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Embedding systems thinking in tertiary chemistry for sustainability

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Abstract: In response to the IUPAC call to introduce systems thinking in tertiary chemistry education, we have developed and implemented two interventions at the first-year undergraduate level: one was designed to integrate systems thinking in first-year organic chemistry using the topic of surfactants and the other in a first-semester service course to engineering students using the stoichiometry of the synthesis of aspirin. We demonstrate how the systems thinking approach in both interventions did not lose the focus of the chemistry content that needed to be covered, exposed students to the concept of systems thinking, started to develop some systems thinking skills, and made a case for the contribution that chemistry can and should make to meet the UN sustainable development goals. Through both the design and the implementation process, it has become clear that introducing systems thinking is complex and it remains a challenge to keep the complexity manageable to avoid cognitive overload. Both interventions leveraged the power of group work to help students deal with the complexity of the topics while also developing participatory competence required for sustainability. The development of systems thinking skills and a capacity to cope with complexity requires multiple opportunities. Infusing syllabus themes that relate to real chemical systems with a systems thinking perspective can provide such an opportunity without compromising chemistry teaching. We believe that skills development should continue throughout the undergraduate chemistry degree to deliver chemistry graduates who can make a difference to global sustainability.

Keywords: chemistry education, graduate attributes, curriculum development, visualization, collaborative learning.

1 Introduction

1.1 Chemistry and Systems Thinking for Sustainability

The UN General Assembly proclaimed 2022 as the International Year of Basic Sciences for Sustainable Development. Their purpose is to raise awareness of the importance of the basic sciences in addressing the Sustainable Development Goals (SDGs). Meeting the SDGs such as zero hunger, good health, clean water, and affordable and clean energy requires an understanding of chemical substances, their transformations and their interactions within the earth system. In addition, the planetary boundaries framework has identified nine processes that regulate the stability and resilience of the earth system (1). These processes have direct links to chemistry either through the measurement of substances or management of chemical transformations. Clearly, chemistry underpins considerations of how present and future generations can live within the limits of our natural world. This is described as chemistry providing “the molecular basis of sustainability” (2). The practice of chemistry without consideration of the implications for the environment has caused significant harm. To address the negative impact of the chemical industry on the environment, green chemistry tools and metrics have been developed by chemists and engineers to promote the sustainable manufacture of products. These encourage practitioners to think holistically about manufacturing across the life cycle of products, from sourcing raw materials to reducing harmful waste. However, despite these advances, the majority of chemicals are synthesized without full consideration of their toxicity to humans and the environment, and their ability to be reused or recycled or sourced renewably (2). For chemists to ensure that the basic science of Chemistry contributes to sustainability, a systems thinking perspective is required (3). This perspective needs to permeate all chemists’ thinking and practice.

A system refers to a set of interdependent or interrelated components that function as a whole. Systems thinking goes beyond fragmented knowledge to a holistic engagement with complex systems. In the context of sustainability, the systems of interest include different domains such as the environment, the economy and society; and different scales from the molecular and microscopic to the macroscopic and global. Systems thinking includes the analysis of the components and considers their interactions and interdependence. Systems thinking has been identified as a key competence needed to build transition strategies towards sustainability (4). Identifying intervention points, anticipating future trajectories, and planning transition processes all require a holistic view of complex chemical, ecological and social systems, and an understanding of their dynamics and molecular basis.

1.2 Systems thinking in Chemistry Education

In 2016 a group of "Chemists for Sustainability" in the International Organization for Chemical Sciences in Development (IOCD) proposed that chemistry teaching needs to be reoriented as a science for the benefit of society, tackling global challenges and contributing to sustainable development (5). To do so, they argued that chemistry needs to incorporate systems thinking into the curriculum. This means that in addition to learning the principles and practice of chemistry, students need to develop the capacity for thinking and working across disciplinary boundaries.

Mahaffy and Matlin brought together ca. 20 global leaders in chemistry education to develop learning objectives and strategies to infuse systems thinking into the teaching of introductory chemistry (or general chemistry) at the post-secondary level. This project was conducted under the auspices of the International Union of Pure and Applied Chemistry (IUPAC) and was funded by the IUPAC (Project No.: 2017-010-1-050).[1] They chose to focus on post-secondary general chemistry courses because these courses serve both future chemists and many other future STEM and health professionals.

Chemistry is not just a fundamental science; it is also very complex. In making chemistry accessible to students, chemistry education has taken a reductionist approach, considering topics of chemistry in isolation. This reductionist approach to science education and scientific research has resulted in a significant increase in our knowledge of the natural world and great technological advances, but it does not prepare students adequately to address global world challenges (6). Furthermore, students often experience learning chemistry as isolated and fragmented disciplinary knowledge. The majority of students in gateway general chemistry courses see little relevance of chemistry to their range of future careers in science, technology, engineering and health care (2). Reorienting chemistry education with systems thinking would provide a framework for connecting chemistry knowledge at the molecular level with the needs of society and the sustainability of the earth and would make the relevance of chemistry obvious thereby advancing meaningful learning. It would also provide an opportunity to develop domain-specific critical thinking and problem solving as topics of discussion are expanded beyond the facts of chemistry to issues which have normative, moral, ethical, or public policy dimensions.

While introducing systems thinking in chemistry education presents many benefits, dealing with complexity on multiple scales is no small task. Educators and curriculum developers will have to develop strategies to introduce complexity with appropriate scaffolding and consideration of learning progressions. They have to be mindful of cognitive overload in setting reasonable goals for learning outcomes, tasks and assessments (7). They will need to use tools to frame and manage the complexity that will help students to develop the capacity to navigate complexity (8). Research from STEM education suggests that systems thinking is not a "natural" way for humans to think and opportunities to develop systems thinking skills will have to be intentionally built into the curriculum (9).

Not specifically designed with the sustainability agenda in mind, the Systems Thinking Hierarchical (STH) Model (Table 1) outlines the components of systems thinking. It presents a hierarchy of difficulties for the development of systems thinking skills which were empirically derived in an earth science context (10). It can be used as a guide for designing teaching interventions with appropriate scaffolding and for managing expectations in chemistry.

Tab. 1: The Systems Thinking Hierarchical (STH) Model (10).

	The ability to …	
Level I: Analysis	1.	identify the components of a system and processes within the system,
Level II: Synthesis	2. 3. 4. 5.	identify simple relationships between or among the system's components, identify dynamic relationships within the system, organize the systems' components, processes and their interactions within a framework of relationships, identify cycles of matter and energy within the system,
Level III: Implementation	6. 7. 8.	recognize hidden dimensions of the system – the patterns and relationships not seen on the surface that give rise to natural phenomena, make generalizations, think temporally: retrospection and prediction.

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[1] A key output of the project was the special issue of the prominent Journal of Chemistry Education on Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry published in 2019.

In the context of chemistry, the advanced level systems thinking skill "to recognize hidden dimensions of the system" readily translates to the domain-specific skill of molecular level reasoning, drawing in the "molecular basis for sustainability". This analysis of the properties, interactions, and spatiotemporal effects of chemical compounds leading to emergent system properties is termed mechanistic reasoning by Talanquer (11). He advocates that chemical systems thinking should at least contain three core components: mechanistic reasoning based on chemical principles, a context-based focus and a sustainable action perspective.

Another valuable contribution to articulating the essential characteristics of systems thinking in chemistry education is the "Characteristics Essential for designing or Modifying Instruction for a Systems Thinking approach" (ChEMIST) table by York and Orgill (9). The table (Table 2), proposed as a guide for designing, analysing and optimizing teaching activities, distilled five essential characteristics of a systems thinking approach: (I) recognizing the system as a whole, (II) Identifying relationships between parts, (III) identifying causal variables, (IV) examining behaviour over time, and (V) identifying interactions of the system with the environment. For each characteristic, activities could be classified on a continuum from a more analytical approach to a more holistic approach and they propose that instruction should include activities that develop both analytical and holistic thinking skills.

Tab. 2: The Characteristics Essential for designing or Modifying Instruction for a Systems Thinking approach (ChEMIST) table (9)

A Systems Thinker in Chemistry Education Should.	**Less Holistic** **More Analytical/Elaborative**	⇄	**More Holistic** **Less Analytical/Elaborative**
I. Recognize a system as a whole, not just as a collection of parts	Identify the individual components and processes within a system	Examine the organization of components within the system	Examine a system as a unified whole
II. Examine the relationships between the parts of a system and how those interconnections lead to cyclic system behaviours	Identify the ways in which components of a system are connected	Examine positive and negative feedback loops within a system	Identify and explain the causes of cyclic behaviours within a system
III. Identify variables that cause system behaviours, including unique system-level emergent behaviours	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	Examine the relative, potentially nonlinear, effects that multiple identified variables have on a given system-level behaviour	Identify, examine, and explain (to the extent possible) emergent system-level behaviours
IV. Examine how system behaviours change over time	Identify system-level behaviours that change over time	Describe how a given system-level behaviour changes over time	Use system-level behaviour-over-time trends under one set of conditions to make predictions about system-level behaviour-over-time trends under another set of conditions
V. Identify interactions between a system and its environment, including the human components of the environment	Identify and describe system boundaries	Consider possible effects of a system's environment on the system's behaviours; consider how the system under study might be a component of and contribute to the behaviours of a larger system	Consider the role of human action on current and future system-level behaviours

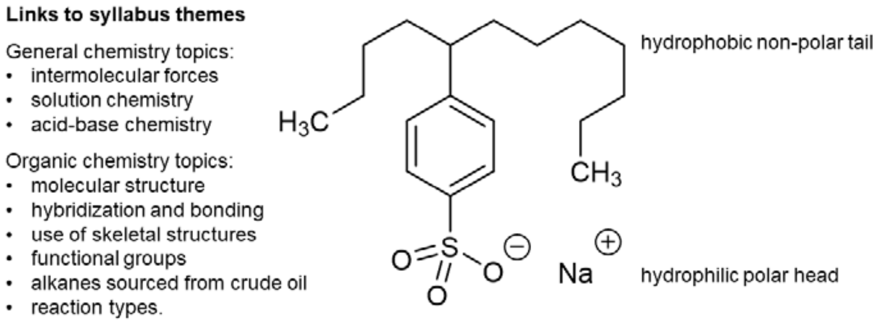
In contrast to STEM disciplines such as engineering, environmental science and biology, there is little experience incorporating systems thinking in chemistry education, and consequently, resources for teaching and assessment are limited. Chemistry instructors have themselves been educated with the reductionist approach and with the pressures they face within the education system are unlikely to adopt novel teaching approaches without being furnished with detailed teaching materials. We describe two projects in Chemistry Education in which we implemented systems thinking teaching interventions for large first-year chemistry courses; one for science students and one for engineering students.

2 Two systems-thinking teaching interventions for chemistry

2.1 Project 1: Systems thinking for first-year organic chemistry – Surfactants

There have been several contributions to developing systems thinking teaching resources for general chemistry, thus our first project was directed at introductory organic chemistry, which in our setting, is taught in the last quarter of the first year of university. Project 1, the MSc Science Education project of Micke Reynders, was initiated during the Covid-19 pandemic and hence was conceptualized for implementation online or face-to-face.

The topic of the intervention was the complex system centred on the surfactant linear alkylbenzene sulfonate (LAS, Figure 1). This surfactant forms the active ingredient of common commercial laundry detergents and hence satisfied the criterion of being a chemical that students encounter in their everyday lives. Several connections to the syllabus were identified building on the general chemistry topics of intermolecular forces, solution chemistry and acid-base chemistry. It also fitted in with the early topics in the organic chemistry syllabus: molecular structure and bonding, use of skeletal structures, functional groups, the alkanes sourced from crude oil and reaction types. These represent the hidden dimensions at the molecular level scale of the system. Furthermore, surfactants, water and air, yield the emergent properties of micelle formation critical to the practical functions of detergency and of foaming at the microscopic scale.



Links to syllabus themes

General chemistry topics:
- intermolecular forces
- solution chemistry
- acid-base chemistry

Organic chemistry topics:
- molecular structure
- hybridization and bonding
- use of skeletal structures
- functional groups
- alkanes sourced from crude oil
- reaction types.

Fig. 1: Linear alkyl benzene sulfonate (LAS) and the connections to the syllabus.

The ability of surfactants to disrupt lipid bilayers of viruses fitted the context of hygiene during the pandemic through connection to the washing of cloth face masks (12). Detrimental associations with human health could be made due to the cytotoxicity of LAS to the skin and its ability to stimulate the growth of colon cancer when ingested at a low level (13). The latter possibility needs to be considered in the light of evidence that when "brown" water containing LAS is used directly for crop irrigation LAS is taken up by carrots in measurable proportions (14). Of additional local relevance considering societal and environmental factors is the use of rivers for washing laundry in rural communities without an alternative water supply and the effect on the river system (15). Similarly, the failure of sewage systems has resulted in the release of large quantities of LAS into river systems with consequent foaming cutting out light that facilitates the biodegradation of LAS (16). Delayed biodegradation extends the ecotoxicity of LAS. The industrial manufacture of LAS provided touchpoints to environmental and economic issues and drew attention to the roles of catalysts and energy systems. Thus, LAS can illustrate the point that chemicals have both hazards and benefits that must be considered together (2).

Criteria applied for choice of Topic for both projects
- organic compound
- chemical of daily life – personal relevance
- fit with syllabus – molecular level scale
- relevance at scale within the domains of society, environment, economy or to their future professions.

2.1.1 Design

A Systems-Oriented Concept Map Extension (SOCME) diagram formed the centre of the intervention design. The SOCME diagram was chosen as the tool to visualize the greater LAS system with its economic, societal and environmental subsystems and their components and relationships. Concept mapping has been used extensively in science education to integrate complex ideas, and SOCME diagrams are said to contain the complexity of systems thinking (17). Visualizations are particularly useful when topics are too complex for internal cognition alone (18).

Group work was incorporated as another important design feature to help manage the cognitive load inherent to both chemistry and systems thinking (19), to engage social constructivist practices for learning and to build interpersonal competence, another key competence for sustainability (4). The jigsaw cooperative learning approach was used to structure the group work. This approach consists of two sets of group configurations for the participants, called home groups and subsystem groups in our case (Figure 2). It works well where sub-topics of similar complexity can be allocated to individual home group members to investigate. Since each sub-topic has inherent complexity, the subtopic is explored within a group setting by members, from different home groups allocated to that subtopic. After working in subsystem groups, members return to the home group equipped to make an informed contribution to the overall picture. In this intervention, each home group had three members, each allocated to a specific subsystem – economic, societal or environmental. Initially home groups engaged with a chemistry concept map, then the subsystem groups elaborated partial SOCME diagrams for their subsystem and finally, home groups integrated and elaborated partial SOCME diagrams for the whole surfactant system with its various subsystems.

Key design elements – Project 1

- Visualization tool (SOCME diagrams)
- Cooperative learning approach (Jigsaw design with individual roles inspired by POGIL)
- Learning outcomes based on the ChEMIST table
- Scaffolding guided by the STH model levels of difficulty.

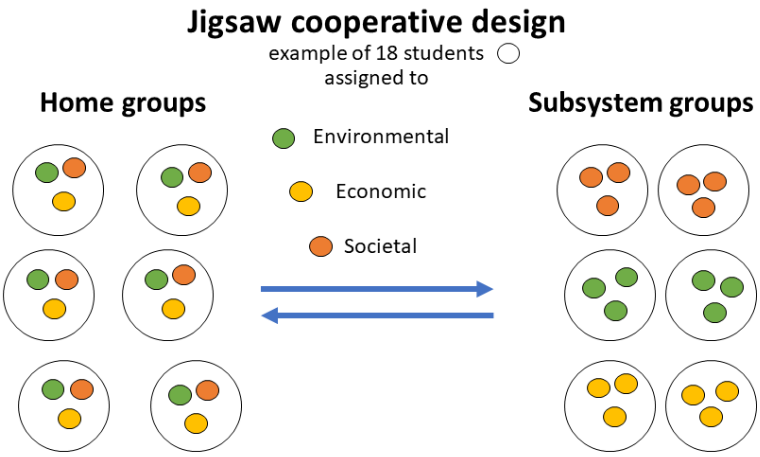


Fig. 2: The Jigsaw cooperative learning approach: each student is a member of a home group and a subsystem group. Within a home group each student is allocated one of the three subsystems to study. Students focus on their subsystem with others similarly allocated within the subsystem group. Appropriately informed, students return to their home group where subsystems are integrated and the system is studied as a whole.

To ensure that the intervention covered all bases of chemical systems thinking, the ChEMIST table was used to inspire the development of learning outcomes for the intervention. Corresponding activities were designed for students to engage with the five characteristics of systems thinking using analytical and holistic perspectives. An alignment of the ChEMIST table outcomes with the STH model allowed us to anticipate the difficulty level of the tasks. To avoid losing students along the journey, more difficult aspects of systems thinking were scaffolded by presenting them in the partial SOCME, providing prompts or requiring simpler activities. Yet, there was an opportunity for students to be creative and make their contributions across the range of systems thinking skills. This would allow the level of systems thinking skill development to be monitored.

After getting students to consider the unsustainable aspects of LAS production and use, the intervention concluded with a presentation of chemistry's contribution to the development of sustainable surfactants. In general, surfactants do not perform well in hard water and a number of chelating additives are added to traditional laundry detergents to circumvent the problem. Chemists are designing surfactants with molecular structures that reduce the need for these additives which themselves have a negative impact on the environment. In addition, these surfactants were prepared from renewable resources (20).

2.1.2 Implementation

The surfactant systems project was implemented online due to Covid-19 restrictions with a group of about 240 first-year students in the second-semester general chemistry course serving students in the Faculty of Natural and Agricultural Sciences of the University of Pretoria. The intervention was implemented in two 3-hour practical time slots a fortnight apart of which two hours each were spent on group work. Groups of 60 students met virtually in a class with two facilitators via the learning management system. They watched short instructional videos during the plenary sessions but worked on group quizzes and their SOCME diagrams in breakout rooms with their home or subsystem groups. Marks were awarded for the quizzes and the final group SOCME diagram. The latter was assessed using a rubric based on the SOLO taxonomy. The marks contributed only a small proportion (<1%) to their final course grade.

2.1.3 Preliminary Findings

While detailed findings will be published elsewhere, our preliminary findings revealed that the students found the intervention accessible. Students were authentically confronted with a complex system and despite expressing that it was difficult for them because they were "not used to it", they embraced the teaching intervention. Although the core chemistry foundation of the system was presented as facts and did not require further extension or application at a molecular level, the research participants declared that they found molecular level reasoning difficult indicating that they had returned to the chemistry to make sense of it once they had understood its relevance to the systems of everyday life. Students also found it difficult to organize systems' components into a framework of relationships. This was the highest-level systems thinking skill that was not specifically prompted. Research participants reflected the development of a range of system thinking skills with more students demonstrating proficiency at the more analytical level and fewer at the more holistic level with a few showing that they had taken the message to heart and demonstrating their wish to advocate for a sustainable action perspective in their daily lives and that of their friends or families.

Challenges of group work in the specific online setting detracted from the experience for some students in the bigger group, but for others it presented the first opportunity that year to engage with their peers at university. The students who volunteered to participate in the research study, being fully committed to the intervention, valued the opportunity for collaborative learning.

The assessment of the group SOCME diagrams proved challenging for our teaching assistants (TAs). While we could identify scope to refine the assessment rubric, this finding revealed that the TAs were capable of grading the lower level systems thinking skills consistently, but not the higher-level systems thinking skills. We attribute this discrepancy to their insufficient competence in systems thinking. However, the assessment was low stakes and the impact on final grades was insignificant.

2.2 Project 2: Systems thinking in chemistry for first-year engineering students – Sustainable aspirin manufacture.

The second project, the MSc Science Education project of Cathrine Chimude, involved a collaboration with chemical engineering researchers. A final year chemical engineering student completed a life cycle analysis (LCA) of aspirin production via various routes, some of which started from renewable feedstocks. This LCA provided the data for our systems thinking teaching intervention in a first-semester general chemistry service course for first-year engineering students. It has been proposed that the introduction of green chemistry and life cycle analysis could provide entry points for considering overlaps between the boundaries of different systems (21). A comparison of different routes can show that how one chooses to design a synthetic pathway to a final product can have significant consequences. It can open an opportunity to discuss how these impacts, especially as chemistry is currently practised, can lead to unintended outcomes that are unsustainable (8). This would highlight the relevance of chemistry to their future profession in engineering and the contribution that they, as engineers, could make to sustainability.

Aspirin was chosen as the signature drug because of its fit with the curriculum – the synthesis of aspirin is a routine laboratory experiment in many introductory chemistry courses. Furthermore, they are likely to have encountered aspirin within their extended families for its use as an antipyretic/analgesic or anticoagulant. The intervention focused on the calculation of green chemistry metrics for three routes to aspirin production and developing a life cycle inventory (LCI) for the two most promising routes. It was placed shortly after the topic of stoichiometry, with students having completed the study themes of bonding, the mole concept and chemical reaction equations. These serve as a necessary foundation for engaging with the synthesis routes for aspirin manufacture. During the intervention, the theory course was moving from the topic of thermochemistry to that of equilibrium and thermodynamics, priming students to think about energy requirements associated with chemistry. In our experience, engineering students are comfortable with calculations and like to use numbers to make decisions. Thus, the calculation of green chemistry metrics and the use of the life cycle engineering tool presented an appropriate starting point for the introduction of systems thinking concerning the consequences of manufacturing choices within the environmental, economic and societal domains.

2.2.1 Design

This project, unlike the first, was limited to a single 3-hour practical session. The design elements specific to this project were individual preparation for a cooperative learning approach, reflection on learning before and after the contact session, a graphic to explain system boundaries (LCI gates), a zoom out approach moving from green chemistry metrics to the LCI to extended systems, and role play. Thus, project 2 also made use of group work to keep the cognitive load manageable. To equip students to make a meaningful contribution to the group, as individuals, they had to calculate the green chemistry metrics for the synthetic routes ahead of the dedicated project session based on an information document that presented the aspirin synthesis routes and the calculations of green chemistry metrics. They also had to complete a reflective questionnaire that prompted thinking about criteria for making decisions for sustainable manufacturing processes.

At the start of the 3-hour session, which was conducted face-to-face, the principles of LCA and the role and working of LCIs were taught. Students were then divided into groups of three or four and had to complete an LCI worksheet using the data provided. This gave them a taste of this chemical engineering practice (22) appropriate to a first-year undergraduate level. Graphical visualization of the cradle to grave product life cycle (Figure 3) was provided to assist students in initially limiting the complexity within the boundaries of the manufacturing process. Throughout the intervention, the system boundaries were expanded incrementally, from the exemplary foreground system to the exemplary background system, for students to consider the effects of different routes on the sustainability of the process. This could be termed a “Zoom out” approach to dealing with complexity (7).

Key design elements – Project 2

- Individual preparation for a cooperative learning approach
- Reflection in learning
- Visualization tool (LCI – gates)
- A zoom out approach moving from green chemistry metrics to the LCI to extended systems
- Role play.

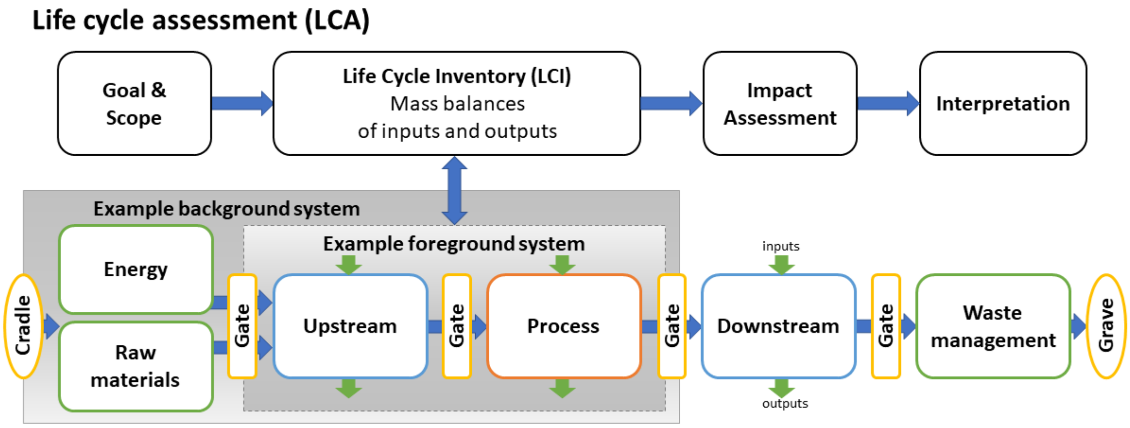


Fig. 3: Life cycle assessment for chemical manufacturing processes. The assessment considers the full life cycle of the product from raw materials (cradle) to disposal after use (grave). To conduct a detailed life cycle inventory (LCI), which includes the mass balances for the processes under consideration, appropriate system boundaries (gate to gate) are chosen. The LCI will provide data to inform the choice, optimization and implementation of the process within the LCA (23).

After completing the group LCI worksheet, the concept of systems thinking was explained to students and groups then had to discuss a question each on raw materials and waste management. Students also learned that making judgements of the most sustainable route based on a single part of the process alone could lead to less sustainable manufacturing in the long term. e.g. the harvesting of salicylic acid from oil of wintergreen has very poor atom economy and carbon efficiency and the use of agricultural land to produce sufficient feedstock of the particular herbs might not be sustainable. An alternative would be to look at renewable sources of phenol from bio-waste. At the other end of the scale, aspirin is fully biodegradable which is important for sustainability (24). By contrast, other painkillers such as Brufen have been reported to have post-use negative effects on the environment (25). It is important to sensitise future scientists and engineers to the need to consider the full life-cycle of the product in order to make sustainable choices.

To conclude the session, the groups were given a scenario in which an engineer had found a more sustainable production route requiring an upgrade of the plant. They had to take on the roles of the Engineer, Financial Manager and Environmental manager on the company board and debate the way forward. This exercise prompted students to envisage potential long-term financial implications of not choosing the more sustainable routes in order to persuade the financial manager that it was worth investing in sustainability.

Within a week after the exercise, they had to again complete a reflective questionnaire on decision making for sustainable manufacturing processes. Reflection in learning helps students build structural connections in their knowledge, personalize and contextualize their knowledge and hence increase the depth of knowledge (26). Reflection is a core component of critical thinking (27), which itself is necessary for systems thinking.

2.2.2 Implementation and preliminary findings

There were approximately 575 students enrolled in the course. They were allocated to one of four sessions and one of two venues per session based on venue capacity. The class was composed of students of chemical, civil, electrical, electronic, metallurgical, and mechanical engineering. Each student attended a 3-hour laboratory session in the laboratory as a “dry” practical activity. This project has only recently been implemented and data collection and analysis are still in progress.

Groups were formed on the spot by the teaching assistants. It took a little time for the group members to trust one another to conduct the calculations to the satisfaction of all members. However, through working towards a common goal the groups formed and by the time it came to the role play, they were performing well. The students experienced the tasks as achievable with minor prompts from the teaching assistants.

Student feedback was overwhelmingly positive. At the start of the laboratory session, it appeared that female students were more interested in the topic than their male counterparts, but by the end of the session, all students were enthusiastically engaged. The role-play question resulted in animated discussions with students owning their roles. The course lecturer and teaching assistants endorsed the values communicated and the objectives of the project.

3 Discussion

We have developed two different systems thinking instructional approaches that centre on chemistry and the importance of considering chemistry in addressing global sustainability challenges. Our criteria for the choice of a systems thinking topic and our key design principles, for stand-alone systems thinking interventions, have been outlined. During and after implementation, we witnessed significant gains in terms of student engagement, development of positive perceptions of the relevance of chemistry and saw hints of ownership of the challenge of sustainability. We also achieved constructive group work because of clear expectations for the contribution of each student. Students endorsed the experience, suggesting that complexity was sufficiently managed. Instructors were similarly convinced of the value of the interventions. We experienced the challenges associated with authentic assessment of skills development, specifically for large student groups, the handicap that teaching assistants and instructors have in terms of their own level of systems thinking skills, and the limit to what can be achieved with a single intervention. This suggests the importance of embedding systems thinking throughout the undergraduate curriculum.

Several barriers to educational reform have been noted (2). One barrier - the time required to develop teaching tools for implementing a systems thinking approach within a chemistry context - was overcome by assigning two MSc Science Education projects to the topic. With teaching material purpose-built for the local context, we experienced no resistance to its use by chemistry lecturers. Instead, the lecturers embraced the opportunity to implement our designs because they are advocates for chemistry and wanted to communicate that chemistry has an important contribution to make to the sustainability agenda. After experiencing the interventions with the students, the lecturers were willing to make these interventions permanent within the programme.

For both groups of students, we found that students were motivated to engage with the chemistry content that was presented within the context of systems and sustainability. This finding fits the expectation that when the relevance of the chemistry is demonstrated, students move toward meaningful learning (28) (29). It also stimulated the professional identity development of first-year science students who normally see themselves as students and not as budding scientists with a contribution to make (30). Authentic assessment of development of systems thinking skills, specifically for large student groups is challenging (31). To display their achievement levels in the full range of skills, students need the opportunity to respond to less algorithmic questions and tasks. Such assignments cannot be graded using simple marking schemes or exemplars typical of textbook questions. Furthermore, because systems thinking has not been a part of chemistry education, instructors and teaching assistants have not had sufficient time or opportunity to develop systems thinking skills themselves. In a short training session, they can learn to assess basic systems thinking skills but a reliable assessment of more complex systems thinking skills, even with the guidance of a rubric, is challenging for teaching assistants delegated the task of grading large groups. This presents a validity challenge to assessment and we therefore recommend assessment to be low stakes and that extra time and care be invested in providing systems thinking training to the TAs beyond training in the use of the rubric.

While we were gratified to see the students embracing the topic and growing systems thinking skills, there is a limit to what can be achieved in the first year through single interventions. First-year tertiary chemistry is appropriate for communicating the importance of chemistry to sustainability and introducing students to the concept of and need for systems thinking, but is insufficient to fully develop systems thinkers. Complex skills such as those that constitute systems thinking take time and repeated opportunities to develop and should be provided throughout the undergraduate programme. In making the case to future scientists, health professionals and engineers that chemistry's, and hence chemists', contribution to the sustainability agenda is key, it is important that the tertiary system develops chemists as systems thinkers so that they are equipped to make the contribution advocated for. This implies that there is a need to embed repeated opportunities to develop systems thinking skills throughout the curriculum. Systems are inherent to chemistry. Molecules and complex ions are systems of atoms with their own emergent behaviour, which is so much more than the sum of the atoms. An emergent property is a novel property of the system, which is not possessed by its constituent parts nor is the sum of them. Chemical reactions, even the small localized reaction in a laboratory flask, are dynamic systems giving rise to new products. Yet, chemistry is not taught as a series of systems and the teaching of the emergent characteristics of chemical entities, their properties and reactions, is neglected (32). A number of student misconceptions have been attributed to this neglect. Despite chemistry not being taught with a systems lens, chemists grow in their systems understanding of chemistry as they build expert knowledge structures.

The recognition of the importance of systems thinking to sustainability has stimulated a re-look at the molecular level with a systems lens. Systems thinking gives us a vocabulary to better communicate the nature of chemical entities to students. By using appropriate terminology when teaching the chemistry content, two goals can be achieved: (i) the nature of chemistry becomes explicit and (ii) systems thinking concepts represented by the terminology become part of the chemists' resources. For example, we are currently working on a third project to infuse a systems focus into the teaching of the competition between substitution and elimination reactions in organic chemistry. This project is yet another example of possibilities for continuous development of systems thinking skills through the undergraduate curriculum by a reorientation and enrichment of the teaching of chemistry content rather than the replacement of content. Where appropriate, connections to sustainability should continue to support meaningful learning and grow the skill of thinking at different scales. For example, in the competition between substitution and elimination reactions, competing reaction pathways lead to unwanted byproducts and increased waste, which can have an impact on the sustainability of manufacturing processes.

4 Conclusions

It is a big task for a lecturer to embed systems thinking into chemistry education because it is counter to their chemistry teaching and learning experience. However, the benefits are worth the effort. Notably, the learning of chemistry is not sacrificed, it is enriched. Systems thinking becomes a tool to cope with the complexity of chemistry so that students can better understand the subject. By making the sustainability perspective central to first-year teaching, students leave a service course with a fresh view of the relevance of chemistry to their daily lives and the centrality of chemistry to addressing the big global challenges. This is so much richer than the current predominant view that chemistry is just a course to be passed on the path to acquiring a degree. Furthermore, considering chemistry in the context of biological, ecological, societal, economic and other systems reveals beneficial and harmful effects. This provides a context for discipline-specific critical thinking instruction because topics are no longer restricted to the factual matters of chemistry, which a first-year student is not well placed to critique, but includes issues that have normative, moral, ethical or public policy dimensions (33). Systems thinking and critical thinking are graduate attributes to be developed. Because chemistry provides the molecular basis for sustainability, chemistry graduates should be empowered to stand up and be counted in big multidisciplinary teams tackling the grand challenges of the planet. Our two interventions contribute to the growing set of resources for teaching and assessment, being developed by chemists dedicated to quality education. Quality chemistry education will serve as a solid foundation for the contribution that chemistry can and should make to sustainable development.

5 Acknowledgements

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Index