



## Article

# Using Systems Maps to Visualize Chemistry Processes: Practitioner and Student Insights

Madeleine Schultz <sup>1,†</sup> , Drew Chan <sup>2,†</sup>, Andrew C. Eaton <sup>3</sup>, Joseph P. Ferguson <sup>4</sup>, Rebecca Houghton <sup>5</sup>, Adlin Ramdzan <sup>6</sup>, Oliver Taylor <sup>7</sup>, Hanh H. Vu <sup>8</sup> and Seamus Delaney <sup>4,\*</sup> 

<sup>1</sup> School of Life and Environmental Sciences, Deakin University, Waurin Ponds, VIC 3216, Australia

<sup>2</sup> Presbyterian Ladies' College, 141 Burwood Hwy, Burwood, VIC 3125, Australia

<sup>3</sup> Wollondilly Anglican College, 3000 Remembrance Dr., Tahmoor, NSW 2573, Australia

<sup>4</sup> School of Education, Deakin University, Burwood, VIC 3125, Australia

<sup>5</sup> Assumption College Kilmore, Sutherland St., P.O. Box 111, Kilmore, VIC 3764, Australia

<sup>6</sup> The Mac.Robertson Girls' High School, 350-370 Kings Way, Melbourne, VIC 3004, Australia

<sup>7</sup> Geelong Grammar School, 50 Biddlecombe Ave., Corio, VIC 3214, Australia

<sup>8</sup> Williamstown High School, 76 Pasco St., Williamstown, VIC 3016, Australia

\* Correspondence: s.delaney@deakin.edu.au

† Some teachers have moved since the program, so these addresses do not necessarily reflect the schools where the project was carried out.

**Abstract:** Discussing socio-scientific issues in a secondary chemistry classroom poses a challenge to traditional classroom practice because students and teachers need to think more broadly about chemical processes. Allowing students to create open-ended maps to generate and represent their understanding of socio-scientific issues while also learning chemistry theory can develop Systems Thinking capacity in students. This manuscript presents three vignettes of the classroom use of mapping exercises within separate action research studies, involving diverse school types, curricula, chemistry topics and student groups. The mapping exercises were effective to engage students in the development of Systems Thinking and were readily integrated into different curricula. Sequential student-generated maps for chemical processes illustrate increasing sophistication in their Systems Thinking approaches.

**Keywords:** Systems Thinking; chemistry education; representational competence; mapping



**Citation:** Schultz, M.; Chan, D.; Eaton, A.C.; Ferguson, J.P.; Houghton, R.; Ramdzan, A.; Taylor, O.; Vu, H.H.; Delaney, S. Using Systems Maps to Visualize Chemistry Processes: Practitioner and Student Insights. *Educ. Sci.* **2022**, *12*, 596. <https://doi.org/10.3390/educsci12090596>

Academic Editors: Mario Pagliaro, Laura M. Ilharco and David Geelan

Received: 1 June 2022

Accepted: 25 August 2022

Published: 31 August 2022

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

As the world grapples with complex problems including food insecurity, climate change and inequality, education has a crucial role to play in preparing responsible and capable citizens of the future. Traditional educational approaches seldom address connections between disciplines and are therefore inadequate to develop the skills needed for young people to prosper in the 21st century [1]. Thus, new teaching strategies are needed that will help students visualize and realize the interconnectedness of modern society [2,3].

One approach to teach in this way involves using Systems Thinking, which has been recommended as a transformational teaching method specifically in the field of chemistry [4]. Over the past five years, chemistry educators have increasingly called for chemistry education to be restructured to incorporate sustainability concepts through a Systems Thinking approach [5]. A useful operational definition of Systems Thinking is:

*... an approach to addressing problems that incorporates the complexity of the whole system in a holistic manner, including intended and unintended consequences, and a cognitive skill.* [6]

(p. 2620)

Systems Thinking in Chemistry Education (STICE) has been claimed to benefit student learning through developing critical thinking and problem-solving skills [7], and to equip graduates to tackle complex problems [8]. In addition, it has been proposed as a pathway to incorporate consideration of sustainability into education, which is required by national curricula in the US [9] and Australia [10].

Although teachers have shown enthusiasm for STICE, they need to be supported with appropriate professional learning opportunities and resources to be able to adopt STICE methods [6,11]. While there has been an emphasis on incorporating Systems Thinking in K-12 science education for other disciplines [7], so far, most STICE proposals have been at the tertiary level [8,12–15].

Complicating the incorporation of STICE at the secondary level is the need to fit any additional teaching and learning into what is recognized to be an extremely crowded curriculum [16–18]. In previous studies, teachers have indicated that lack of time and space in the curriculum is one of the biggest challenges to implementing STICE [6]. Thus, it is critical to find strategies that teachers can easily use in their classrooms to teach STICE and allow students opportunities to explore this way of analyzing problems.

One way to support students to integrate new information into their knowledge structures is through the use of mapping to illustrate relationships between phenomena [19]. By undertaking such mapping, students are provided with opportunities to engage in the representation construction practices of science, which form a key part of their induction into the epistemic practices of the discipline [20]. Multiple different forms of mapping have been proposed for use in science education, with the predominant forms being concept maps [21] and mind maps [22]. Other types of maps have also been used, including argument maps [23], causal maps [24] and network maps [25]. Controversy maps have been used to empower students to productively negotiate socio-scientific issues [26]. Recently, Systems Oriented Concept Mapping Exercises (SOCME) have been developed specifically as a way to represent and enact STICE [5,27].

While strict definitions for each type of mapping have been created and there are important differences between them, all forms of mapping have a common capacity to display a complex body of knowledge in a two-dimensional format, showing links between related concepts. Such maps function as diagrams that make evident through their iconicity the deep structural relations between components of the system [28,29]. These “visual tools may help our students develop better recall, comprehension and critical thinking skills,” [23] (p. 137). Different forms of mapping are appropriate for different purposes [22,23]. For example, in high school geography classes, causal maps have been utilized to help students appreciate systems-level effects [30], and the use of causal maps is also recommended in teaching and learning about human evolution [24]. Encouraging students to draw mind maps during class in small groups comprises good teaching practice through the promotion of active and collaborative learning [31]. In undergraduate organic chemistry classes, student-constructed concept maps have been shown to be effective to illustrate understanding [32]. Recent publications support the assertion that student drawing in science can improve both teachers’ and students’ metarepresentational competence [33,34], with open-ended mapping exercises constituting a form of student drawing.

The use of a variety of graphical mapping tools for STICE has been explored, and the advantages and disadvantages of different tools have been detailed [35]. Wheeldon and Faubert have argued for definitional flexibility in the use of maps in qualitative research, stating that:

*A broader definition of maps, allowing for data collection based on a participant’s generated visual expression of meaning, is more in line with the theoretical starting place generally associated with qualitative research [36]*

(pp. 71–72)

Wheeldon and Faubert found that participants did not always construct a map according to the definition provided, but this does not make their data invalid. Our experience

supports this argument. Although we use the term “systems map” in this manuscript, we are aware that the maps drawn by students may fall into other categories according to strict definitions. We thus adopt a pragmatist approach to defining maps as representations [20], in the sense that the meaning of the maps is constituted in how they are used by teachers and students.

Systems maps have been described as including:

*Components or the different parts (the ‘who’ and ‘what’) that are involved in the function of a selected practice; connections between components that exhibit how students believe components are related (e.g., inputs and outputs); feedback loops, visible when outputs are fed back into a system as inputs. [37]*

(p. 1511)

In this manuscript, we describe and explore the use of mapping exercises in six Australian high schools and as part of a teacher professional development program within three vignettes. The purpose of the mapping exercises was to provide opportunities for students to explore and express concepts and connections related to specific chemical or manufacturing processes as a way to develop their systems thinking capacity. Further aims were to support teachers to value students’ ideas and to prompt classroom discussions. To link the systems to sustainability, labels for corresponding UN Sustainable Development Goals (SDGs) (<https://sdgs.un.org/goals>; accessed on 24 August 2022) were added to relevant parts of the maps. Our preliminary work found this format to be suitable and useful for integrating STICE into a chemistry classroom without requiring additional time or resources [38]. Here, we present student-generated maps from different contexts, along with interview data from students and teachers, and teacher reflections, describing their perceptions of the mapping exercises. We address the following research question in this paper: how can the generation of systems-oriented maps of chemical processes engage students with the development of systems thinking skills?

## 2. Context and Methodology

The first two vignettes come from similar but slightly different contexts. First, we present a longitudinal study at an independent NSW secondary school with year 12 students, including both in person and online iterations of the project. The teacher incrementally improved their STICE teaching over four years using the mapping exercises.

Second, we present a single iteration of the STICE exercise run simultaneously at five Victorian schools within upper-level chemistry classes as part of a professional learning community project. That project was initiated in February 2020 and was conducted during a period when students were required to learn from home. The teachers involved adopted slightly different approaches and integrated the systems maps into different parts of the enacted curriculum.

Table 1 summarizes the implementation of these two vignettes. In both cases, a teacher action research co-design methodology was followed [39], giving the teachers involved ownership as agents of reform [40,41].

In the third vignette, maps were drawn as part of professional learning within a Graduate Certificate program, which was designed to upskill out-of-field science teachers [42]. One unit of the Graduate Certificate focused on improving teachers’ skills to teach chemistry. The program was offered in 2021 and 2022, and 65 teachers participated over the two years.

In every case, the concept and process of Systems Thinking was first introduced to participants (students in vignettes 1 and 2, teachers in vignette 3), using a combination of examples, videos and class discussion. The participants were shown an example of a systems map as a way to represent Systems Thinking for a chemical process [37]. They were then guided to produce their own systems maps for chemical processes, focusing on sources of starting materials, uses of products, and intended and unintended consequences of the process.

**Table 1.** Summary of school classes in which systems mapping exercises were implemented (vignettes 1 and 2).

Teacher Code	Teacher Experience	Type of School	Curriculum	Number of Students	Implementation Year(s)	Systems Maps Topics
T1	>20 years	Regional private	NSW	7–10 per year	2019–2022	Biofuels, Haber, Contact, Solvay, esterification
T2	6–10	Selective public girls' school	Vic	39	2020	Acid rain, ocean acidification
T3	1–5	Public	Vic	25	2020	Ocean acidification, fuels, N95 masks, hydrogen
T4	1–5	Public	Vic	20	2020	N95 masks, fertilizers
T5	6–10	Regional catholic	Vic	19	2020	Polyvinyl chloride (PVC), Polylactic acid (PLA), water
T6	10–15	Independent girls' school	IB	13	2020	Polypropylene

The maps were broadly defined, and participants created them by hand or using computer programs, being as creative as they chose, so the outputs are very variable. Students in vignette 2 completed pre- and post-surveys about their orientations to chemistry, sustainability and Systems Thinking in addition to submitting several maps, and the full survey instrument is available in the Supplementary Information S1. The participating teachers were interviewed during and after the project to explore their perceptions of using systems maps in their classrooms.

Given the variability of how the data collection was conceived across the three vignettes, the framework we have utilized in our analysis is the purposeful selection of examples to include from the student and teacher interviews [43]. We posit this is also in agreement with Wheeldon and Faubert, as an approach to qualitatively analyze a collection of maps (and student and teacher interviews regarding these maps) that together do not narrowly follow a particular map definition [36]. The maps presented here have been chosen to be methodologically sound and to provoke conversation about the issues raised by the use of mapping to represent Systems Thinking. Selection of quotes from these groups does not mean that the opinions can be generalized to other groups, rather they illustrate the utility of mapping in these contexts and allow others to envision adopting mapping within their own classrooms.

Institutional ethical approval for the studies was obtained as follows: Deakin University: HAE-19-180, HAE-19-206, HAE-21-023; Victorian Department of Education and Training: 2019\_004196, 2021\_004358; Melbourne Archdiocese Catholic Schools: 0949.

### 3. Results and Discussion

#### 3.1. Vignette 1

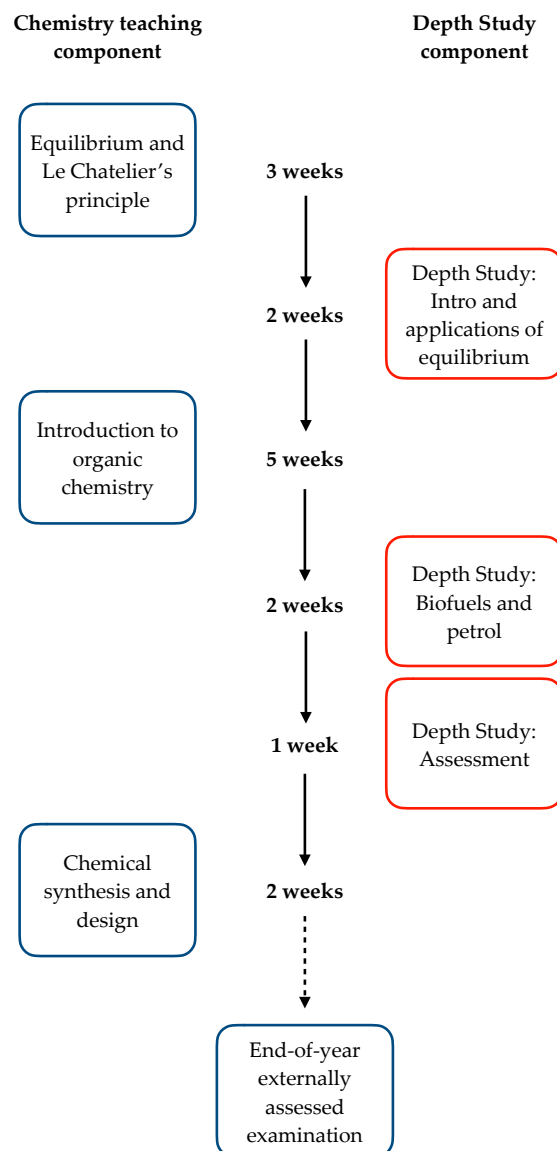
As previously described [38], Stage 6 (Years 11 and 12) Science syllabuses in NSW require that students must undertake Depth Studies in each year, totalling a minimum of 15 in-class hours per year [44,45]. Starting in late 2018, the highly experienced teacher in this project (T1) designed and refined a Depth Study featuring Systems Thinking for his Year 12 chemistry students using a teacher action research [41] iterative reflective cycle [46]. For both 2020 and 2021 iterations, COVID-19 restrictions meant that students were learning from home for part of the time and the systems maps were created at home.

To teach Systems Thinking within the mandated curriculum, Systems Thinking teaching was interleaved with traditional teaching approaches, as illustrated in the timeline in Figure 1. Details of T1's delivery are included in Supplementary Information S2.

Throughout the process, students received formative feedback on draft maps and connections to SDGs from the teacher. Their summative assessment consisted of three tasks:

- (a) an essay comparing current research for two different systems they had studied, and their respective effects on SDGs;

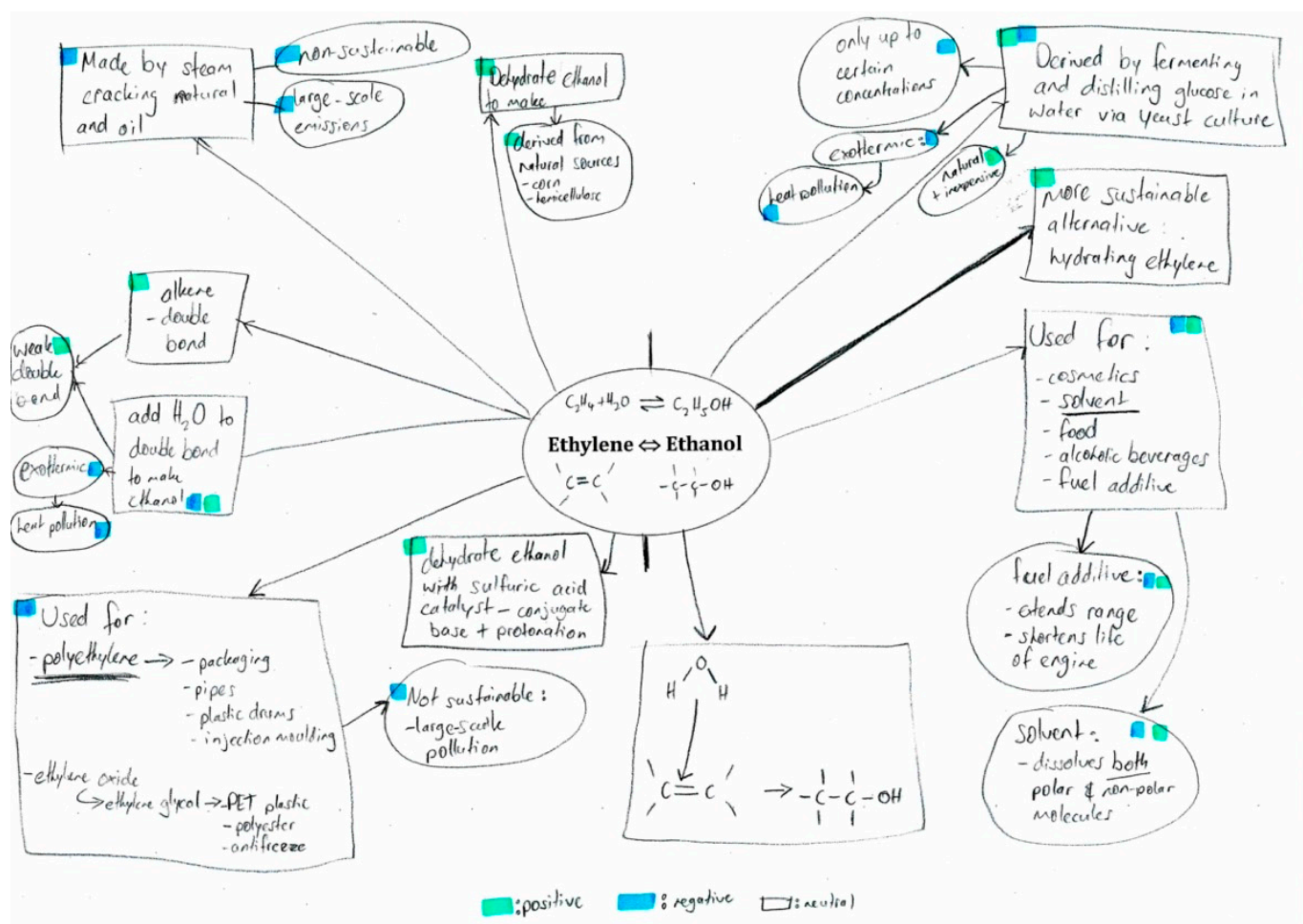
- (b) construction of a system map for a process with which they were familiar, the inter-conversion of ethylene and ethanol; and
- (c) evaluation of a systems map drawn by the teacher on the Solvay Process, which they had not previously seen, in relation to SDGs.



**Figure 1.** Timeline of content over three terms of teaching, showing interweaving of Systems Thinking and traditional teaching approaches. Blue: traditional teaching. Red: Systems Thinking (through implementation of the Depth Study).

This set of assessment tasks provided a valid indication of student engagement and understanding of sustainability, Systems Thinking and current research. An example of a student-generated map for task (b) is shown in Figure 2 and further examples are available in Supplementary Information S3.

The student-generated systems maps in task (b) were marked based on the logic of the structure, the breadth of connections and the interrelationships shown as connections across nodes. Similarly, student inclusion of SDGs for task (c) was marked based on the number of SDGs per node, breadth of SDGs across the systems map, consideration of negative and positive factors and justified weighting of SDGs due to influence and importance. Student results for the Depth Study were higher than typical assessment tasks and were comparable to research-based assessments used in the past.



**Figure 2.** Student-drawn systems map for the interconversion of ethylene and ethanol, highlighted to show processes that have positive or negative impacts on sustainability. The student has included chemical reactions, uses and sustainability considerations throughout the map. All of the information is correct although few cross-links are shown.

### 3.1.1. Teacher Reflections

As T1 became more comfortable with delivering the Depth Study, he implemented incremental improvements to explaining how and why the students should complete systems maps and link them to SDGs. He linked the logical structure of a systems map to the different sides of the chemical equation and explained how multiple nodes (either for reactants or products), showed a broader of understanding of the process and how links beyond the initial nodes, especially if they connected to other parts of the systems map, showed a greater awareness of the relationships that are intertwined in all chemistry. For example, energy is an important component of the systems map for any chemical process and is required from extraction and production of key reactants and catalysts, to production within and beyond the process. The explicit nature of the explanations of what constitutes a meaningful systems map led to students producing more logical, yet more complex, maps in each year of the project.

Similarly, T1's explanations of how and why we use SDGs to evaluate chemical processes within systems maps became clearer and more explicit through iterative improvements. In 2022, to develop students' evaluation skills, he suggested that students first identify as many SDGs as possible for each node before weighting SDGs, based on their judgement of importance and influence. Students found this approach easier than students in previous years and understood the importance of their judgement to a greater extent, indicating that their Systems Thinking capacity increased.

Overall, T1 enjoyed using systems maps in a Depth Study and will continue to do so. It is evident that this approach transforms simple chemical processes, usually represented by a chemical equation, into something greater, embedded in the global context. Previous research-based assessment tasks have been perceived by students as jobs to complete and not valued for their additional learning outcomes. In contrast, the systems mapping exercise was effective to stimulate interest.

### 3.1.2. Student Perceptions

Most students in this vignette had a positive impression of the systems mapping exercise. The three student quotes below show that the students valued the broader perspective on chemistry afforded by Systems Thinking.

*You actually have to really think about the broad impact of it, you know, "what's that ethanol then being used for? How's that affecting every single part of society?" And on top of that, "where is the ethanol coming from? And how is that impacting everything?" It's like, on its own, it's almost like doing a Depth Study for each systems map. So you're looking more in depth into the reactions rather than just doing a surface level, "this is the reaction, this plus this equals this ... "*

This student appreciated being guided to think more deeply about chemical processes beyond simple chemical equations.

*I really enjoyed doing the map. I liked—you break it down into its specific aspects ... . It makes it, it gives a really good visual demonstration of its true benefits, benefits and negatives and like neutral aspects of the processes ... . so it's definitely a broader focus on science in general, rather than just chemistry.*

This student explained that creating a visual representation helped them appreciate multiple aspects of the chemical process. The approach designed by T1 allowed them to conduct the mapping task in a structured way.

*I found it really helpful. Writing down the positives and negatives, and then you find out like, explosives, it actually has a positive, I guess, but then, it obviously has heaps of negatives ... You find things that, oh, wow, that actually has a negative effect, even though I thought it was a quite positive thing. But it has a negative effect on the environment.*

This student valued the opportunity to reflect on multiple aspects of processes and developed their Systems Thinking skills through evaluating processes holistically.

However, a few students were ambivalent, and some could not appreciate how the Depth Study fitted into the course as a whole, as illustrated by the following quote.

*I felt was more like geography than chemistry to be 100% honest, 'cause it was more about the increasing jobs and environmental impact. It's not how I picture chemistry.*

This likely reflects a goal-oriented learning focus, in which a direct link between classroom activities and examination results dominates some students' attitudes to learning.

### 3.2. Vignette 2

The five teachers in this vignette were participating in a year-long professional development program through which they were supported to carry out a chemistry education research project in their classroom [38]. The professional development program commenced with two full days of face-to-face workshops through which all participants provided with opportunities to try out methodologies explore and topics in current chemistry education research. One of the topics introduced was STICE. During the second day, participants selected topics of interest for their research project and formed groups based on common topics. Five teachers were interested in STICE and formed the group whose experiences are described and explored in this vignette.

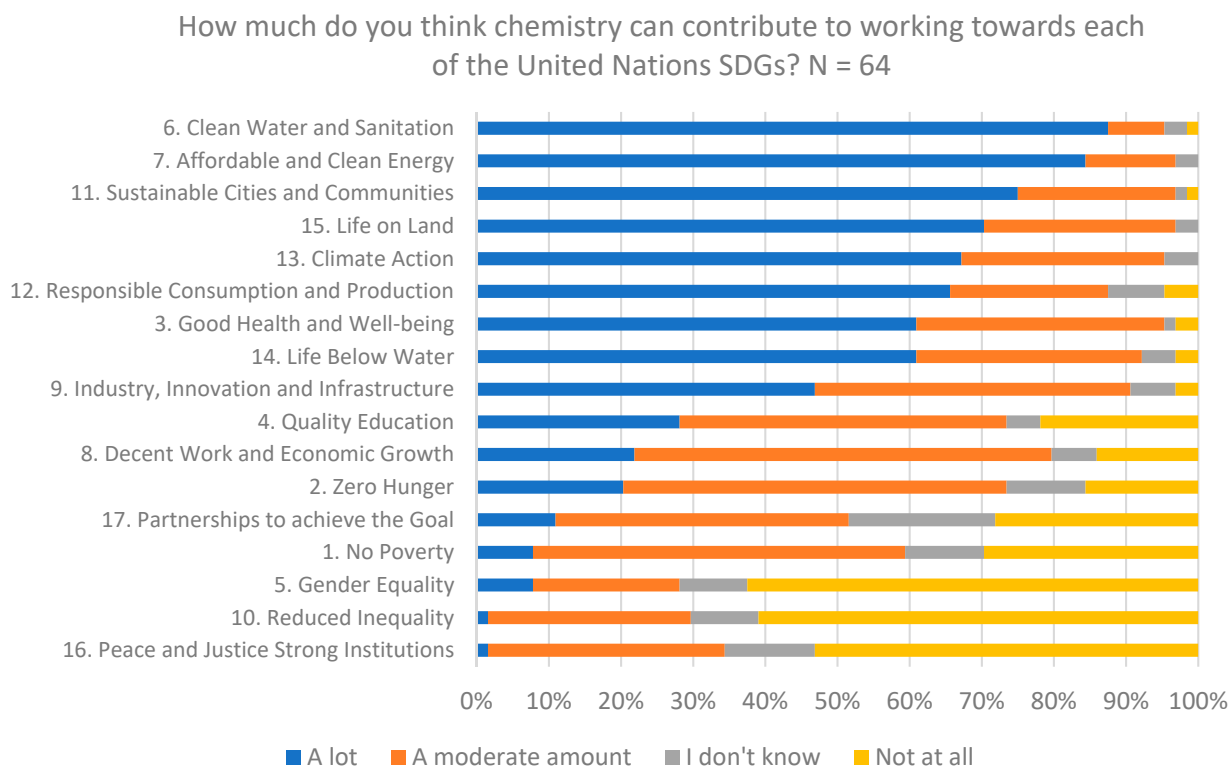
The workshops were conducted in February 2020 and at the time, the teachers expected to carry out their projects during a normal school year. However, the year was anything

but normal in Victoria, with around four months of learning from home due to COVID-19 restrictions. Thus, all teaching described here was carried out online, and students used computers to engage with all instruction.

The Victorian senior secondary chemistry curriculum is different from NSW and does not include a Depth Study. Systems Thinking was a natural fit to Unit 3 of the curriculum (taught in the first half of the second year of a two-year program, typically year 12), entitled “How can chemical processes be designed to optimize efficiency” [47]. However, due to their student groups and timing, some teachers chose to introduce it within Unit 1 (taught in the first half of the first year of a two-year program, typically year 11) entitled “How can the diversity of materials be explained?” or Unit 2 (taught in the second half of the first year) entitled “What makes water such a unique chemical?”.

Prior to introducing the concept and process of Systems Thinking, students within this vignette were surveyed about their interest in chemistry, their understanding of sustainability and Systems Thinking and the relevance of chemistry to the 17 SDGs. 64 students from 4 of the involved schools completed the pre-survey, with an equal mix of male and female participants. Over 85% of these students, who had chosen chemistry as an elective subject, found chemistry interesting and over 90% thought it was a driver of global change. However, only 62% considered chemistry relevant to their everyday life. When asked to select why sustainable chemistry is important, over 75% selected the options “to protect the environment”, “to improve human health and safety” and “to conserve energy”, while 55% of the students also selected the other options “to make experiments safer” and “to improve chemistry research”. At that time, 15% of students selected the option “I don’t know what sustainable chemistry means”.

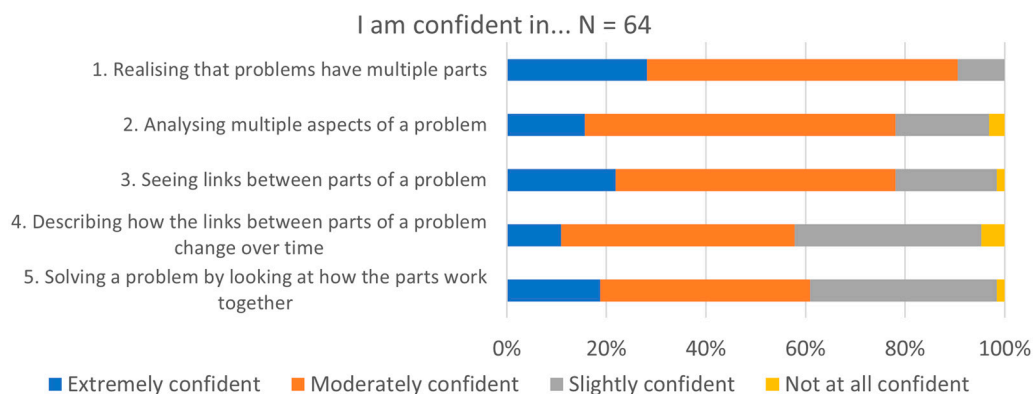
Figure 3 illustrates the perceived relevance of chemistry to each of the 17 SDGs. It shows that for this group of high school students, chemistry is clearly related to SDG3, SDG6, SDG7, SDG11, and SDGs 13–15, with over 90% of students thinking that chemistry can contribute to working towards these goals. Conversely, these students did not perceive a clear link between chemistry and SDG5, SDG10 or SDG16, with fewer than 40% perceiving possible contributions from chemistry.



**Figure 3.** Student perceptions of relevance of chemistry to SDGs prior to project involvement.

Prior to the project, 83% responded that they had not previously heard of Systems Thinking. Those that had heard of it were able to provide accurate definitions, showing that they may have encountered Systems Thinking in other school subjects.

The pre-survey also asked students to rate their confidence in a set of five skills associated with Systems Thinking capacity. This set of skills was developed within this project based on current STICE literature [48]. These skills can be considered to form a hierarchy of Systems Thinking, and student confidence was higher for the lower-order skills than for the higher order skills. Figure 4 illustrates the responses to this part of the pre-survey.



**Figure 4.** Student confidence in five Systems Thinking skills prior to project.

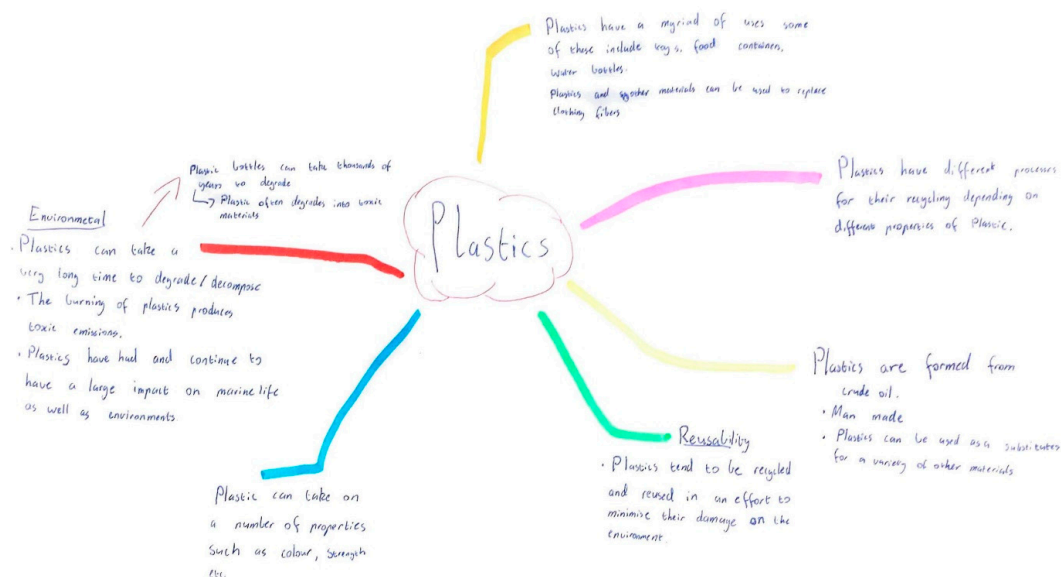
### 3.2.1. Teacher Implementation of Systems Thinking Using Mapping Exercises

The five teachers within this vignette chose to introduce their students to Systems Thinking and the use of systems maps in different ways, as described in Supplementary Information S4. T2 chose to introduce Systems Thinking within the topic of acids and bases, which falls within Unit 2, focussing on the issues of ocean acidification and acid rain. For their maps, the students were asked to include chemical equations, sources of contaminants, impacts of human activities on the environment and secondary (larger scale) impacts.

T3 incorporated Systems Thinking into her instruction on fuels within Unit 3 in 2020. The focus was formation, sources, uses and environmental impacts of different fossil fuels. She first asked the students to draw a practice system map to illustrate the impact of fuel combustion on ocean acidification. A student example is shown in Supplementary Information S5. She then showed and discussed maps for both gasoline and diesel, asked the students to compare these two fuels. Finally, students drew their own maps for coal and labelled inputs and outputs according to the SDGs. An example by the same student is presented in Supplementary Information S5 and demonstrates an increase in Systems Thinking skills as they were better able to visualise the interconnectedness of social, economic and environmental aspects to the chemistry. In 2021, T3 uses systems maps when discussing N95 masks and forms of hydrogen.

T4 chose the topical context of N95 masks to introduce Systems Thinking and mapping, within Unit 1. Students drew practice systems maps including the whole life cycle of the mask showing how intended and unintended consequences of plastics might be interconnected. Following this, instruction on polymerization and plastics was presented by T4. This enabled the students to draw a second systems map for N95 masks, focussing on the chemical process of polymerization. They then discussed the SDGs and finally added SDGs where relevant to their maps. A student example is shown in Supplementary Information S5. For a second round of maps, the students examined an environmental chemistry issue: water contamination from fertilizer run-off, and a student map is presented in Supplementary Information S5.

T5 also used the topic of polymerization and plastics within Unit 1. The students first drew a mind map related to plastics; an example is shown in Figure 5.



**Figure 5.** Student-drawn mind map about plastics prior to Systems Thinking instruction. There are no connections between the different pieces of information.

After an introduction to Systems Thinking and the SDGs, students drew a systems map on PVC. Following specific instruction by T5 on polymerization and the uses of polymers, students created a final systems map including SDGs on PLA. The map shown in Figure 6 was drawn by the same student who drew Figure 5. An increase in Systems Thinking skills is clearly observable in the multiple links between different components of the system [48]. In addition, the student has made connections to sustainability through mentions of negative greenhouse gases, biodegradability and recyclability. A series of maps from a different student is presented in Supplementary Information S5.



**Figure 6.** Student-drawn systems map for PLA, highlighted to show processes that have positive or negative impacts on sustainability. This student has linked some properties to applications and also appreciated the importance of this alternative material to multiple sustainability challenges.

T6 was teaching within the International Baccalaureate (IB) curriculum [49], which has more emphasis than either Victorian or NSW curricula on student understanding of societal impacts of science. However, the IB curriculum has less flexibility in assessment, so STICE and the systems maps were conducted as a class exercise and not assessed. T6 first demonstrated drawing a systems map using the example of polyethylene and showed the inclusion of SDG labels and evaluation of positive and negative impacts. Students then drew maps on polypropylene.

### 3.2.2. Teacher Perceptions and Reflections

T2 struggled with the time constraints in implementing systems mapping within the senior secondary curriculum during the project. However, she subsequently adopted the use of systems maps with lower secondary students for two topics, and this was very rewarding for her and the students. Their high engagement with the systems maps and discussions has led T2 to revisit the use of systems maps with upper secondary students. Reflecting one year after the project, she indicated that despite the challenges she plans to incorporate Systems Thinking activities into her teaching in the future, but she is aware that they must be valued by the students to be effective. Her reflections below describe this journey of a highly motivated and experienced teacher in a performance-oriented school environment.

*I didn't spend as much [time] explaining what systems mapping was, because I did this with my year 11 s, and I remember that I chose not to, because I was behind curriculum . . .*

*. . . I did an activity, system mapping for year 9 s with acid rain, we had an acid rain practical investigation, it was great to see them thinking about other impacts. So for them, they weren't able to see impacts such as economic impacts beyond chemistry, and it was great to have a discussion, and I thought it was really quite powerful. And I did the same thing with global warming with my year 9 s again, and again, we had a conversation about using fossil fuels and renewable energy. And so yeah, definitely lots of positive impacts in my teaching . . .*

*[At the start of the project] to be honest, I was a little hesitant as to how it would work. But I think this is something definitely I would want to think about doing more in my senior years. It's just trying to make the year 12 s or 11 s see that this is an important activity, rather than a feelgood activity, if you know what I mean. Because it was so powerful in year 9, but in year 12, or 11, I feel like their engagement with this sort of activity isn't as strong.*

The tension between what she experienced as a valuable classroom activity with year 9 students and anticipated lack of engagement by year 11 students again points to the challenges of a goal-oriented learning environment, as exhibited by some of T1's students.

T3 also reflected on the difficulty of achieving student engagement with activities that are not considered to be directly tied to assessment tasks.

*And it is hard to sell for the students to a certain extent, depending on the students . . . not everyone likes, you know, that kind of exploration. So, "why are we learning all this?" Not all of them enjoy that. They just want you to give them the facts, and what do I need to know, and need to practice. So it is a little bit difficult to sort of sell that.*

In this case, as a relatively new teacher, T3's own perceptions of chemistry were changed by her involvement in the project, as evident in the following quote.

*It really sort of makes me see how you can really use chemistry to change people's perception on how they live their lives, which I think affects me more personally, rather than the way the students see this. "Oh, where do I get this from? Can I recycle this?" . . . I feel I started thinking about those things a lot more after I become more aware of the whole idea of a circular economy. I think I definitely appreciate it more.*

She valued the maps as a useful approach to teaching chemistry content.

*I think they found the visual very useful when you have a lot of content that they need to remember and also the connections between them.*

T4 is also quite new to teaching but had a stronger focus on sustainability prior to his teaching career. He found the use of systems maps an effective way to embed sustainability within his chemistry teaching.

*I was always, you know, passionate about teaching sustainability, but I guess this project's given me kind of a more clear understanding and how to do that via chemistry education.*

In her reflections, T5 emphasised that a benefit of using systems maps is that students made connections with unintended consequences of chemical processes. She introduced systems maps early in the senior curriculum, intending to use them in multiple topics.

*The mapping worked. The students were able to make the broader real world connections with the topic. Often students miss these connections, particularly the unintended uses/consequences/outcomes of materials, and linking it with the SDGs gave it real depth and richness. I also think the polymers topic was an excellent introduction point for this type of task. Doing it in Unit 1 then allows for the Systems Thinking approach to be built upon as students move through the course.*

After participating in this project, T5 considered Systems Thinking as a skill that has to be explicitly taught, rather than just being assumed within contexts in the chemistry curriculum. Her description of her planning for the next iteration shows how she has refined her understanding of how to best implement systems maps with her students.

*I plan to do it again. I think I would spend additional time on teaching about Systems Thinking and how to construct the maps. I went with quite a student-led approach, letting them 'do it their way'. Whilst I guided with key information, some of their representations left a lot to be desired. Systems Thinking in itself is a concept which requires teaching, before adding content to it.*

Both T5, teaching the Victorian curriculum, and T6, teaching IB curriculum, felt that the maps could not be directly assessed in their contexts. This contrasts with T1, who was able to embed drawing and evaluating systems maps within his assessment in a Depth Study in the NSW curriculum.

*T5: I don't feel that maps as assessment would be a fair representation of all students' understanding. There is potential for them to be used in conjunction with another task to create a richer assessment task, but I would not use this as a stand-alone assessment piece.*

*T6: And in that sense, there maybe wasn't a strong kind of assessment outcome from it. It was just an activity done for the sake of, hey, let's learn about Systems Thinking. So I thought that was my personal biggest limitation: Implementing that with my class.*

### 3.2.3. Post-Survey

Few students (15) from only one school participated in the post-survey, so the data should be interpreted with this in mind. However, some trends were observed. In particular, agreement with the item "I find chemistry relevant to my everyday life" increased from 62% to 73%. Strong agreement with "I think chemistry is a driver for global change" increased from 43% to 67%, while agreement with "I find chemistry interesting" did not change. Thus, drawing the systems maps seemingly increased these students' perception of the relevance of chemistry.

For the relevance of chemistry to the SDGs, "I don't know" responses decreased, and these were only recorded for four of the SDGs, whereas in the pre-survey, all 17 of the SDGs received some "I don't know" responses. This indicates increased awareness by the students of the SDGs during the teaching period. Student confidence in their five Systems Thinking skills (Figure 4) did not change in the post-survey. Although we did not observe a change in this measure of Systems Thinking capacity, we plan and encourage others

to explore this further in the future. It is vital to establish a valid instrument to measure Systems Thinking capacity and use this to evaluate the impact of classroom activities.

### 3.3. Vignette 3

The Graduate Certificate of Secondary Science is an ongoing course “tailored for teachers who are not formally qualified for mathematics or science, although they may have some background in studying or teaching the subject” [42] (p. 40). Part of the course involves science teachers taking part in four intensive days and three shorter online workshops across a trimester focussed on teaching chemical science for lower secondary students. Whilst the bulk of the four days focussed on addressing the curriculum content, one session focussed on introducing systems mapping as an approach to connecting the chemistry being learned (balancing chemical equations, conservation of mass, role of energy) to the bigger picture of how chemistry impacts the lives of students and society. As in vignettes 1 and 2, the SDGs were introduced at the same time to make the connection between chemistry and societal challenges more apparent.

To introduce systems maps, participants were shown a figure representing the relationships between the chemistry of reactive nitrogen and selected SDGs [5] (p. 363). Groups of teachers then completed an activity that involved them creating similar maps for a chosen context (plastics, fertiliser, concrete, increased CO<sub>2</sub> emissions). In 2020, the day 3 intensive was undertaken remotely, so this mapping activity was completed online using the free web platform Padlet (<https://padlet.com/>; accessed on 24 August 2022). In 2021, while the day 3 intensive was conducted face-to-face in a seminar room, the activity was still run using Padlet because the technology facilitated the activity; teachers could easily copy and paste SDGs and connect them to their central node, and groups could see the responses from other groups online. An example is shown in Figure 7.



**Figure 7.** Example of a map developed by a group of teachers representing the relationships identified by teachers between increased CO<sub>2</sub> emissions and the sustainable development goals (SDGs).

Within their seminar groups, participating teachers then discussed some specific characteristics of Systems Thinking, drawing upon the essential characteristics that have been defined [50]. As in vignette 2, the participants were then shown the teacher-generated systems map that we had previously published [38]. In small groups, the participants finally built a systems map for a chemical process chosen from the following list.

- (a) Smelting iron ore:  $\text{Fe}_2\text{O}_{3(s)} + 3 \text{CO}_{(g)} \rightarrow 2 \text{Fe}_{(l)} + 3 \text{CO}_{2(g)}$
- (b) Addition polymerization:  $n \text{C}_2\text{H}_4(l) \rightarrow (\text{C}_2\text{H}_2)_n$
- (c) Dissolving calcium carbonate (seashells) in oceans at lower pH:  $\text{CaCO}_{3(aq)} \rightleftharpoons \text{Ca}^{2+}_{(aq)} + \text{CO}_3^{2-}_{(aq)}$
- (d) Forming pure Aluminium from Bauxite ore:  $2 \text{Al}_2\text{O}_{3(s)} \rightarrow 4 \text{Al}_{(l)} + 3 \text{O}_{2(g)}$

Having learned from our previous experiences (vignettes 1 and 2) and acknowledging that the teachers in vignette 3 did not have strong science content knowledge, we provided a detailed scaffold that was essentially a series of questions for them to answer by way of their representations on their maps. This scaffold is shown in Figure 8.

Pick a chemical process
—

For today, this is given to your group in the Padlet, but you could look at any of the chemical processes mentioned in the Victorian curriculum - see the [Assignment Task 2 instructions](#) C

What are your inputs?
—

- What are reactants? Where do they come from?
- Does this process require energy? Where does *that* come from?

What are your outputs?
—

- What does the process produce?
- Are these intended products? Are these waste products?

What happens with the intended products?
—

- How are they used in society and industry? For what benefit?
- Are they replacing a previous way we used to do something in society or industry? In what way?

What happens to the waste products?
—

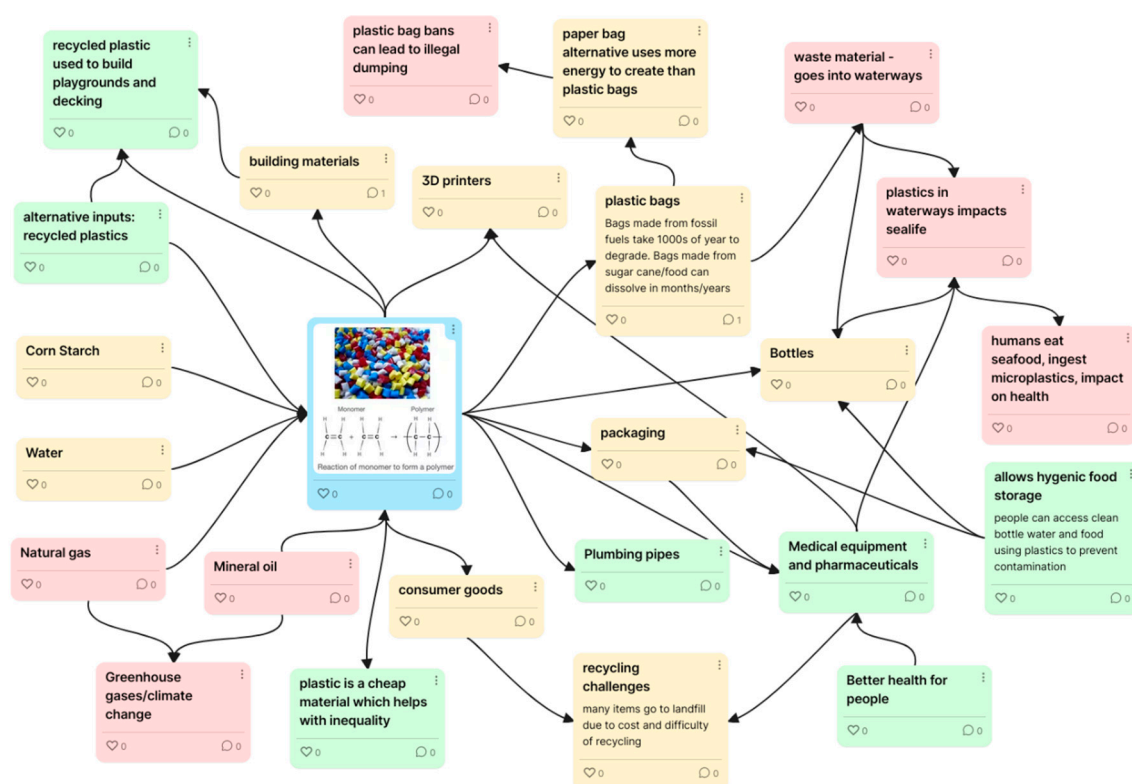
- How does society and industry deal with these? How successful are they?
- Is there any possibility to use some of the waste products as reactants for other process? Recycling potential?

What are some of the unintended consequences of this process?
—

- Has an over-utilisation of this chemical process in society and industry lead to problems? In what way?

**Figure 8.** Scaffold provided online to facilitate teachers completing the systems mapping exercise.

The final part of the activity was to colour some of the parts of their map green (positive), red (negative), or yellow (neutral) with respect to their perceived impact on contributing to the SDGs. Unlike our previous example [38], participants did not refer to a specific SDG number, but many did this verbally when presenting and discussing their group's response to the rest of the seminar cohort. An example response from a small group of teachers in Figure 9 illustrates what these participants chose as key features.



**Figure 9.** Example of a systems map for addition polymerization, developed by a group of teachers, highlighted to show processes that have positive or negative impacts on the SDGs.

As a post-activity, the teachers were prompted to consider how they interpreted the activity. Many teachers stated that it was a “great to link chemistry to everyday objects from a sustainability lens”, and others noted that this was a practical manner to link the chemical science curriculum content to the ‘Learning about sustainability’ cross curriculum priority in the Victorian curriculum [51]. For their final assignment for the unit, each teacher was also asked to draw a systems map relevant to the context of a series of lessons they presented. It was apparent from the maps that teachers were able to meaningfully connect chemistry understanding with specific SDGs.

Through this activity, participants demonstrated an emergent understanding of the mass and energy inputs and outputs for a given chemical process as being components of a system, with interconnected relationships. The participants were able to visually represent the intended (and unintended) outputs for a chemical process, as well as the sources for the mass and energy inputs for a chemical process, and importantly how these dictate the impact and interaction of the process with its environment (and therefore with other systems). Exploring this further, with follow-up activities, the participants may have also been able to demonstrate these to be causal variables. Figure 9 shows early evidence of this, in that the participants represented on the left side of their systems map the different possible feedstocks for monomers (natural gas—red/negative, corn starch—yellow/neutral, recycled plastics—green/positive) relative to the system’s capacity to address sustainable development challenges.

#### 4. Conclusions

As educators, we want students to make meaningful links between the content they learn and their current and future lives. In these vignettes, we validated the use of systems maps to incorporate sustainability into classroom through supporting students to determine and visualize connections between chemistry content and sustainable development. By labelling their maps with SDGs and positives/negatives, students connected sustainability with their chemical process. This is a relatively facile approach that can be used across

science, which we suggest offers opportunities for educators and researchers alike seeking to infuse sustainable development into the enacted curriculum.

We have demonstrated that systems maps can be used to teach secondary chemistry content and can be effectively implemented within professional development. They are useful within different curricula and are applicable for multiple age levels, settings and topics. The open format of the maps allows creative experimentation by the students as they play with the iconicity of the maps as diagrams, and potentially supports development of their metarepresentational competence.

It is difficult to quantify the development of Systems Thinking skills through analysis of student-drawn maps, because the maps are also impacted by students' background knowledge and their level of engagement with the content. However, our use of maps was designed to lead students to visualize chemical processes as systems, leading to the development of Systems Thinking skills, including identifying components and relationships within the system as well as its boundaries [48]. Students also started to think about the impacts of their chemical process on SDGs. We did not measure Systems Thinking capability directly; however, drawing the maps gave students the opportunity to view a chemical process as a system, developing their Systems Thinking capacity within the framework of STICE [50].

The main challenge to using systems maps in the classroom is finding time and space in the curriculum. However, the teachers in our vignettes perceived their usefulness, were able to incorporate them and planned to continue their use. When planning their use as a classroom exercise, students require productive constraints to make meaningful maps. A specific recommendation is to use systems maps for polymerization reactions because there are many examples with clear links to sustainability within students' everyday experiences.

Several teachers perceived that this sort of open-ended task may be unpopular with goal-oriented students, because it requires creativity and does not have a single correct answer and may be perceived as taking time away from core content. However, given that teachers aim to include a range of teaching and assessment approaches, we suggest that there is merit in these tasks as part of inquiry-based and representationally rich approaches that align with the epistemic practices of science [20,34]. They are particularly suitable as formative assessment tasks and provide teachers with insights into students' broader thinking.

Only vignette 1 involved scoring maps as part of a summative assessment task, and the teacher developed their scoring methods over time. Evaluating a completed map makes it difficult to understand all the links, because the maps are often very complicated and disorganized. For a more nuanced evaluation, it would be necessary to see the map being drawn. Remote learning made this particularly challenging, and all of the teachers mentioned that in both 2020 and 2021, COVID-19 restrictions caused massive disruption to learning and assessment.

In undertaking this project as participatory action research, we coped with ever-changing COVID-19 restrictions and lockdowns, a sudden and unexpected transition to online learning, and different circumstances at each school. Thus, the data are messy [52]. Despite this mess, all teachers involved found the maps to be useful and intend to use them in the future. The student-generated maps confirmed that this approach allows students to engage with Systems Thinking and to represent System Thinking skills while visualizing chemical processes.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/educsci12090596/s1>, S1: Survey instrument. S2: Vignette 1: Details of classroom teaching approach. S3: Vignette 1: Further examples of student-generated maps. S4: Vignette 2: Details of classroom teaching approaches. S5: Vignette 2: Further examples of student-generated maps.

**Author Contributions:** Conceptualization, M.S. and S.D.; methodology, M.S., J.P.F. and S.D.; validation, S.D.; formal analysis, M.S., S.D. and J.P.F.; investigation, D.C.; A.C.E.; R.H.; A.R., O.T.; H.H.V.;

resources, S.D.; writing—original draft preparation, M.S.; writing—review and editing, M.S., J.P.F. and S.D.; project administration, S.D.; funding acquisition, S.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Chemistry Education Association (Victoria) and the Victorian Government Department of Education and Training.

**Institutional Review Board Statement:** The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Boards of Deakin University: HAE-19-180, HAE-19-206, HAE-21-023; Victorian Department of Education and Training: 2019\_004196, 2021\_004358; Melbourne Archdiocese Catholic Schools: 0949.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study. For student participants aged under 18, parental consent and student assent was obtained prior to commencement of the study and again before interviews were conducted. Student artefacts, including maps, were submitted online to the university-based researchers as de-identifiable research outputs with consent.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** We thank the schools and the students who participated in all three vignettes for their huge effort during a stressful time. We are grateful to Lisa Chiavaroli (project officer) as well as the Chemistry Education Association for their financial support in facilitating the professional learning program described in vignette 2. We thank Amanda Peters (project officer) and the Victorian Government Department of Education and Training for the financial support of Secondary Maths and Science Initiative described in vignette 3.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. UNESCO. *Learn for Our Planet: A Global Review of How Environmental Issues Are Integrated in Education*; UNESCO: Paris, France, 2021. Available online: <https://unesdoc.unesco.org/ark:/48223/pf0000377362> (accessed on 31 May 2022).
2. Gilbert, J. Transforming Science Education for the Anthropocene—Is It Possible? *Res. Sci. Educ.* **2016**, *46*, 187–201. [CrossRef]
3. Monroe, M.C.; Plate, R.R.; Oxarart, A.; Bowers, A.; Chaves, W.A. Identifying effective climate change education strategies: A systematic review of the research. *Environ. Educ. Res.* **2019**, *25*, 791–812. [CrossRef]
4. Mahaffy, P.G.; Krief, A.; Hopf, H.; Mehta, G.; Matlin, S.A. Reorienting chemistry education through systems thinking. *Nat. Rev. Chem.* **2018**, *2*, 126. [CrossRef]
5. Mahaffy, P.G.; Matlin, S.A.; Holme, T.A.; MacKellar, J. Systems thinking for education about the molecular basis of sustainability. *Nat. Sustain.* **2019**, *2*, 362–370. [CrossRef]
6. Delaney, S.; Ferguson, J.P.; Schultz, M. Exploring opportunities to incorporate systems thinking into secondary and tertiary chemistry education through practitioner perspectives. *Int. J. Sci. Educ.* **2021**, *43*, 2618–2639. [CrossRef]
7. York, S.; Lavi, R.; Dori, Y.J.; Orgill, M. Applications of Systems Thinking in STEM Education. *J. Chem. Educ.* **2019**, *96*, 2741–2751. [CrossRef]
8. Michalopoulou, E.; Shallcross, D.E.; Atkins, E.; Tierney, A.; Norman, N.C.; Preist, C.; O'Doherty, S.; Saunders, R.; Birkett, A.; Willmore, C.; et al. The End of Simple Problems: Repositioning Chemistry in Higher Education and Society Using a Systems Thinking Approach and the United Nations' Sustainable Development Goals as a Framework. *J. Chem. Educ.* **2019**, *96*, 2825–2835. [CrossRef]
9. Next Generation Science Standards. Human Sustainability. 2013. Available online: <https://www.nextgenscience.org/topic-arrangement/hshuman-sustainability> (accessed on 31 May 2022).
10. ACARA. Sustainability. ACARA. Available online: <https://www.australiancurriculum.edu.au/f-10-curriculum/cross-curriculum-priorities/sustainability/> (accessed on 31 May 2022).
11. Szozda, A.R.; Bruyere, K.; Lee, H.; Mahaffy, P.G.; Flynn, A.B. Investigating educators' perspectives towards systems thinking in chemistry education from international contexts. *J. Chem. Educ.* **2022**, *99*, 2474–2483. [CrossRef]
12. Fisher, M.A. Systems Thinking and Educating the Heads, Hands, and Hearts of Chemistry Majors. *J. Chem. Educ.* **2019**, *96*, 2715–2719. [CrossRef]
13. Petillion, R.J.; Freeman, T.K.; McNeil, W.S. United Nations Sustainable Development Goals as a Thematic Framework for an Introductory Chemistry Curriculum. *J. Chem. Educ.* **2019**, *96*, 2845–2851. [CrossRef]
14. Summerton, L.; Clark, J.H.; Hurst, G.A.; Ball, P.D.; Rylott, E.L.; Carslaw, N.; Creasey, J.; Murray, J.; Whitford, J.; Dobson, B.; et al. Industry-Informed Workshops to Develop Graduate Skill Sets in the Circular Economy Using Systems Thinking. *J. Chem. Educ.* **2019**, *96*, 2959–2967. [CrossRef] [PubMed]

15. Nagarajan, S.; Overton, T. Promoting Systems Thinking Using Project- and Problem-Based Learning. *J. Chem. Educ.* **2019**, *96*, 2901–2909. [CrossRef]
16. Tytler, R.; Osborne, J. Student Attitudes and Aspirations Towards Science. In *Second International Handbook of Science Education*; Fraser, B.J., Tobin, K., McRobbie, C.J., Eds.; Springer: Dordrecht, The Netherlands, 2012; pp. 597–625.
17. Education for Sustainability and the Australian Curriculum Project: Final Report for Research Phases 1 to 3, Australian Education for Sustainability Alliance, Melbourne, Australia. 2014. Available online: <http://www.aeee.org.au/wp-content/uploads/2017/08/AEEE-Education-for-Sustainability-and-the-Australian-Curriculum-Project-Final-Report-2015.pdf> (accessed on 31 May 2022).
18. Timms, M.J.; Moyle, K.; Weldon, P.R.; Mitchell, P. *Challenges in STEM Learning in Australian Schools, Policy Insights*; Australian Council for Educational Research: Camberwell, VIC, Australia, 2018; Volume 6. Available online: <https://research.acer.edu.au/cgi/viewcontent.cgi?article=1007&context=policyinsights> (accessed on 31 May 2022).
19. Hay, D.; Kinchin, I. Using concept mapping to measure learning quality. *Educ. Train.* **2008**, *50*, 167–182. [CrossRef]
20. Tytler, R.; Prain, V.; Hubber, P.; Waldrip, B. *Constructing Representations to Learn in Science*; Sense Publishers: Rotterdam, The Netherlands, 2013.
21. Novak, J.D. Concept mapping: A useful tool for science education. *J. Res. Sci. Teach.* **1990**, *27*, 937–949. [CrossRef]
22. Davies, M. Concept mapping, mind mapping and argument mapping: What are the differences and do they matter? *High. Educ.* **2011**, *62*, 279–301. [CrossRef]
23. Santiago, H.C. Visual Mapping to Enhance Learning and Critical Thinking Skills. *Opt. Educ.* **2011**, *36*, 125–139.
24. Hanisch, S.; Eirdosh, D. Causal Mapping as a Teaching Tool for Reflecting on Causation in Human Evolution. *Sci. Educ.* **2021**, *30*, 993–1022. [CrossRef]
25. Neiles, K.Y.; Todd, I.; Bunce, D.M. Establishing the Validity of Using Network Analysis Software for Measuring Students' Mental Storage of Chemistry Concepts. *J. Chem. Educ.* **2016**, *93*, 821–831. [CrossRef]
26. Elam, M.; Solli, A.; Mäkitalo, Å. Socioscientific issues via controversy mapping: Bringing actor-network theory into the science classroom with digital technology. *Discourse Stud. Cult. Politics Educ.* **2019**, *40*, 61–77. [CrossRef]
27. Matlin, S.A. *Introducing the SOCME Tool for Systems Thinking in Chemistry*; Technical Resource; International Organization for Chemical Sciences in Development: Namur, Belgium, 2020. Available online: [http://www.iocd.org/v2\\_PDF/2020-TechRes0301-SOCME-Intro.pdf](http://www.iocd.org/v2_PDF/2020-TechRes0301-SOCME-Intro.pdf) (accessed on 31 May 2022).
28. Stjernfelt, F. *Diagrammatology: An Investigation on the Borderlines of Phenomenology, Ontology, and Semiotics*; Springer: Dordrecht, The Netherlands, 2007.
29. Stjernfelt, F. *Natural Propositions: The Actuality of Peirce's Doctrine of Dicisigns*; Docent Press: Boston, MA, USA, 2014.
30. Cox, M.; Steegen, A.; Elen, J. Using Causal Diagrams to Foster Systems Thinking in Geography Education. *Int. J. Des. Learn.* **2018**, *9*, 34–48. [CrossRef]
31. Budd, J.W. Mind Maps As Classroom Exercises. *J. Econ. Educ.* **2004**, *35*, 35–46. [CrossRef]
32. Burrows, N.L.; Mooring, S.R. Using concept mapping to uncover students' knowledge structures of chemical bonding concepts. *Chem. Educ. Res. Prac.* **2015**, *16*, 53–66. [CrossRef]
33. Chang, H.-Y.; Lin, T.-J.; Lee, M.-H.; Lee, S.W.-Y.; Lin, T.-C.; Tan, A.-L.; Tsai, C.-C. A systematic review of trends and findings in research employing drawing assessment in science education. *Stud. Sci. Educ.* **2020**, *56*, 77–110. [CrossRef]
34. Tytler, R.; Prain, V.; Aranda, G.; Ferguson, J.; Gorur, R. Drawing to reason and learn in science. *J. Res. Sci. Teach.* **2020**, *57*, 209–231. [CrossRef]
35. Aubrecht, K.B.; Dori, Y.J.; Holme, T.A.; Lavi, R.; Matlin, S.A.; Orgill, M.; Skaza-Acosta, H. Graphical Tools for Conceptualizing Systems Thinking in Chemistry Education. *J. Chem. Educ.* **2019**, *96*, 2888–2900. [CrossRef]
36. Wheeldon, J.; Faubert, J. Framing Experience: Concept Maps, Mind Maps, and Data Collection in Qualitative Research. *Int. J. Qual. Methods* **2009**, *8*, 68–83. [CrossRef]
37. Jablonski, E.; Abrams, E.; Honwad, S.; Marhefka, E.; Eckert, R.; Middleton, M. SMART: Systems mapping analysis research tool. Proceedings of European Science Education Research Association conference, Dublin, Ireland, 21–25 August 2017.
38. Eaton, A.C.; Delaney, S.; Schultz, M. Situating Sustainable Development within Secondary Chemistry Education via Systems Thinking: A Depth Study Approach. *J. Chem. Educ.* **2019**, *96*, 2968–2974. [CrossRef]
39. Delaney, S.; Schultz, M. Honouring the Ethos of Co-design Methodology in Contemporary Socio-scientific Teaching Research. In *Methodological Approaches to STEM Education*; White, P., Tytler, R., Cripps Clark, J., Ferguson, J., Eds.; Cambridge Scholars Publishing: Cambridge, UK, 2022; Volume 3.
40. Capobianco, B.M.; Feldman, A. Repositioning Teacher Action Research in Science Teacher Education. *J. Sci. Teach. Educ.* **2010**, *21*, 909–915. [CrossRef]
41. Pine, G.J. *Teacher Action Research: Building Knowledge Democracies*; Sage Publications: Thousand Oaks, CA, USA, 2009.
42. Tytler, R.; Hobbs, L.; Brown, J.; White, P.; Campbell, C.; Cripps Clark, J.; Delaney, S.; Herbert, E.; Peters, A.; Sawatzki, C.; et al. Theory and practice relations in design-based research: Designing professional learning with teachers teaching mathematics and science out-of-field. In *Methodological Approaches to STEM Education Research*; White, P.J., Tytler, R., Ferguson, J., Cripps Clark, J., Eds.; Cambridge Scholars Publishing: Cambridge, UK, 2021; Volume 2.
43. Ferguson, J.; Aranda, G.; Tytler, R.; Gorur, R. Video research: Purposeful selection from rich data sets. In *Video-Based Research in Education*; Xu, L., Aranda, G., Widjaja, W., Clarke, D., Eds.; Routledge: London, UK, 2018; pp. 124–139.

44. NSW Education Standards Authority. Depth Studies: Year 11 and 12. Available online: <https://educationstandards.nsw.edu.au/wps/portal/nesa/11-12/stage-6-learning-areas/stage-6-science/chemistry-2017/depth-studies> (accessed on 31 May 2022).
45. NSW Education Standards Authority. Science Stage 6. Available online: <https://educationstandards.nsw.edu.au/wps/portal/nesa/11-12/stage-6-learning-areas/stage-6-science/> (accessed on 31 May 2022).
46. McNiff, J.; Whitehead, J. *You and Your Action Research Project*; Routledge: London, UK, 2016.
47. Victorian Curriculum and Assessment Authority. Chemistry Study Design. 2016. Available online: <https://www.vcaa.vic.edu.au/curriculum/vce/vce-study-designs/chemistry/Pages/index.aspx> (accessed on 31 May 2022).
48. Orgill, M.; York, S.; MacKellar, J. Introduction to Systems Thinking for the Chemistry Education Community. *J. Chem. Educ.* **2019**, *96*, 2720–2729. [CrossRef]
49. International Baccalaureate. Chemistry. Available online: <https://www.ibo.org/programmes/diploma-programme/curriculum/sciences/chemistry/> (accessed on 24 August 2022)
50. York, S.; Orgill, M. ChEMIST Table: A Tool for Designing or Modifying Instruction for a Systems Thinking Approach in Chemistry Education. *J. Chem. Educ.* **2020**, *97*, 2114–2129. [CrossRef]
51. Victorian Curriculum and Assessment Authority. Learning about Sustainability. 2017. Available online: <https://victoriancurriculum.vcaa.vic.edu.au/static/docs/Learning%20about%20Sustainability%20Mapping%20document%2020%20Jan%202017.docx> (accessed on 31 May 2022).
52. Cook, T. The purpose of mess in action research: Building rigour though a messy turn. *Educ. Action Res.* **2009**, *17*, 277–291. [CrossRef]