAS for us and generally what the background knowledge we needed to know, but I guess we found them challenging because we could only really kind of get an understanding based in that contex "	
	"provide additional resources maybe that included that type of terminology, if people have time and wanted to understand the terms a bit better in other contexts."	
	"Like you did contextualize surfactants and LAS for us and generally what the background knowledge we needed to know"	
	"The terms were challenging because I wasn't fully sure how to use them in the context of the assignment as some of the terms are found were relatively similar. So yes, they definitely added to the confusion."	*15*
"new"	*"I think the terms were not challenging. It's just new concepts and once you have introduced them, it is easy."*	*6*
	"the more you discuss it, the easier you know you can understand it. So I can't think back on anything that was specifically challenging for me to understand because at the end of everything I was able to understand most of the terminology"	*5*
	"we've never heard some of them or haven't been taught or educated about the terms that we used, so I guess it was just very new to us and some things that we haven't heard of before."	
	"the SOCME diagrams were a little bit confusing to me because I'd never seen that concept or idea before. I understand it was like a mind map, but it is quite different from a mind map as well."	*8*
	"Like ecotoxicity was a new term for me completely. So I was a bit unsure about that"	*17*
	"I don't think it's very often in our vocabulary when we speak of something. I don't think we use those words as often"	*10*
	"It is better to explain some of the words because it's new, so then everyone can know what the words mean."	
	"when you learn a new concept in another subject. In the beginning, it's weird and you don't know what it is, but later do you understand it better and get used to it. So it was just the new terms"	*17*
	"whenever I come across new terms that can be quite difficult to understand, like cyclic behaviors, system boundaries, and stuff like that. I try to give myself a very simple example "	*2*
Code Category: Understanding		
progressive	*"I didn't understand what you meant with systems thinking, but when we started with the practical and all the subdivisions that we had to choose from, then I understood that now you have to link everything and think more about how they come together and then I understood the terminology"*	*10*
	"I was a bit unsure, but after the introductory PowerPoint then I understood completely what it meant. So in the beginning I was a bit unsure, but afterward, I knew what it meant and had a clear idea"	*17*
	"at the end of everything I was able to understand most of the terminology"	*5*
	"Google that after the introduction. I went to the Internet just to get a better understanding of what we are going to be working with"	*3*
	"I was completely lost at first. I will also the Internet. Yes, I had a beta understanding."	15
	"your introductory video really helps as you would just straight out define them for us and get making us familiar with them instead of only really seeing them when we are getting tested on them"	*16*
	"the introduction and our group used Google as well, to be honest."	*8*

conducting research	*"Google that after the introduction. I went to the Internet just to get a better understanding of what we are going to be working with"*	3
	"I was completely lost at first. I will also the Internet. Yes, I had a beta understanding."	15
	"provide additional resources maybe that included that type of terminology, if people have time and wanted to understand the terms a bit better in other contexts."	16
Code Category: Suggestions		
"make it easier"	*"whenever I come across new terms that can be quite difficult to understand, like cyclic behaviors, system boundaries, and stuff like that. I try to give myself a very simple example"*	2
	"if we could take these terms and put them in a very simple example, I think it would help people to grasp the concept a lot quicker."	
	"It is better to explain some of the words because it's new, so then everyone can know what the words mean."	10
	"it's also much easier to learn from examples you know and things that you already know. If I can make it relevant to that then it's much easier to get an idea of what it is "	5
	"provide additional resources maybe that included that type of terminology, if people have time and wanted to understand the terms a bit better in other contexts."	16
	"something as simple as a terminology list could be helpful as well "	8
	"I find it easier to understand terms when we have an example we can relate to"	15
	" I'm not a very creative person so if someone gives me a terminology list I quite like a list"	17
	"a terminology list is much better and maybe a summary that explains everything that makes understanding better."	3

Code Category: Perception of systems thinking skills		
Code	**Quotations**	**Student ID**
"hidden dimensions"	*"I found the actual content more difficult than the construction of systems thinking if that makes sense."*	*2*
	"I found the surfactants more difficult than actually having to assemble the diagram and the linking things"	
	"I found it really, really interesting and pretty easy to find connections, and to do that I just found the whole surfactant part difficult but the actual building and linking of ideas was not too difficult for me. I enjoyed that part"	
	"So to me, it's just recognizing how many like different things come into play when you have one chemical or physical thing."	
	"to realize how there are so many layers to a concept"	
	"I found practical five a lot better to find the hidden dimensions because you actually have to think of the concepts yourself and not just put concepts in the correct order."	
	"I'm not entirely confident that I do understand it fully, but if I think about I concepts and you understand the relationship, I would say the hidden dimension would be an explanation of the relationship or just extra detail that makes you understand why is there a relationship like that."	*16*
	We were just uncertain, which made it a challenging skill. We weren't really sure if we were ticking off that skill as something that we were able to do confidently because we weren't sure if what we were doing was counted as being able to recognize a hidden dimension. So the vague understanding of what it meant made us unsure if we were achieving that skill"	
	"I think it's just when you have the full diagram, that's when you can take a step back and see the hidden dimensions to do with chemistry and also the other underlying relationships."	
	"I don't wanna lie. I totally didn't understand the skill when I saw it, it felt like it was just all chemistry-related like it required a deep chemistry knowledge of the building blocks of the whole concept."	*15*
	" I could see or understand the hidden dimensions way better in the full SOCME because even if I couldn't see a concept on its own, the way it relates with concepts I understand. It made things easier."	
	"I didn't understand it when we did it until someone explained to me what it meant. I didn't even have a definition of it for myself. It's just something I was unsure about. I only understand it now in someone says these are the examples then I understood it."	*17*
	"I found it easier to understand it when we got the full SOCME in practical four because when I did my own one from the partial one it was a bit harder for me to link hidden dimensions with concepts"	
	" It's easier for me to deduce the hidden dimensions if I have a full SOCME from when I have a partial one, where I still had to put in the concepts in whereas a full SOCME is easier for me to figure out. "	
	"I want to say I also didn't understand the hidden concept and so one of my group members (student 2), explained things thoroughly and that's when I understood."	3

	"I think partial SOCME was easier to demonstrate the hidden dimensions because with the full SOCME it was going to be overwhelming and complicated things for me"	
	"I feel is something that stands out to me when it comes to hidden dimensions. It's the effects of some things are hidden beneath the overall bigger image that we see that we don't necessarily go looking for the things below deeper than that."	*5*
	"We gave our idea of the hidden dimensions related to linear alkyl benzene sulfonate. It was definitely in practical 5 where we were able to demonstrate the hidden dimensions"	
	"o me, the hidden dimensions are the effects of linear alkyl benzene sulfonate but not the obvious effects necessarily."	
	"With practical five we had the freedom of exploring the hidden dimensions ourselves and developing our ideas. We had to think for ourselves and think deeper to see where concepts would fit into the system."	*6*
"organization"	*" fits into the bigger picture is like a puzzle, and you need all the pieces to fit and every piece interacts differently."*	*6*
	"With practical five we had the freedom of exploring the hidden dimensions ourselves and developing our ideas. We had to think for ourselves and think deeper to see where concepts would fit into the system."	
	"breaking down a particular topic into smaller subparts and then linking those parts to other parts in a different system like what we did with the whole economic subsystem, social subsystem, and environmental subsystem. We broke it down into smaller parts and then linked those smaller parts to each other across subsystems "	*2*
	"it's organizing the system components and processes you know, figuring out where they go relative to how they interact with each other, and seeing the relationship between them."	*5*
	"divide them into kind of groups, and then you must link the groups together. So you must divide them and then you must be able to link these specific groups with each other to form relationships between the groups "	*17*
	"it's the thing of combining and almost like an overview perspective and also looking at the detail of looking at how all these concepts link together but still keep the general broad idea in mind "	*16*
	"concepts scattered everywhere and you're linking everything but you don't have that overview feel of how would you organize these into groups "	
	"I think it's not really the skill itself like I think we are very capable of interlinking concepts it' just that we are not put into a lot of positions where we have to use the skill a lot."	
	"I think organisation skills are key to working effectively and efficiently."	*15*
	"being able to connect the relationships a certain factor has with different subsystems like global warming and how it can affect everything from the environment to the economy and how they all relate and affect each other."	
	"understand it like you have to link words, you have to find the relationship between two concepts "	*10*
	"organize was telling me that you needed to have this skill in order to put them to decide which relationships connected where and how to link everything that had flowed and made sense."	*8*
	"was very overwhelming with the SOCME diagram because of the examples and adding new subsystems. I think we were overthinking it, instead of adding new subsystems we were thinking about what could be on the same lane with environmental and economic "	*3*

Systems thinking skills integration: organization

Codes	**Text Content**	**Student ID**
Challenge: complexity	*"You didn't know where to start exactly because you're thinking about everything. If you link it to this concept, where can you link it? As there are so many things you can link it to. I struggled because I was thinking that we are overthinking it and putting too many irrelevant concepts in."*	10
	"everything is in one way or another connected and interacts with each other. So it is hard to know where should I connect or organize this into the whole system?"	5
	"we found quite hard because we had a lot of the other places and couldn't get one and then we struggled to link those big concepts with each other."	17
	"t was very overwhelming with the SOCME diagram because of the examples and adding new subsystems. I think we were overthinking it, instead of adding new subsystems we were thinking about what could be on the same lane with environmental and economic"	3
Challenge: complexity, Challenge: reductionism	*"we tend to focus on a specific part of the diagram and then never look at the whole system and then expand on a single part instead of thinking about how everything fits together."*	6
	"we just get taught things in isolation and we get at the panicked when we have to interlink a lot of concepts together"	16
	"we're so used to being taught things in isolation"	16

Challenge: reductionism	*“within organic chemistry and analytical chemistry, everything was still quite separate and then when we did have to combine things, it felt a bit daunting and unfamiliar”*	16
	“You also focus or think about the other three subsystems that you completely forget other things can also affect that, other than the three subsystems”	10
Challenge: reductionism Challenge: lack of creativity	*“we mainly focused on environmental, societal, and economic. So I feel like that's why most of us didn't think of anything else or struggled because in high school we were trained for five years to only think about those three”*	8
	“your brain is very focused on only those 3 subsystems that we were given, you struggle to expand on that. You're focused on the subsystems instead of trying to think out of the box and trying to create a new subsystem”	5
Challenge: lack of creativity	*“everything that we had thought of was already on the SOCME diagram that was given to us”*	8
	“ Under pressure is difficult to think outside of the box for new subsystems.”	8
	“I just honestly couldn't think of another subsystem. It felt like the where there contained everything”	17
Challenge: expectation Challenge: lack of creativity	*“because it was the first time we did it, we were kind of trying to play it safe and if we do it more and more and more, maybe we'll start thinking about other subsystems as we get used to doing it.”*	17
Challenge: expectation	*“we found instructions a bit unclear in some ways. Like everyone interpreted the instructions differently. So when we came together as a group to work on it, we all had different points of view.”*	8
	“So we were unsure of what was needed from us”	8
	“we didn't really think of more subsystems is because from the information we were given, you feel like you have to stick with what we were given in terms of the slides you gave us with the information you gave us”	16
	“I guess we were just nervous that we would get it wrong somehow”	16
Challenge: lack of practise	*“think it's a skill that we haven't really been super like trained in and it's a bit unfamiliar”*	16
Systems thinking skill chemistry understanding		
Challenge: reductionism	*“I only look at these terms from a scientific perspective”*	2
	“we are just looking at the obvious and for that, we were taught to look at”	10
	“when you got the full one, you could find an area you were familiar with and then work from that to the areas you weren't familiar with”	8
Challenge: relevance	*“I don't consider how they could affect me in real life”*	2
	“in chemistry, they explain how chemistry works, but they don't give us an example of how it applies to everyday life. So that's why the practical I think made it a bit challenging because you have to bring them together.”	5
	“They have to link to the context of the work so that we can have practice why something happens if it does”	10
Challenge: reductionism Challenge: relevance	*“In science, we learn about surface tension, intermolecular forces and we consider it on a physical or chemical level.”*	2
Challenge: relevance Challenge: lack of practise	*“With the SOCME the whole purpose of the practical was to look at these very scientific terms from a real-life practical perspective, which you don't do every day. It was a whole change of mindset. It made it difficult for me because I've never had to consider these things from a real-life perspective before.”*	2
Challenge: lack of practise	*“I think it's like a skill you have to practice and we are not practicing that skill in our everyday life. We have the skills, but it's not exercised. I think that's why I also struggled with that.”*	10
Challenge: complexity,	*“So to me, it's just recognizing how many like different things come into play when you have one chemical or physical thing.”*	2
	“I think partial SOCME was easier to demonstrate the hidden dimensions because with the full SOCME it was going to be overwhelming and complicated things for me”	3
Challenge: complexity, Challenge: difficult to visualize	*There are just too many things going on to also be focusing on the hidden dimensions. I think it's just when you have the full diagram, that's when you can take a step back and see the hidden dimensions to do with chemistry and also the other underlying relationships.*	16
Challenge: difficult to visualize	*“It's not always easy to look deeper and see the overall effect, even the effects of the effects and to dig deeper and expand the layers of the aspect.”*	6
	“I think it's difficult to visualize. If you can't see it directly it is difficult to visualize.”	6

	I don't think in pictures so it is sometimes difficult to see how it works but it's difficult to understand how the processes work and what impact it has on other processes.	6
Challenge: expectation,	*“We were just uncertain, which made it a challenging skill. We weren't really sure if we were ticking off that skill as something that we were able to do confidently because we weren't sure if what we were doing was counted as being able to recognize a hidden dimension. So the vague understanding of what it meant made us unsure if we were achieving that skill”*	16
	we were given a basic framework with the SOCME diagrams, but we did have a lot of room to make our own thing, in terms of our answers as well. We were still uncertain about it, but we didn't feel like we were too much in a box, compared to other projects that we usually get for chemistry and other subjects.	16
	“I feel like I was extra worried in order to get marks will for chemistry.”	8
	“I enjoyed learning new things, but I was really worried about marks. I wanted to get as much as possible. I didn't want to indicate concepts or words I didn’t understand or take a gamble with something.”	17
Challenge: expectation, Challenge: lack of creativity	*“I really enjoyed this project because it really allowed us to think outside the box. We have so little opportunity, I think maybe it's just us being in the first year, but we don't have too much opportunity of going away from a rubric because even the chemistry practicals we are still at a basic level we can't design our own experiments and come up with our own hypotheses and stuff, but we aren't exposed to being pushed out of what is expected of us and using our creativity. We have this expectation that our main priority is doing what we think the examiner wants from us compared to what we think is a valid answer to a question. We don't really allow ourselves to use our own interpretations like we're worrying that's our own interpretation is wrong and it has to be the in the context since that the examiner wants us to be thinking within.”*	16
Challenge: lack of creativity	*I don't do my own thing or think creatively.*	17

D6. SUBMITTED AND ANALYSED SOCME DIAGRAMS

Home Group 1

Student 1H,2M,3L

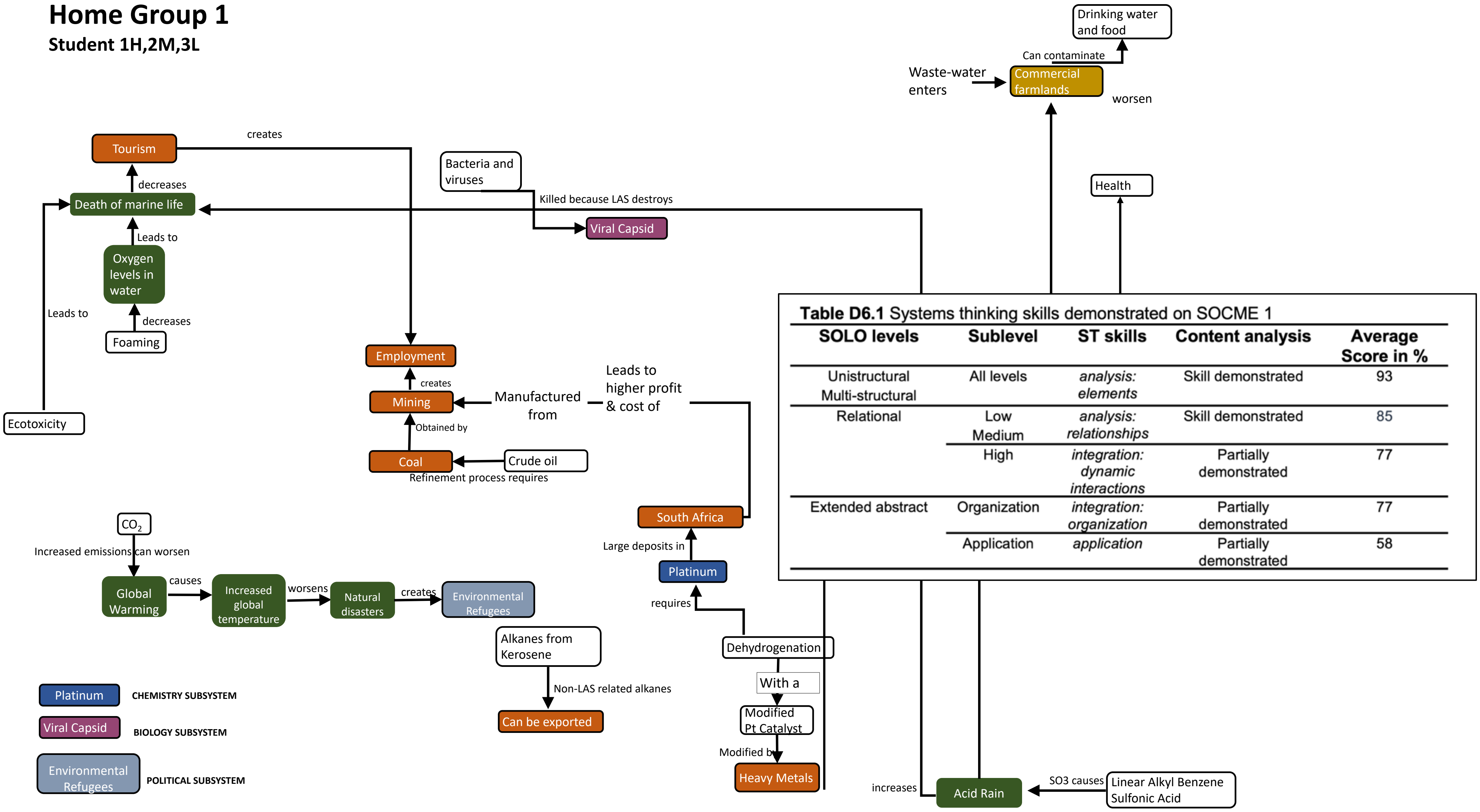


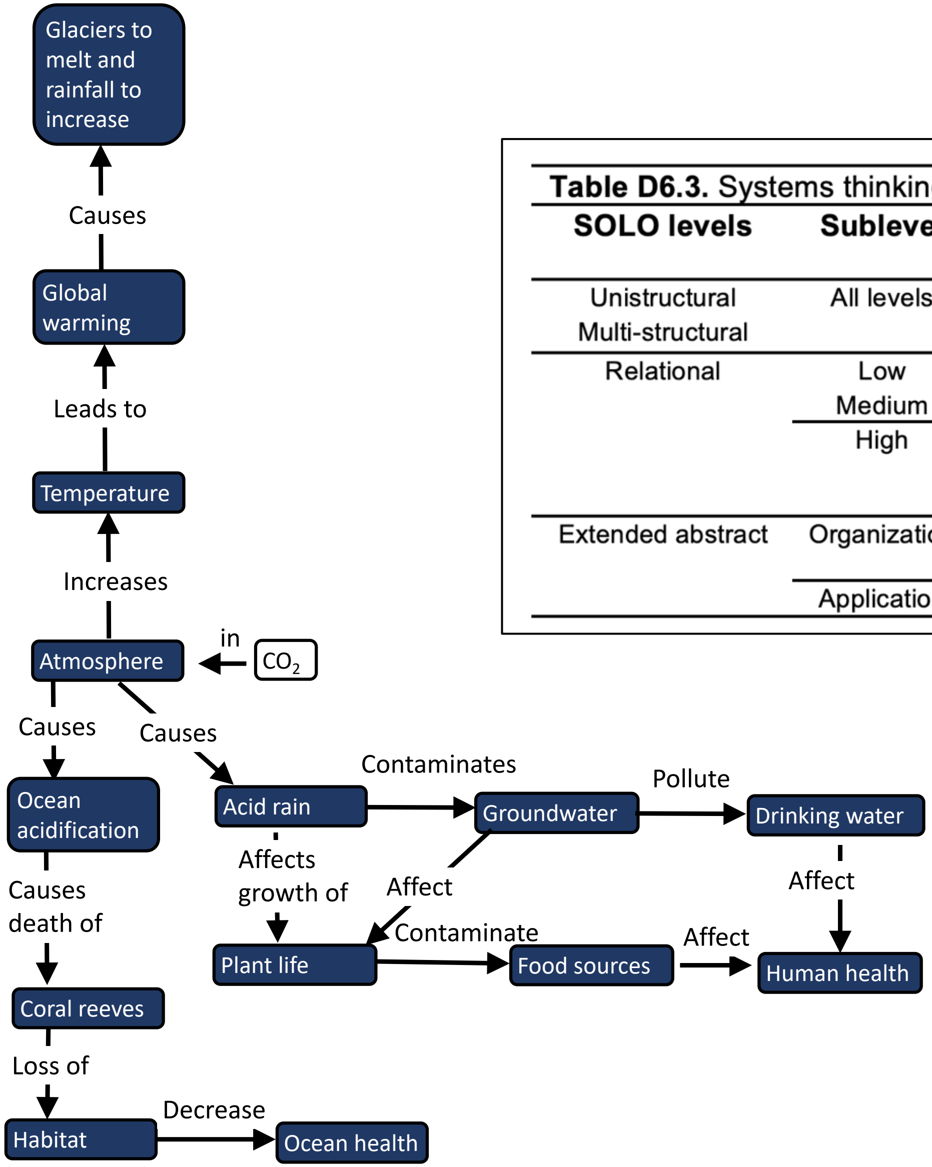
Table D6.1 Systems thinking skills demonstrated on SOCME 1

SOLO levels	Sublevel	ST skills	Content analysis	Average Score in %
Unistructural Multi-structural	All levels	*analysis: elements*	Skill demonstrated	93
Relational	Low Medium	*analysis: relationships*	Skill demonstrated	85
	High	*integration: dynamic interactions*	Partially demonstrated	77
Extended abstract	Organization	*integration: organization*	Partially demonstrated	77
	Application	*application*	Partially demonstrated	58

Data analysis of SOCME 1

Table D6.2 Data analysis of SOCME 1

SOLO levels	**Sub level**	**Total per level**	**Level average 3 raters**	**Systems thinking skills**	**Rater feedback**	**Content Analysis**	**Demonstration and development of systems thinking skills**
Unistructural		8	8,00	*Analysis: elements*	• Rater 2 *“mostly good concepts” were added.*	• 17 new concepts added • Relevant and in the correct format.	Demonstrated and was developing
Multi-structural	Low	8	7,33				
	Medium	8	7,33				
	High	8	7,00				
Relational	Low	10	8,00	*Analysis: relational*	• Rater 1: *“good understanding of the connections” “some linking words that could have been chosen more appropriately”.* • Rater 2 *“linking words are not always propositions ”*and *“do not fit well as linking words”.*	• Some connections did not have linking words or were poorly described, lacking in quality. • Example: *“Crude oil refinement process requires coal obtained by mining creates employment” and “death of marine life decreases tourism, creates employment”* No linking words were added between South Africa *and mining*	Demonstrated and were developing
	Medium	10	9,00				
	High	10	7,67	*Integration: dynamic interactions*	• Rater 1 *“good understanding of interlinking the different subsystems”*	• 3 connections were made between subsystems with poor quality linking words • Examples: “*acid rain contaminates commercial farmlands” “heavy metals worsen health*” and *“acid rain increases death of marine life, decreases tourism”.* • 2 relationships had linking words that implied possible change over time (“Acid rain” *increases* “death of marine life” which *decreases* “tourism”)	Partially demonstrated and thus were developing to a lesser extent
Extended abstract	Organization	10	7,67	*Integration: organization*	• Rater 2 “SOCME as a whole was very disorganized and very hard to read”.	• 3 new subsystems added as concepts • Poor organization of concepts • *Environmental refugees* formed part of the *political subsystem*, *viral capsid* as part of the *biology subsystem* and *platinum* as part of the *chemistry subsystem*.	Partially demonstrated, developing to a lesser extent
	Application	8	4,67	*Application*	• Rater 2 “did not relate most of their concepts to Prediction B”	• concepts and connections relating to global warming and to the political subsystem. • lacking integration across subsystems	Partially demonstrated, skill developing
Averaged total out of 80		**67**					



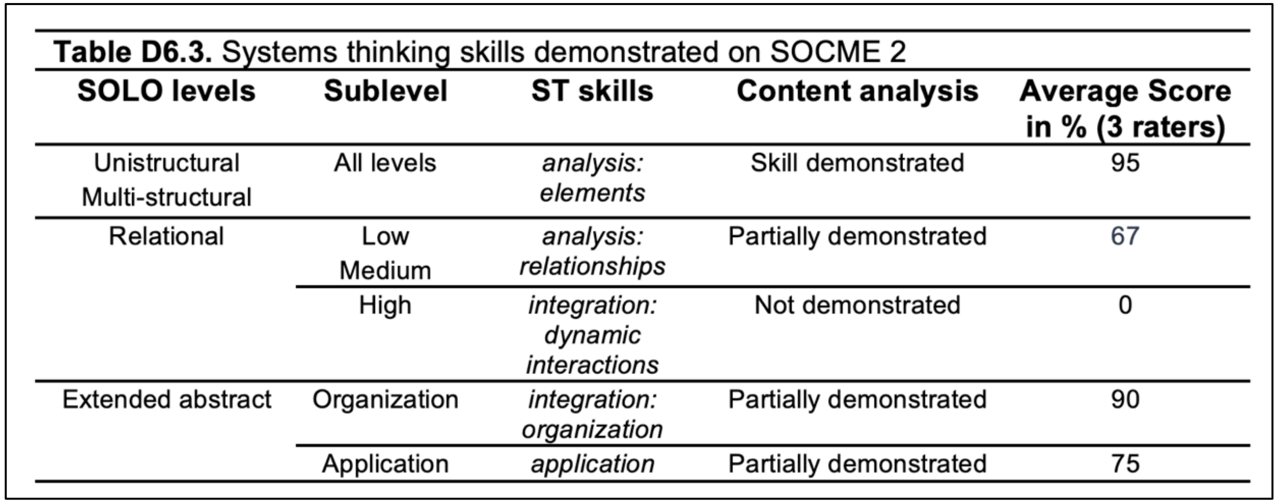


Table D6.3. Systems thinking skills demonstrated on SOCME 2

SOLO levels	Sublevel	ST skills	Content analysis	Average Score in % (3 raters)
Unistructural Multi-structural	All levels	*analysis: elements*	Skill demonstrated	95
Relational	Low Medium	*analysis: relationships*	Partially demonstrated	67
	High	*integration: dynamic interactions*	Not demonstrated	0
Extended abstract	Organization	*integration: organization*	Partially demonstrated	90
	Application	*application*	Partially demonstrated	75

Home Group 2

Student 4H,5M,6L

Table D6.4. Data Analysis of SOCME 2

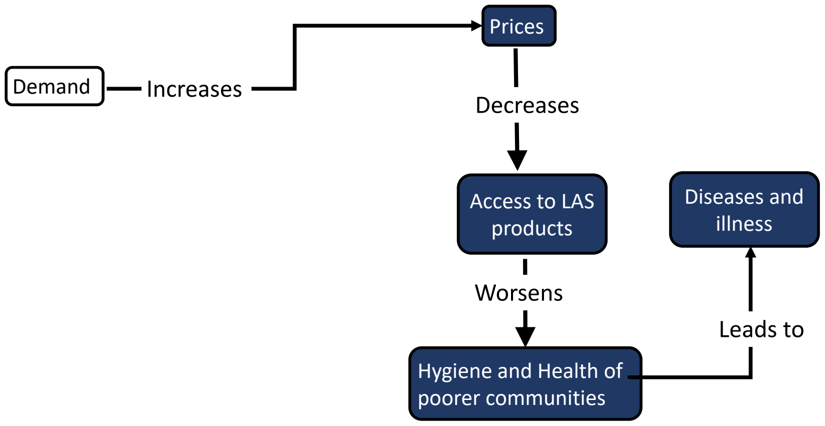
SOLO levels	Sub level	Total per level	Level average or 3 raters	Systems thinking skills	Rater feedback	Content Analysis	Demonstration and development of systems thinking skills
Unistructural		8	7,67	Analysis: elements	- Rater 1 commented that the SOCME had a “very good section for one subsystem”. - Rater 2 commented that the group needed to “add new concepts for more than one subsystem “ as the group “only added new concepts related to the environmental subsystem”	- 14 new concepts in the correct format were added, that was only relevant to future predictions. - Good quality concepts - One concept (*glaciers to melt and rainfall to increase)* contained a linking word and could have been improved.	Demonstrated and was developing.
Multi-structural	Low	8	7,67				
	Medium	8	7,67				
	High	8	7,33				
Relational	Low	10	10,00	Analysis: relational	- No rater feedback	- connections made between concepts were good within the new subsystem. - good quality linking words with the use of verbs indicating cause and affects	Demonstrated and were developing
	Medium	10	3,33				
	High	10	0,00	*Integration: dynamic interactions*	- Rater 1 commented that there were “not enough connections between subsystems.”	- concepts weren't linked to other subsystems, connections were only made within the new subsystem. - Almost all connections added could imply change over time with the linking words *causes, increases and affects”*	Not demonstrated, developing to a lesser extent.
Extended abstract	Organization	10	9,00	*Integration: organization*	- Rater 1 commented that “the focus was only on the one subsystem and the others were almost completely omitted”	- a new subsystem without labels were added - only based on a prediction - all concepts belonged within the environmental subsystem except human health and food sources, which could have been connected to the societal subsystem.	Partially demonstrated, developing to a lesser extent.
	Application	8	6,00	Application	- No rater feedback	- Students did a great job at applying knowledge on the future impacts of LAS - Lacking in overall connections to other subsystems was lacking.	Partially demonstrated, developing to a lesser extent.
Averaged Total out of 80		**59**					

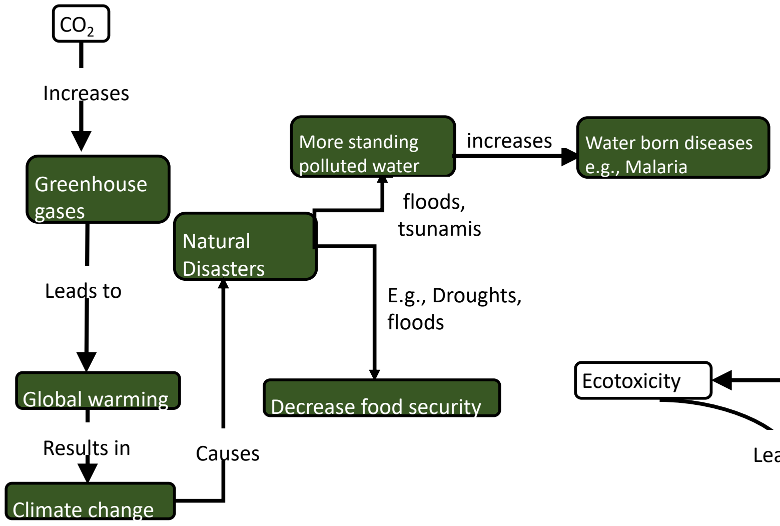
Table D6.5. ST skills demonstrated on SOCME submitted by Homegroup 3

SOLO levels	Sublevel	ST skills	Content analysis	Average Score in % (3 raters)
Unistructural Multi-structural	All levels	*analysis: elements*	Skill demonstrated	98
Relational	Low Medium	*analysis: relationships*	Skill demonstrated	82
	High	*integration: dynamic interactions*	Partially demonstrated	57
Extended abstract	organization	*integration: organization*	Partially demonstrated	47
	Application	*application*	Partially demonstrated	79

Home Group 3

Student 7H,8M,9L


Demand
Increases
Prices
Decreases
Access to LAS products
Worsens
Hygiene and Health of poorer communities
Leads to
Diseases and illness


CO_2
Increases
Greenhouse gases
Leads to
Global warming
Results in
Climate change
Causes
Natural Disasters
floods, tsunamis
More standing polluted water
increases
Water born diseases e.g., Malaria
E.g., Droughts, floods
Decrease food security

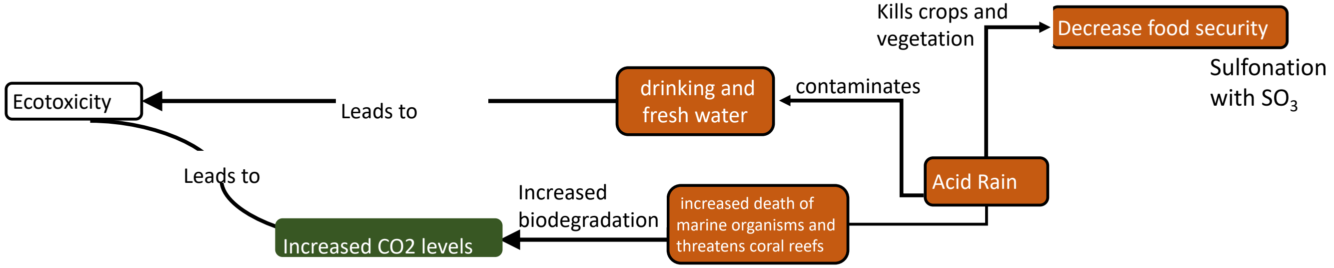

Acid Rain
Kills crops and vegetation
Decrease food security
Sulfonation with SO_3
contaminates
drinking and fresh water
Leads to
Ecotoxicity
increased death of marine organisms and threatens coral reefs
Increased biodegradation
Increased CO2 levels
Leads to

Table D6.6. Data Analysis of SOCME 3

SOLO levels	Sub level	Total per level	Level average	Systems thinking skills	Rater feedback	Content Analysis	Demonstration and development of systems thinking skills
Unistructural		8	8,00	Analysis: elements	• Rater 1 commented that "some good ideas and concepts" were added to the partial SOCME • Rater 2 agreed that "a lot of the concepts were good"	• 16 new concepts were added, where linking words were part of some of the concepts, such as *decreased food security* and *increased CO_2 levels*. • good concepts added, with some lacking in quality.	Demonstrated and was developing.
Multi-structural	Low	8	8,00				
	Medium	8	8,00				
	High	8	7,33				
Relational	Low	10	9,00	Analysis: relational	• Rater 1 commented that "the implementation and connection" of the concepts "were lacking"	• Connections added between concepts some linking words are not appropriate to form good propositions. • Example: *Linear Alkyl Benzene Sulfonic acid mixed with water acid rain.* • connections weren't even made within all three subsystems, only in environmental subsystem.	Demonstrated and were developing
	Medium	10	7,33				
	High	10	5,67	Integration: dynamic interactions	• Rater 1 commented that "some concepts were used multiple times in different subsystems and instead of connecting the subsystems via these concepts they were kept isolated"	• 3 Connections were made between subsystems, where two connections linked the economic with societal subsystem and one connections between economic and a new subsystem.	Partially demonstrated, developing to a lesser extent.
Extended abstract	Organization	10	4,67	Integration: organization	• Rater 1 commented that "the SOCME was not very neat, which made it difficult to follow the propositions and flow of thoughts" • Rater 2 commented that the concepts were " not fit them into their correct subsystems" and	• a new unlabelled subsystem was added • concepts in new subsystem fit better into the economic and societal subsystems. • lack in organization of concepts in the economic subsystem, that fit better into the environmental subsystem.	Partially demonstrated, developing to a lesser extent.
	Application	8	6,33	Application	• No rater feedback	• Students had a good prediction in the environmental subsystem, with good concepts and linking words, however, the overall picture of the SOCME was lacking.	Partially demonstrated, developing to a lesser extent.
Averaged Total out of 80		**64**					

Home Group 4

Student 10H,11M,12L

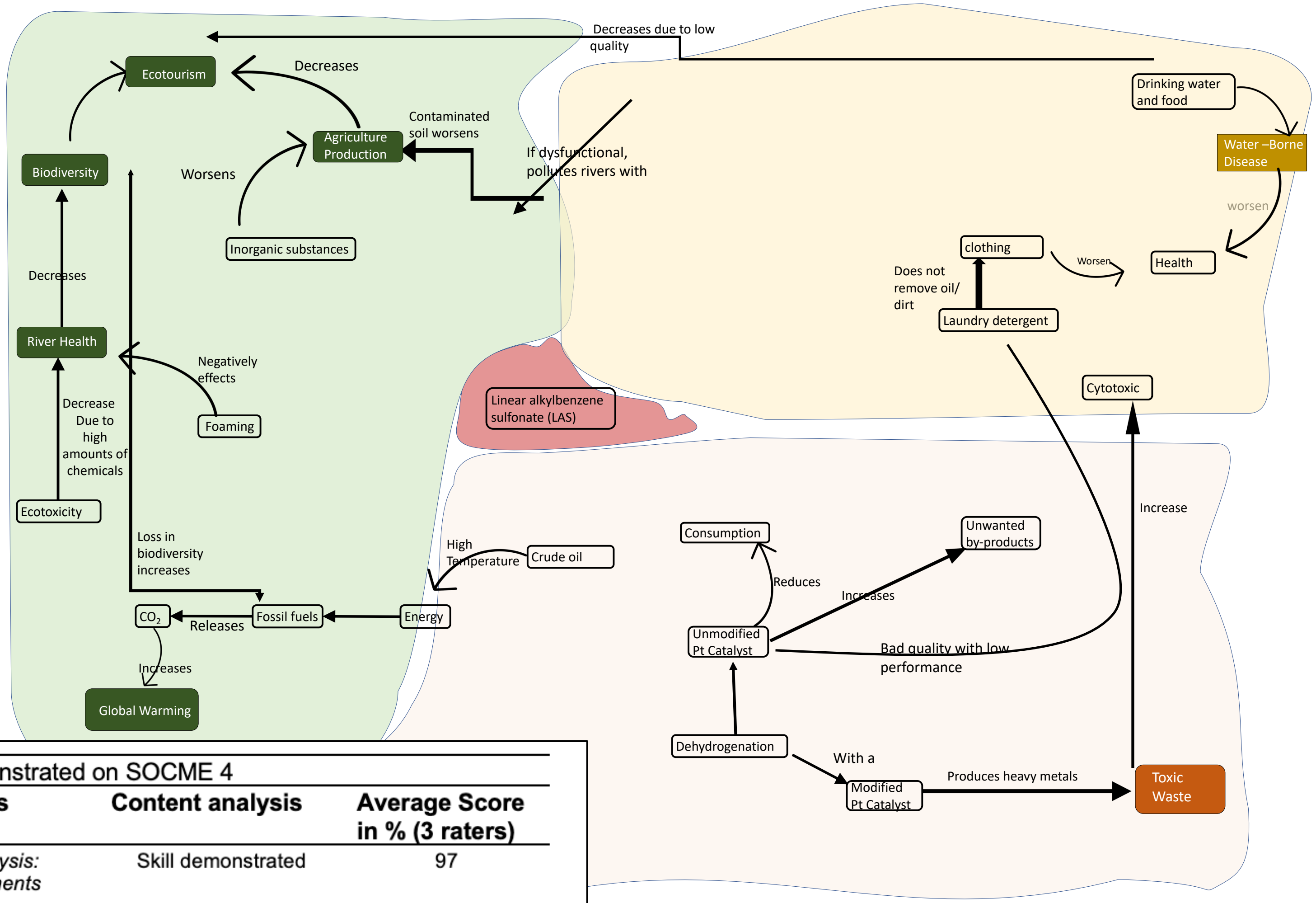


Table D6.7. Systems thinking skills demonstrated on SOCME 4

SOLO levels	Sublevel	ST skills	Content analysis	Average Score in % (3 raters)
Unistructural Multi-structural	All levels	*analysis: elements*	Skill demonstrated	97
Relational	Low Medium	*analysis: relationships*	Skill demonstrated	83
	High	*integration: dynamic interactions*	Partially demonstrated	67
Extended abstract	Organization	*integration: organization*	Partially demonstrated	70
	Application	*application*	Partially demonstrated	38

Table D6.8. Data Analysis of SOCME 4

SOLO levels	Sub level	Total per level	Level average of 3 raters	Systems thinking skills	Rater feedback	Content Analysis	Demonstration and development of systems thinking skills
Unistructural		8	8,00	Analysis: elements	- Rater 1 “*Overall some good concepts were added.*”	- 7 new concepts added that were good quality	Demonstrated and was developing.
Multi-structural	Low	8	7,67				
	Medium	8	7,67				
	High	8	7,67				
Relational	Low	10	9,33	Analysis: relational	- Rater 1 *“lacking in the linking words. Some connections are not clear and end up leading nowhere”* - Rater 2 *“some of your arrows did not connect to anything, did not have arrowheads, or were weird sizes”*	- Most connections made between existing concepts, with the addition of linking words - linking words were poorly described making it difficult to read - some unclear connections - example “*ecotoxicity decreases due to high amounts of chemicals”*	Demonstrated and were developing
	Medium	10	7,33				
	High	10	6,67	Integration: dynamic interactions	- No rater feedback	- This group made 4 connections between different subsystems. - Example “*toxic waste increase cytotoxic”* linking economic and societal subsystems - Lack in quality making it difficult to read propositions - Example “*drinking water and food decreases due to low quality ecotourism”* - Words increases and decreases could imply change over time	Partially demonstrated, developing to a lesser extent.
Extended abstract	Organization	10	7,00	Integration: organization	- Rater 2 “*Your blocks needed to be coloured according to each subsystem, which you did not do. You also did not add in a new subsystem”*	- This group organized the concepts into relevant subsystem boundaries that were provided but did not construct new subsystem boundaries and thus did not add any new subsystems	Partially demonstrated, developing to a lesser extent.
	Application	8	3,00	Application	- Rater 2 *“You chose prediction B but did not mention much about it. You needed to mention water quality, high concentration, washing in rivers, excessive foaming, blocking of sunlight, aquatic life, water pollution, etc.”*	- students evaluated the impact of ecotoxicity on river health but did not make a future prediction that is clear and upfront - meaningful connections were made, the concepts were not relevant to the prediction the group has chosen to expand on which was about global warming concepts	Partially demonstrated, developing to a lesser extent.
Averaged Total out of 80		**64**					

Home Group 5

Student 13H,14M,15L

Table D6.9. ST skills demonstrated on SOCME 5

SOLO levels	Sublevel	ST skills	Content analysis	Average Score in % (3 raters)
Unistructural Multi-structural	All levels	*analysis: elements*	Skill demonstrated	100
Relational	Low Medium	*analysis: relationships*	Skill demonstrated	88
	High	*integration: dynamic interactions*	Partially demonstrated	90
Extended abstract	Organization	*integration: organization*	Skill demonstrated	97
	Application	*application*	Partially demonstrated	75

Agricultural subsystem

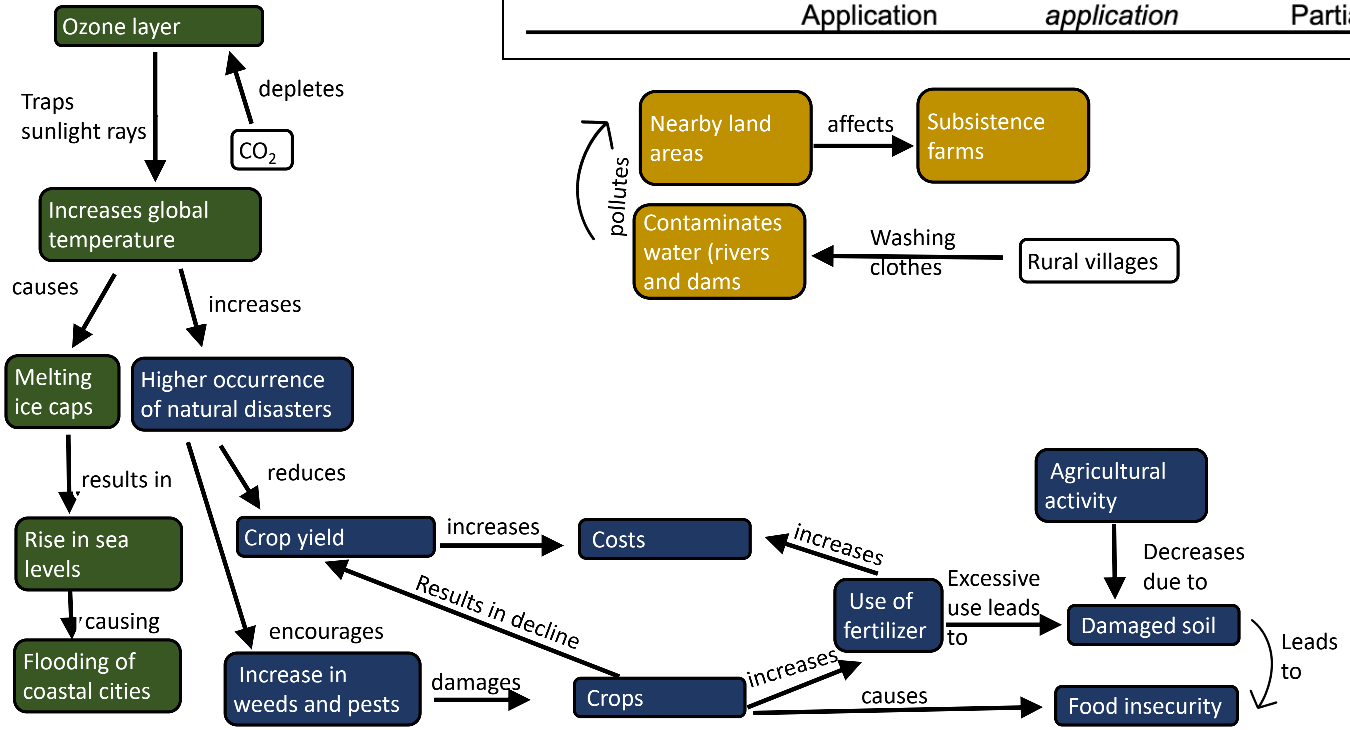
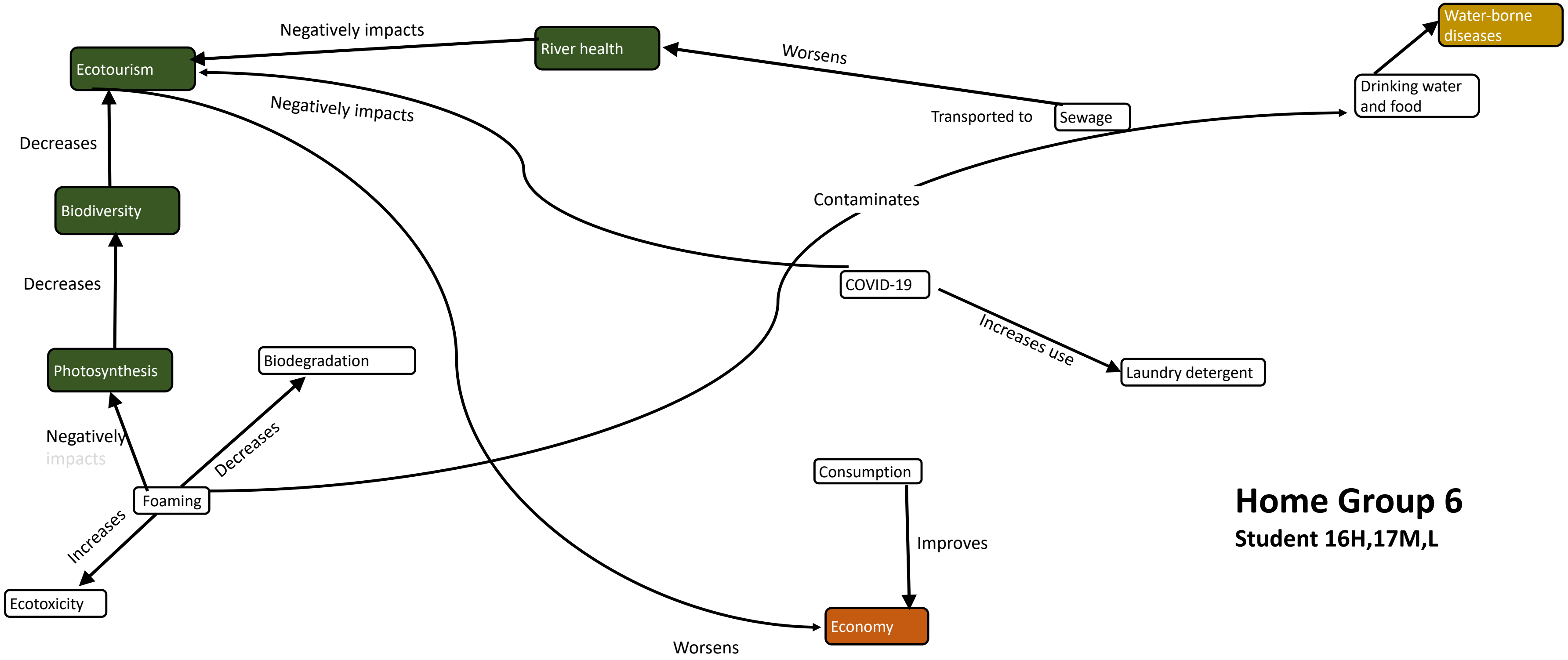


Table D6.10. Data Analysis of SOCME 5

SOLO levels	Sub level	Total per level	Level average	Systems thinking skills	Rater feedback	Content Analysis	Demonstration and development of systems thinking skills
Unistructural		8	8,00	Analysis: elements	• no rater feedback	• 17 new concepts were added, good quality concepts • some concepts contained linking words. *(increases global warming)* • All concepts are about future predictions Some concepts are not used correctly in context. For example, *carbon dioxide depletes the ozone layer, which blocks sunlight and increases the global temperature.*	Demonstrated and was developing.
Multi-structural	Low	8	8,00				
	Medium	8	8,00				
	High	8	8,00				
Relational	Low	10	9,67	Analysis: relational	• no rater feedback	• good linking words, that are mostly verbs. *(increases, decreases, causes, envourages..)* • Propositions are easy to read and coherent.	Demonstrated and were developing
	Medium	10	8,00				
	High	10	9,00	Integration: dynamic interactions	• no rater feedback	• the group made only 1 connection between subsystems, which was related to a future prediction (*increases global temperatures and higher occurrence of natural disasters)* • Most connections could imply changes over time	Partially demonstrated, developing to a lesser extent.
Extended abstract	Organization	10	9,67	Integration: organization	• no rater feedback	• creative subsystem on agriculture added with relevant concepts • added concepts in new subsystem are well organized. • Some of the concepts in the subsystem could have been part of the societal subsystem *(food insecurity)*	Skill demonstrated, developing to a lesser extent.
	Application	8	6,00	Application	• Rater 2 "Good work, but your added concepts could have related more to your Prediction (A)."	• The application of knowledge to make predictions on future impacts was good and included a new area of impact, which is the agricultural subsystem • The lack of integration between subsystems has revealed a lack of application to make predictions that relate to impacts on other subsystems.	Partially demonstrated, developing to a lesser extent.
Averaged Total out of 80		**74**					



Home Group 6

Student 16H,17M,L

Table D 6.11. Systems thinking skills demonstrated on SOCME 6

SOLO levels	Sublevel	ST skills	Content analysis	Average Score in % (3 raters)
Unistructural Multi-structural	All levels	*analysis: elements*	Skill demonstrated	100
Relational	Low Medium	*analysis: relationships*	Skill demonstrated	88
	High	*integration: dynamic interactions*	Partially demonstrated	93
Extended abstract	Organization	*integration: organization*	Partially demonstrated	83
	Application	*application*	Partially demonstrated	58

Table D6.12. Data Analysis of SOCME 5

SOLO levels	Sub level	Total per level	Level average	Systems thinking skills	Rater feedback	Content Analysis	Demonstration and development of systems thinking skills
Unistructural		8	8,00	Analysis: elements	- No rater feedback	- 6 concepts were added of good quality *(water-borne diseases, river health, ecotourism, biodiversity, photosynthesis and economy)*	Demonstrated and was developing.
Multi-structural	Low	8	8,00				
	Medium	8	8,00				
	High	8	8,00				
Relational	Low	10	9,67	Analysis: relational	- Rater 1 *"Generally very good in the overall connections and linking words"*	- Good linking words that are verbs used (*decreases, worsens.)* - connections were made mostly with the newly added concept in the environmental subsystem - limited connections within other subsystems. - More explanations on linking words required	Demonstrated and were developing
	Medium	10	8,67				
	High	10	9,33	Integration: dynamic interactions	- No rater feedback	- 3 connections made between subsystems (*economy and ecotourism, foaming and drinking water and food and sewage and river health)* - Connections and integration across all the subsystems not shown - Potential change over time clear in one connections, others not so clear (example sewage worsens river health could occur over time.)	Partially demonstrated, developing to a lesser extent.
Extended abstract	Organization	10	8,33	Integration: organization	- No rater feedback	- Students did not add new subsystem boundaries, however, the overall organization of concepts within and between already existing subsystems was good.	Partially demonstrated, developing to a lesser extent.
	Application	8	4,67	Application	Rater 1 *"lacking in several concepts and especially concepts relevant to the prediction chosen."*	- No application of knowledge to make predictions or generalisations that relate to possible effects in the future of global warming or foaming to a large extent, even though *"foaming decreased biodegradation was added"*	Partially demonstrated, developing to a lesser extent.
Averaged Total out of 80	**73**						

D7. RATER FEEDBACK QUESTIONS AND RESPONSES

Question 2

In your opinion, which of the following systems thinking skills were too difficult for students to apply as they constructed their SOCME diagram?

	Systems Thinking Skills from the STH model	Rater feedback
1	The ability to identify the components of a system and processes within the system (Identify relevant concepts that fit into a subsystem and the whole system)	
2	The ability to identify relationships among the system's components (Identify meaningful linking words that describe the relationship between concepts)	Tutor 1 "some struggled with this but to a lesser extent"
3	The ability to identify dynamic relationships within a system (changing relationships, this could also be feedback loops)	Both tutors
4	The ability to organize the system's components and processes (within and between subsystems)	Both tutors Tutor 1 comment, "only between"
5	The ability to understand the cyclic nature of systems (from their origin in crude oil to their ultimate biodegradation, also feedback loops)	Both tutors
6	The ability to generalise (generalisations based on feedback loops relating to unwanted by-products, its influence on the detergent quality and market consumption, modified catalysts and hazardous waste, fractional distillation, fossil fuels and global warming, reagents used in syntheses, such as sulfuric acid and sulfur trioxide and it's environmental, societal and economic impacts) generalisations are inferences made from specific cases.)	
7	The ability to recognise the hidden dimensions of the system (intermolecular forces, surface tension, molecular geometry, acidity, and basicity, nucleophilicity, solubility, polarity)	Both tutors
8	Thinking temporally: including the effects of past human action and predicting the effects of future human action. (Prediction A and B)	

Question 3

In your opinion, which of the following learning outcomes do you think students achieved as you assessed their SOCME diagrams?

Learning Outcomes	ST Skill	Rater Feedback
List and **illustrate** the causes of cyclic behaviours within the social, economic, and environmental systems by drawing in positive or negative feedback loops.	Skill 5	Rater 1 "to a certain degree" only few loops mainly outcomes"
Identify variables in a subsystem that influence the whole system by referring to hidden dimensions within the chemistry (intermolecular forces, surface tension, molecular geometry, acidity, and basicity, nucleophilicity, solubility, polarity)	Skill 7	No response
Analyse whether the concepts combine to yield a system property/behaviour that could not be predicted by looking at LAS alone.	STH model does not account for this	Both raters
Make predictions and **generalisations** based on trends and hidden dimensions that influence how systems-level behaviour changes over time when the chemistry variables are altered.	Skill 6 Skill 8	Both raters

Question 4

From the SOCME diagrams that you have assessed, how many groups were able to identify new system boundaries of subsystems within the economic, social, and environmental systems. Any other observations?

"In general the groups were able to add generalized concepts & ideas and connect them to each other & existing concepts. 2-3 groups identified new system boundaries and included new subsystems in the SOCME. The chemistry aspect to surfactants was lacking. Most of the groups stuck to generalized concepts such as global warming ect."Rater 1

"A lot of students did not add in new subsystems to their maps. Their maps were quite disorganized and had crossing arrows. The ones that did add new subsystems had concepts that did not match the new subsystem" Rater 2