Integrating systems thinking and essential skills into chemistry education: the CLEAR initiative for sustainability

Integrating Systems Thinking and Essential Skills into Chemistry Education:

The CLEAR Initiative for Sustainability

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Abstract

Traditional reductionist approaches in chemistry education, which focus on breaking down complex systems into individual components, often fail to provide students with a holistic understanding of these systems and their dynamic interactions. This limitation becomes particularly evident when addressing sustainability topics, which require an integrated view of how chemical, environmental, economic and societal factors interact. To bridge this gap, the **C**hemistry **L**earning for **E**nvironmental **A**ction and **R**esponsibility (CLEAR) initiative at the University of Twente's Chemical Science & Engineering programme integrates systems thinking into its bachelor curriculum. The aim is to equip students with the knowledge, skills, and attitudes necessary to tackle complex sustainability challenges. CLEAR is built on three pillars: Essential Skills Development, Sustainability-Driven Curriculum Enhancement, and a Supportive Learning Environment. Since its implementation, the initiative has engaged three cohorts, involving 150 students trained to critically analyse sustainability claims. Early evidence suggests that CLEAR has the potential to serve as a model for other engineering programmes seeking to incorporate similar approaches into their curricula, thereby advancing education for sustainability on a broader scale.

1 Introduction

Preparing future engineers and scientists to address the grand challenges of the 21st century, such as the United Nations' Sustainable Development Goals (SDGs), requires more than technical expertise. It demands a deep understanding of how systems interact within their broader environments (Darling-Hammond, 2006; Griffin et al., 2012). Global issues like climate change, biodiversity loss, and urban growth are inherently interconnected, requiring a shift from isolated problem-solving to a holistic, systems-oriented approach (Mahaffy et al., 2018).

In the context of chemistry education, systems thinking (ST) provides a lens through which students can analyse and solve real-world problems by considering the interdependencies between chemical processes, environmental factors, and societal impacts (Pazicni & Flynn, 2019). However, traditional chemistry curricula often focus on isolated concepts and reductionist approaches, which may limit students' ability to grasp the broader implications of chemical phenomena within complex systems (Mahaffy et al., 2018). To bridge this gap, the CLEAR initiative integrates systems thinking and essential skills into a Chemical Science & Engineering bachelor curriculum. The aim is to equip students with the knowledge, skills, and attitudes necessary to tackle complex sustainability challenges and develop an understanding of the interconnectedness of processes within larger systems.

2 Theoretical background

2.1 Systems Thinking in Chemistry Education

ST is increasingly recognized as a transformative approach in education, particularly in disciplines like engineering, where addressing complex, interconnected problems is fundamental (Flynn et al., 2019). Defined as "*the ability to understand and interpret complex systems*", ST helps students visualize interconnections, examine changes over time, and analyse how system-level phenomena emerge from the interactions of parts (Evagorou et al., 2009). This approach fosters higher-order thinking by encouraging learners to go beyond rote memorization and engage in analysis, synthesis, and evaluation (Forehand, 2010). Moreover, a key strength of ST is its emphasis on multiple perspectives. For example, when addressing challenges like energy storage or waste management, students must consider technical specifications alongside ecological and societal implications. This multidimensional perspective is essential for engineers, who must balance stakeholder needs and long-term consequences in their designs (Krab-Hüsken et al., 2023). Chemistry, often called “the central science” for its connections to other disciplines (Balaban & Klein, 2006), is uniquely positioned to benefit from ST.

2.2 Pedagogical Shifts to Support Systems Thinking

Implementing ST into existing chemistry education requires careful consideration of several interconnected factors. First, a recurring theme in the literature is the necessity of embedding ST deeply within curriculum design, beyond superficial modifications (Flynn et al., 2019). This could include developing case studies, problem-based learning scenarios, or interdisciplinary projects that encourage students to analyse systems rather as a whole than in isolation (Orgill et al., 2019; York et al., 2019). Additionally, assessments must be redesigned to evaluate students' ability to apply ST concepts, such as identifying relationships between components, predicting system behaviour, and proposing solutions to complex problems (Krab-Hüsken et al., 2023). Secondly, Integrating ST necessitates a shift in pedagogical strategies toward student-centred approaches. ST can initially appear abstract and challenging for students, particularly those transitioning from high school to university, as they may be accustomed to more linear and reductionist modes of learning (Krab-Hüsken et al., 2023). Effective scaffolding, such as using relatable examples, visual tools like concept mapping, and collaborative projects can gradually build ST proficiency (Krab-Hüsken et al., 2023). Thirdly, the role of teachers must evolve to support this transition. They must move beyond their traditional role as transmitters of knowledge and adopt the mindset of learning facilitators (Richardson et al., 2012). This facilitator role involves guiding students through complex problem-solving tasks, encouraging critical thinking, and fostering collaborative discussions that allow diverse perspectives to emerge (Garrison & Vaughan, 2011).

3 The CLEAR Initiative

3.1 Overview

This project is conducted at the University of Twente (UT) in the Netherlands, within the programme Chemical Science & Engineering (CSE). In 2018, the CSE programme transitioned into an internationally oriented, English-taught curriculum, reflecting the university's commitment to global education and interdisciplinary collaboration. The programme is structured around the Twente Educational Model, which organizes bachelor's education into twelve 15-EC (European Credit) thematic modules, each spanning 10 weeks. Each module contains a project, which requires students to incorporate concepts from the module. This approach provides a foundation for embedding ST into the curriculum, highlighting the interconnectedness of elements within the systems. The CLEAR framework was designed to foster students' systems thinking, supported by three interrelated pillars (see Figure 1):

- Essential-Skills Development,
- Sustainability-Driven Curriculum Enhancement, and a
- Supportive Learning Environment

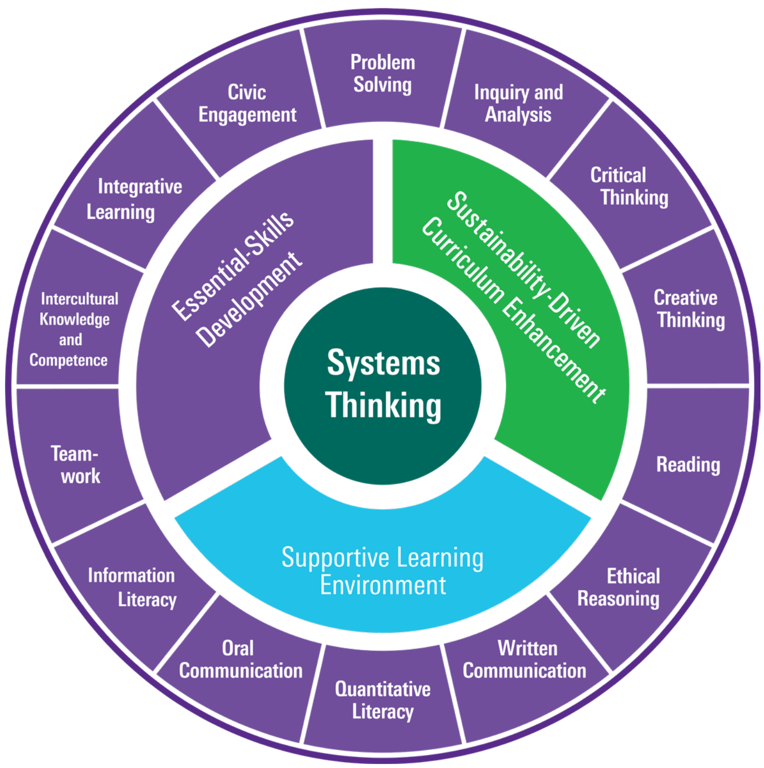

Figure 1: CLEAR framework

Supported by conceptual modelling, a practical tool for navigating sustainability topics, ST is embedded progressively across the programme (Krab-Hüsken et al., 2023). In Module 1, students engage in collaborative projects that lay the groundwork for understanding complex systems. For example, students assess per- and polyfluoroalkyl substances (PFAS) or heavy metals accumulation in water and their implications for the environment and society, or how to turn carbon dioxide into valuable products. By Module 4, they practice ST through advanced projects in laboratory settings, including exploring batteries using electrochemical tools and validating their propositions within sustainability frameworks. In Module 5, they perform a Social and Environmental Life Cycle Assessment (SELCA). In Module 8, students systematically evaluate and reach a consensus on sustainability solutions. We are also working on incorporating ST into Module 12; the thesis project of the bachelor programme. This structured progression helps students to synthesize their learning across the curriculum, enabling them to apply their evolving ST to address sustainability issues and develop practical solutions.

3.2 Pillar 1: Essential-Skills Development

CLEAR equips students with a set of fourteen essential skills (Figure 1) to tackle global sustainability challenges, drawing inspiration from Engineering for One Planet (Reynante, 2022) and the AAC&U VALUE rubrics (AAC&U, 2017). These skills are categorized into two groups: those directly related to ST, such as critical thinking, or inquiry and analysis for sustainable solutions, and those that support ST indirectly, such as information literacy and communication. The development of these skills is reinforced through a structured reflection cycle. Students begin with a self-assessment, practice the skills during a 10-week project, and conclude with another self-assessment and a written reflection, which is reviewed by teachers for feedback. This iterative process helps students articulate their progress, identify areas for growth, and take ownership of their learning (Chuanchom et al., 2024; Masui & De Corte, 2005). Two illustrative examples of skill development include:

- Quantitative literacy: In small groups, students perform back-of-the-envelope calculations: e.g., estimating an airplane's range with a battery replacing fossil fuels, daily pipette-tip usage at our institution, or annual carbon dioxide storage by an oak tree. They articulate assumptions, calculate outcomes, and reflect on their quantitative-literacy skills *(interpretation, representation, calculation, application, assumptions, communication*) using the rubric (AAC&U, 2017).

- Intercultural Knowledge & Competence: Given the diversity of our student body, with approximately half of the students being Dutch, a quarter coming from other EU countries, and a quarter from non-EU countries, CLEAR provides opportunities for students to develop intercultural competence within multicultural project teams. Students practice integrating diverse perspectives when addressing sustainability challenges, fostering cultural awareness and open communication, particularly around differing understandings of sustainability (Krab-Hüsken et al., 2022). Additional exercises on communication styles, time perception and differing views on SDGs enhance their ability to collaborate across cultures, a vital skill for tackling global sustainability problems (Krab-Hüsken et al., 2022).

3.3 Sustainability-Driven Curriculum Enhancement

CLEAR has led to a curriculum renewal that integrates interdisciplinary approaches reflecting sustainability principles. For example, In Module 5, students leverage knowledge from Module 2, particularly thermodynamics and separation methods, to evaluate the sustainability of industrial processes using social-environmental life cycle analyses. Case studies involve evaluating a recycling process (jeans-to-jeans) and sustainable fuel to replace diesel and kerosine.

Module 8 focuses on ST through the concept of the three "Capitals": Natural Capital (e.g., resources like clean air and healthy ecosystems), Social and Human Capital (community engagement); and Manufactured and Financial Capital (economic impacts of solutions). This interdisciplinary approach encourages students to think systemically about environmental, social and economic consequences of sustainable technical innovations and collaboratively develop balanced solutions. Students first gain fundamental knowledge about sustainable materials and collaborate in groups to propose and evaluate technical improvements, guided by teachers through a structured five-step method that reinforces ST (Ashby, 2022): (1) consider the technical innovation, including its size scale and time scale; (2) identify stakeholders and their interests; (3) collect and research all relevant facts; (4) orally discuss to reach a balanced judgment; and (5) collectively reflect on the outcomes.

To foster a broad perspective, students debate each other's innovations and their implications while taking on different stakeholder roles. An environmentalist evaluates natural-capital impacts, while community representatives address social considerations and business representatives assess economics and profitability. This interdisciplinary approach encourages critical thinking about interconnected systems based on factual data and enables students to collaboratively reach a balanced consensus on effective solutions.

3.4 Supportive Learning Environment

A supportive learning environment is critical for fostering the development of ST, because students need to engage with complex, interconnected problems that have no single correct answer. To help students build both confidence and competence in applying ST, CLEAR places strong emphasis on creating a collaborative and reflective learning culture, where students feel encouraged to experiment, make mistakes, and learn from each other. One key success of this pillar is the Learning Assistants program. Over the past five years, 34 students have been trained to serve as Learning Assistants, supporting their peers in collaborative projects across the CSE curriculum. These assistants focus on facilitating group processes by mediating discussions, resolving conflicts, and ensuring equitable participation.

Teachers in the CLEAR initiative have piloted innovative pedagogical approaches, such as embedded peer assessment, to foster a more reflective learning environment. For example, students participate in collaborative projects that challenge them to consider multiple perspectives, debate potential solutions, and critically reflect on their learning outcomes.

4 Methods

This study employs a continuous, iterative research method (Creswell & Creswell, 2017) to gather insights from students, educators, and experts in the field of chemistry education and beyond. Since this project is still ongoing, multiple data collection methods have been implemented to ensure a comprehensive understanding of students' learning experiences and to incorporate expert perspectives on curriculum development and pedagogical improvements.

Student Data Collection To gain insight into student perspectives, we have conducted semi-structured interviews over the past three years. A total of 46 students from the first, second, and third years voluntarily participated in these interviews to reflect on their learning experiences, particularly in relation to the integration of systems thinking and essential skills into the curriculum. In addition to interviews, standard course evaluations are administered at the end of each 10-week module. These evaluations provide quantitative and qualitative feedback on teaching effectiveness, curriculum design, and the overall learning experience. Furthermore, student-teacher evaluation panels are held for each module, offering a platform for direct dialogue between students and educators.

Interdisciplinary Collaboration and Institutional Support We used the internal university channels to share preliminary findings and gather feedback from a diverse range of stakeholders. Faculty from various disciplines—including mechanical engineering, civic engineering, advanced technology, geo-information science and earth observation—engaged in discussions on cross-disciplinary applications through workshops and study program director seminars. Furthermore, the university's Centre of Expertise in Learning & Teaching, a team of educational consultants, offered specialized feedback on scaffolding systems thinking and evaluating critical skills.

Expert Consultation To ensure the curriculum remains aligned with best practices in chemistry education and sustainability, we engaged experts from academia and industry. Their input was documented and used to inform adjustments to the project.

5 Results

The findings from the CLEAR initiative demonstrate its impact on students' learning experiences, curriculum development, and broader educational and societal contributions.

5.1 Student Perceptions

Interviews and evaluations reveal that students generally value the integration of ST and essential-skills development in the CSE curriculum. One student remarked, "*CSE should definitely continue to offer skills development to new students*," emphasizing the perceived long-term benefits. A second-year student noted that, "*Systems thinking forced me to think more thoughtfully about solutions, and I see a difference in how I approach problems*," This reflects the increased awareness of sustainability and the ability to consider multiple perspectives that were not initially apparent to them. Several students noted an increased awareness of sustainability issues, particularly the ability to view problems from multiple perspectives. As one third-year student explained, "*We thought we understood sustainability, but through explicit discussions with peers from diverse perspectives, we realized how little we actually knew and how essential it is to address all aspects of the issue*."

Students particularly appreciated the structured integration of the fourteen essential skills into the curriculum, noting that without such integration, skills development might become "*more superficial*" or overly supervisory. Teamwork, intercultural competence, critical thinking, inquiry and analysis, and quantitative literacy received particular praise. However, some students expressed less enthusiasm for skills like creative thinking and problem-solving, which they perceived as more abstract. One student raised an interesting point: "*How can you be creative in the field of chemistry? It might be dangerous.*" Despite the positive feedback, students also highlighted challenges. For instance, they found that reflections on their learning were sometimes superficial, as they were often motivated by the requirement to complete them rather than by intrinsic interest. This suggests a need for further refinement of reflective practices to deepen student engagement and ownership of their learning.

5.2 Expanding Interdisciplinary Efforts

The CLEAR framework has been extended to other programmes within the university, including Advanced Technology, Nanotechnology, and Mechanical Engineering. Non-CSE students can also enrol in two CSE modules as part of their minor studies, where they are introduced to three essential skills and the principles of SELCA. This interdisciplinary expansion has been positively received, as noted by a professor from the faculty of Engineering Technology:

> *"The VALUE Rubrics and especially the way they are used in skills education at CSE are an excellent example to apply in many other engineering bachelor programmes. The rubrics give students the vocabulary and make skills explicit; insightful activities show importance and create ownership; skills training takes place in regular education; and the student reflects on the skill level achieved, completing the cycle."*

Furthermore, since 2021, an online course in Nano Sustainability has been developed in collaboration with international partners, including Tec de Monterrey (Mexico), the Technical University of Denmark, Universitat Autònoma de Barcelona (Spain), and Kaunas University of Technology (Lithuania) (Susarrey-Arce & Pei, 2024). Students from different countries explore diverse global perspectives on sustainability, engaging in projects like building solar cells and analysing the CO_2 footprints of products. An expert from the chemistry industry in the Netherlands further noted:

> *"A wide range of 14 non-technical skills was integrated with the technical project modules of the existing education program. This curriculum upgrade has greatly improved the systems thinking competencies of chemistry students, as measured during various sustainability challenges. CLEAR can be considered as a new best practice for chemistry educations at Dutch universities. Next to that, it provides inspiration for improving the level of systems thinking in other educations, and for other education levels as well."*

5.3 Societal Impact

Recognizing the importance of fostering sustainability competencies at an early stage, the CLEAR initiative has extended its approach to secondary education. To date, six secondary schools across the Netherlands have participated in the CLEAR project, integrating conceptual modelling into their chemistry curricula. This approach enables high school students to explore the structure and properties of complex systems, providing them with foundational insights into sustainability and systems thinking.

6 Discussion and conclusion

CSE underwent a substantial update to prioritize sustainability, incorporating ST to develop students' knowledge, skills, and attitudes. However, several limitations must be acknowledged. The evaluation of ST and essential skills development relies primarily on qualitative methods, rather than quantitative metrics. While these approaches provide rich insights into student perceptions and experiences, they lack the precision to objectively measure the depth of ST proficiency or skill mastery. Additionally, assessing attitudinal shifts toward sustainability is also challenging due to their subjective nature and reliance on self-reporting. Future work will address these gaps through a longitudinal study, using alumni interviews and surveys to assess long-term impacts on professional competencies and career choices aligned with sustainability. Quantitative tools, like ST rubrics, will also be developed to strengthen evaluation rigor. Addressing these limitations, the initiative can continue to equip future scientists and engineers with the competencies necessary to tackle complex, real-world sustainability challenges. Despite these, CLEAR has demonstrated its potential to serve as a model for integrating systems thinking and skills-line into engineering education. By equipping students with the tools to navigate complex systems and fostering a mindset of interdisciplinary collaboration, CLEAR is preparing a new generation of scientists and engineers to tackle the interconnected challenges of the 21st century.

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