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Systems thinking of pre- and in-service science and engineering teachers

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ABSTRACT
Systems thinking is an important skill in science and engineering education. Our study objectives were (1) to create the basis for a systems thinking language common to both science education and engineering education, and (2) to apply this language to assess science and engineering teachers' systems thinking. We administered two assignments to teacher teams: first, modelling the same adapted scientific text, and second, modelling a synthesis of peer-reviewed articles in science and engineering education, with teams selecting a topic from a list and summarising them. We assessed those models using a rubric for systems thinking we had developed based on our literature review of this topic. We found high interrater reliability and validated the rubric's theoretical construct for the system aspects of function, structure and behaviour. We found differences in scores between the assignments in favour of the second assignment, for two attributes of systems thinking: 'expected outcome/intended purpose' and 'main object and its sub-objects'. We explain the first attribute difference as stemming from the modellers' domain expertise as science or engineering teachers, rather than as scientists or engineers, and the second attribute difference – from the larger amount of information available for modelling the articles synthesis assignment. The theoretical contribution of this study lies in the definition of the systems thinking construct as a first step in establishing a common language for the science education and engineering education communities. The study's methodological contribution lies in the rubric we developed and validated, which can be used for assessing the systems thinking of teachers and potentially also of undergraduate students.

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systems thinking; assessment; in-service teachers; pre-service teachers

Introduction

The quality of science, technology, engineering, and mathematics (STEM) education is widely considered to contribute to economic prosperity (Caprile, Palmén, Sanz, & Dente, 2015; Donovan, Mateos, Osborne, & Bisaccio, 2014). The integration and interrelatedness of the different disciplines of STEM is considered to be important for effective

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STEM education (Daugherty & Carter, 2018; The International Council of Associations for Science Education – ICASE, 2013).

When discussing the Tee in STEM education, it is important to distinguish between 'technology education' and 'educational technology': while the former involves learning about technological knowledge and processes for solving problems, the latter involves using technology – specifically, modern electronic media technology – as a tool for improving the learning process (Dugger & Naik, 2001; de Vries, 2018). Design and Technology Education (D&TE) refers to the design of products using technology, with or without integration of other STEM subjects (Barlex, 2018a; MacGregor, 2018). In this paper, we refer to technology education, or D&TE, and not to educational technology. When we refer to engineering education in this paper, we refer to the educaton of engineers in traditional, *Problem-* or *Project-Based Learning* (PBL), or *Conceive-Design-Implement-Operate* (CDIO) settings (Edström & Kolmos, 2014).

The Next Generation Science Standards (NGSS) require students to operate at three dimensions of learning: (1) science and engineering practices, (2) disciplinary core ideas, and (3) crosscutting concepts, where two of these crosscutting concepts are *systems* and *system models* (NGSS Lead States, 2013). With systems growing larger and more complex, the need for systems thinking – the ability of comprehending systems holistically – is coming to the fore (Crawley, Cameron, & Selva, 2015; Frank, 2000) and approaching problems and phenomena via a systems perspective (Checkland, 2000).

Systems thinking has been researched in science education (e.g. Dori, Lavi, & Dori, 2016; Riess & Mischo, 2010), engineering education (e.g. Gero & Zach, 2014; Koral Kordova, Ribnikov, & Frank, 2015), and technology education (e.g. Andreucci, Chatoney, & Ginestie, 2012; Frank, 2006); however, it has been defined and assessed differently within each discipline, for example, within biology education (e.g. Hmelo-silver, Marathe, & Liu, 2007) or earth system(s) education (e.g. Ben-Zvi-Assaraf & Orion, 2005). Therefore, the creation of a common language – a shared terminology – for systems thinking is required to bridge this gap between and within the disciplines of science, engineering, and technology education. Due to the research population of the present study – science and engineering teachers – we decided in the present study to focus mainly on science and engineering education.

We assume that fostering teachers' systems thinking can help them in facilitating their students' systems thinking and conceptual modelling skill. Our study is the first, to our knowledge, to apply a methodology taken from model-based systems engineering to foster and assess systems thinking in science and engineering education. The purpose of the present study was twofold: (1) to create a common language for systems thinking in science education and engineering education, and (2) to assess systems thinking of science and engineering teachers – pre- and in-service – based on this common language.

Theoretical background

The present section includes a presentation of systems, systems thinking and conceptual modelling – with emphasis on science and engineering education – to serve as a central foundation for the following section explaining the study methodology.

Systems and systems thinking

Herein we provide a working definition of *system* to place our use of the term *systems thinking* in the context of science, technology, and engineering education: (1) a system is an entity made up of interacting parts; (2) this entity provides a function for a specific intended purpose, or end (in engineering), or outcome (in science); (3) this purpose or outcome is achieved through the interaction of all (or the main) parts of the system; (4) the interaction between the system parts are maintained by cause and effect relationships; (5) systems feature multiple levels of system integration; (6) each level of system integration exhibits whole-system properties not belonging to parts or combination of parts at lower levels of the system; (7) in engineering, systems are artificial, while in science, natural phenomena can be described as systems; and (8) artificial systems include means-ends relationships, while natural phenomena do not (Ben-Zvi-Assaraf & Orion, 2005; Barlex, 2018b; Batzri, Assaraf, Cohen, & Orion, 2015; Checkland, 2000; Dori, 2016; Dori, & Sillitto, 2017; Svensson, 2018).

In systems engineering, systems are often divided into three system aspects, namely *function* (utility), *structure* (form) and *behaviour* (dynamics). A system's structure and behaviour together enable the system's function, which in turn fulfils the purpose of the system, i.e. delivers its intended value. A system's purpose always concerns human beings (Crawley et al., 2015; Dori, D., 2016). Since any system's purpose is determined by (human) design, it is appropriately addressed in management systems or technological systems, but not in natural systems, in which the term *natural outcome*, or simply *outcome*, may more appropriately be used (Batzri et al., 2015).

Systems thinking can be described as the dual ability to understand systems and analyse circumstance, questions, or problems from a systems perspective (Ben-Zvi-Assaraf & Orion, 2005; Checkland, 2000; Crawley et al., 2015; Frank, 2000). However, the definition and assessment of systems thinking have been conducted differently in different disciplines of science and engineering education, such as biology education (e.g. Tripto, Assaraf, & Amit, 2013), earth science education (e.g. Batzri et al., 2015), or engineering education (e.g. Wengrowicz, Dori, & Dori, 2016).

Conceptual modelling

The term *concept* can be defined as 'a perceived regularity (or pattern) in events or objects, or records of events or objects, designated by label' (Novak & Cañas, 2007, p. 33). Since *concept* can be referred to as the basic unit of knowledge construction, concept acquisition, i.e. conceptual understanding, can be achieved when new knowledge is introduced into an existing knowledge construct in a logical manner (Duit & Treagust, 2003; Roth, 1990). Conceptual modelling is also a topic of interest in science education (e.g. Venville, & Dawson, 2010) and engineering education (e.g. Carberry & McKenna, 2014).

Concept maps were originally devised by Joseph D. Novak as a tool for understanding children's change in science knowledge – to represent students' declarative knowledge structure. In accordance with the tenets of constructivist learning, concept maps enable students to create their own knowledge, by linking their prior knowledge with new information through descriptive linking of concepts (Phillips, 1995). Concept maps are typically comprised of blocks representing concepts and linking lines with descriptions representing relationships between concepts (Novak & Cañas, 2007; Novak & Gowin, 1984; Ruiz-Primo & Shavelson, 1996). Concept maps are thought to facilitate meaningful learning, as they relate new information to relevant prior knowledge, creating new knowledge. They are also effective tools for evaluating students' existing knowledge and its validity (Novak & Cañas, 2007).

Conceptual models are central artefacts in model-based systems engineering: they are the products of respresenting systems. Conceptual models are structured like concept maps, but with more detail, including various types of components and interrelationships by using formalised methodology (Dori, 1995, 2011, 2016). While conceptual models in science are descriptive, serving to represent existing natural phenomena, conceptual models in engineering can also be normative, representing artificial systems that do not yet exist, but are instead under design (Barlex, 2018). Research has shown that training engineering students in conceptual modelling can foster understanding of system dynamicity (Carberry & McKenna, 2014) as well as representational fluency – the ability to translate between different types of representation (Moore, Miller, Lesh, Stohlmann, & Kim, 2013).

There are various methods for scoring concept maps created by students, depending on the goal of assessment. Watson, Pelkey, Noyes, and Rodgers (2016) distinguished between three types of methods for scoring concept maps: (a) traditional – evaluating a concept map by its individual elements, (b) holistic – evaluating a concept map as one whole and focusing on attributes relating to the entire map, and (c) categorical – evaluating a concept map based on pre-determined conceptual categories. While traditional scoring may 2010 be fully automated using software (e.g. Ifenthaler, 2010), categorical scoring may only be automated assuming conceptual categories are already determined, which is normally carried out by a human – the educator or evaluator (e.g. Segalàs, Ferrer-Ballas, & Mulder, 2008). Holistic scoringis difficult to automate, since it requires one to judge the correctness of the concepts and relations included in the concept map, and this normally requires manual (human) evaluation (e.g. Wengrowicz et al., 2016).

In the next section we describe our study methodology, specifically how we administered conceptual modelling assignments to pre- and in-service science and engineering teachers and how we scored those conceptual models.

Materials and methods

The present section is divided into two sub-sections, based on our research objectives: the first sub-section is concerned with the creation of the basis of a common language for systems thinking in science education and engineering education, while the second subsection is concerned with assessing systems thinking of science and engineering teachers based on an application of the aforementioned language. We conducted a mixed-method study, where mainly quantitative research was supplemented by qualitative research.

Method for creating a common language for systems thinking

As described below, our method for creating a systems thinking language for science and engineering education involved a literature search, the creation of a systems thinking rubric, and assessment of its reliability and validity.

Literature search

We carried out a literature search for peer-reviewed articles published over the years 2000–2017 on ‘Systems Thinking’ and similar concepts in STEM education, specifically in secondary school and higher education. We constructed our rubric for assessing systems thinking based on the results of this review, through collaboration with three experts: a science education expert, an engineering education expert, and a systems engineering expert.

We then assessed the interrater reliability, internal consistency, and construct validity of our systems thinking rubric. First, we assessed the interrater reliability of our rubric by having three experts score the same eight conceptual models created by teacher teams, and calculated Spearman correlations between raters’ scores of each systems thinking attribute using SPSS 20. The raters were: an expert in conceptual modelling, a systems engineering expert, and an engineering education expert.

We also assessed the internal consistency of our rubric by calculating Cronbach’s α in SPSS 20 for all 34 conceptual models submitted by teacher teams. One of the co-authors of the present paper scored all 34 models.

Finally, we conducted confirmatory factor analysis of our construct of systems thinking which our rubric was based on – the three system aspects of function, structure, and behaviour, each one with its respective attributes of systems thinking. We conducted this analysis using SPSS-AMOS 23 for all 34 models submitted by teacher teams.

Method for assessing systems thinking of science and engineering teachers

The present sub-section describes the study participants, study design, the data collection tools we used, and how we conducted data analysis.

Study participants included 42 pre- and in-service science and engineering teachers enrolled in one of three combined B.Sc. and M.Sc. courses in science and engineering education over the Fall and Spring semesters. From here on we shall refer to the study participants interchangeably as ‘participants’ or as ‘teachers’. At the beginning of the study, we asked participants to organise themselves independently into ‘teacher teams’ of two or three. Table 1 summarises key data regarding the participants.

Following the university ethics regulations and explicit permission by the course lecturer, we asked the students who participated in an undergraduate and graduate course to take part in the research and asked them to sign an informed consent during the first lecture of their respective courses. We obtained approval for the study from the University Behavioural Sciences Research Ethics Committee (2015-145).

Study design

As described in further detail in the following sub-sections, the present study involved small teams of pre- and in-service teachers. We trained teachers in conceptual modelling

Table 1. Study population.

Semester	Gender		Teaching experience	
	Women	Men	Pre-service[a]	In-service[b]
Fall	8	4	6	6
Spring	26	4	18	12
Total	34	8	24	18

[a] BSc students.

[b] MSc students.

using a software tool so they were able to use this tool to create conceptual models. We then administered to each team a conceptual modelling assignment concerning a scientific phenomenon. Following this assignment, we administered to each team a second assignment concerning a science education or engineering education topic, chosen by each team separately. We administered the scientific assignment first, because it involved much less information than the second assignment. We assumed the simpler assignment would get participants accustomed to conceptual modelling and to using the software tool, with an instructor available onsite to assist them. The second assignment allows participants more freedom with choosing a topic for conceptual modelling and with where and when to conduct the assignment. Another reason we administered assignments with different domain of expertise was to assess whether this would result in a significant difference in systems thinking scores between the conceptual models created by participant teams. Since teacher teams were mixed with pre- and in-service teachers, we did not compare systems thinking scores between teams, but rather within teams and between assignments.

Data collection

In the present sub-section, we describe in detail the conceptual modelling assignments we administered to participants and the semi-structured interviews we conducted with some of them.

Object-process methodology and its software tool. Object-Process Methodology (OPM) is a model-based systems engineering methodology originally created for conceptual modelling of information systems (Dori, 1995). It has since been recognised by the International Organization for Standardization (ISO) as ISO 19450:2014 for Automation Systems and Integration. OPM uses visual and textual modalities in tandem, which caters to the dual channel processing multimedia learning assumption (Mayer, 2009); bimodal representation is considered to help facilitate cognition and improve learning (Glenberg & Langston, 1992). OPM has been adapted for use in many domains, including science (e.g. Somekh, Haimovich, Guterman, Dori, & Choder, 2014), engineering (e.g. Dori, D., & Thipphayathetthana, 2016), science education (Dori, Lavi, & Dori, 2016), and engineering education (e.g. Wengrowicz et al., 2016). However, OPM has never been utilised for assessing systems thinking in science education – until the present study.

We selected OPM for the present study over concept maps – also used for conceptual modelling – for three reasons: first, unlike concept maps, OPM's elements are more expressive and are not limited to just concepts and their interrelationships; second, concept maps do not allow for easy-to-follow management of different levels of the system, like in the case of OPM; and third, OPM is based on a standard, which means that every element in the model has a clear definition and role, unlike in the case of concept maps, where definitions and roles may differ for each element, depending on the topic and on the person doing the mapping. We also selected OPM for this study for two more reasons unrelated to concept maps: first, its domain-independence – with syntax in natural English, OPM is ideally suited for interdisciplinary problem representation; and second, the realative ease of learning OPM, with its single diagram type composed of several elements, making it particularly suitable for studies with short time frames.

The visual (graphical) aspect of an OPM model is represented by a hierarchically organised set of Object-Process Diagrams (OPDs), while the verbal (textual) aspect is represented by equivalent, automatically generated set of sentences in Object-Process

Language (OPL), which is a subset of natural English based on context-free grammar. The graphical and textual modalities together comprise the *OPM system model*. This model can be represented at various levels of complexity and detail, with a top view OPD and OPL depicting the main process of the system and its main related objects, and refined views in separate OPDs and OPLs depicting child processes or child objects. OPM models are comprised of elements: *Things* (objects and processes) and *links* between things. Objects are static and may contain states, while processes are dynamic. Links are either structural – mainly between objects or between processes – or procedural – mainly between objects and processes. OPD links relevant to the present study are presented and explained in Tables A1 and A2 in Appendix 1.

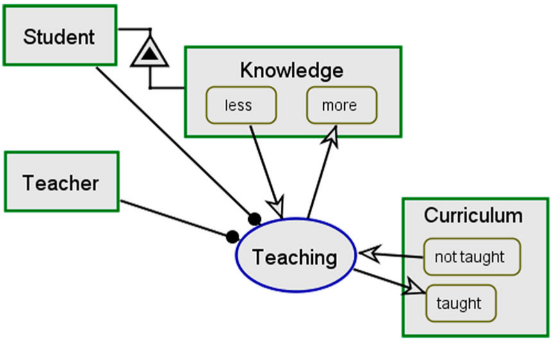
OPM has a dedicated tool which is a Java-based desktop computer software. It is freely available and intended for creating OPM system models.

Figure 1 depicts the top view – the most abstract level – of an example OPM model for a teaching system.

Conceptual modelling assignments. The present study involved teams of teachers as participants, with each team comprising two or three participants. A distinction can be made within team problem solving between *collaborative* and *cooperative* problem solving: while the former involves working together on some or all portions of a problem, the latter involves dividing the work on different components of the problem between team members (Roschelle & Teasley, 1995). The present study involved full collaboration within teams, on every assignment.

The assignments we administered to teachers concerned descriptive conceptual modelling, i.e. conceptual modelling meant to describe a specific phenomenon, problem, or topic. Participant teams used the OPM software tool for conceptual modelling. Being a model-based systems engineering methodology, using OPM to construct conceptual models meant teacher teams constructed system representations of the phenomenon, which suited our objective of assessing the systems thinking expressed in these models. We do, however, acknowledge natural phenomena can be represented in other ways, e.g. with concept maps (Tripto et al., 2013), dynamic visualisations (Chiu & Linn, 2012), and graphs (Dori & Sasson, 2008).

We developed two conceptual modelling assignments and administered them to participants, in the following order: (1) an adapted scientific text assignment – the same



Student exhibits Knowledge.
Knowledge can be less or more.
Student handles Teaching.
Curriculum can be not taught or taught.
Teacher handles Teaching.
Teaching changes Knowledge from less to more and Curriculum from not taught to taught.

Figure 1. Top view OPD and OPL of teaching system.

Note. Rectangles and green text represent objects; ellipses and blue text – processes; rounded rectangles and gold text – object states.

text for every team – and (2) a science or engineering education article synthesis assignment where each team can select a topic from a list. These assignments helped us to assess our systems thinking rubric under different attributes.

Adapted scientific text assignment: scientific articles are used as tools for instruction and assessment (van Lacum, Ossevoort, & Goedhart, 2014). We adapted scientific papers from reputable peer-reviewed journals into one text of an expository. genre, or *case study* (Dori, Avargil, Kohen, & Saar, 2018; Dori, & Sasson, 2008; Herscovitz, Kaberman, Saar, & Dori, 2012). Such texts contain narratives with fewer evidence to back their claims when compared with the primary papers they are based on. Adapted scientific texts have been used previously for fostering and assessing higher-order thinking skills, e.g. transfer of knowledge, modelling, inquiry and metacognition (e.g. Herscovitz et al., 2012; Kaberman & Dori, 2009). The adapted scientific text we created was a one-page document concerning an interdisciplinary topic: the gecko's surface adhesion ability, based on Izadi, Stewart, and Penlidis' (2014) article.

Following training in OPM and its software tool, we asked teacher teams to (1) read the article, (2) identify one problem, question, or research question in the text, (3) write a brief description of it (one or two lines in natural English), (4) conceptually model it using OPM software to two levels of system model, with some constraints on the number of things (objects or processes), and (5) submit the OPM software file for assessment along with the problem description. The participants carried out the assignment in the classroom.

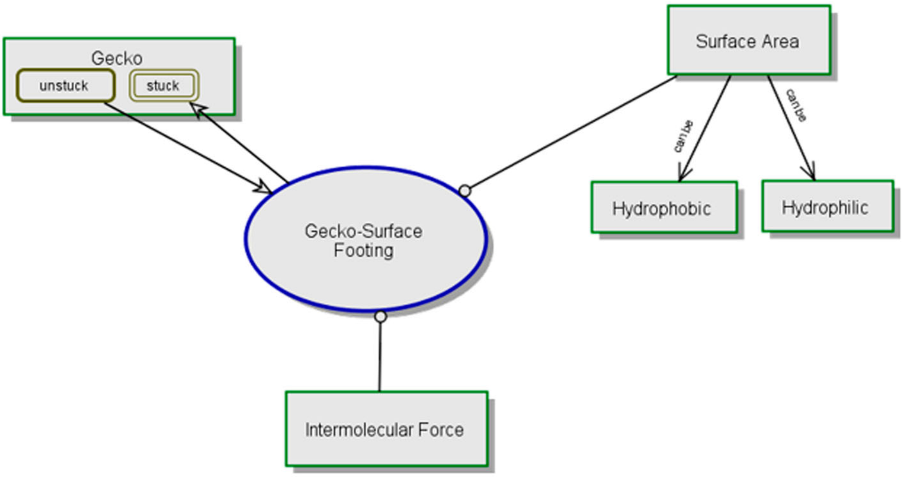
Figure 2 shows top view OPD and OPL of one of the OPM system models created by one of the teacher teams as part of the adapted scientific text assignment. For the detailed view and for an explanation of how we scored this model, see Figure 5 in the 'Findings' section.

Science or engineering education articles synthesis assignment: two weeks following the adapted scientific text assignment, we provided participant teachers with a list of reputable peer-reviewed journals in science and engineering education research. We asked teacher teams to search for and select five articles from their selected topic, such as learning in context, assessment, and metacognition, among others. Each team summarised the five articles they selected by creating an OPM system model with two levels of detail, without constraints on the number of things included in the model. Participants carried out this assignment out of the classroom, since it required many preparatory activities prior to modelling, as described above. Teacher teams were given a deadline of about one month and access to one of the authors of the present paper as a conceptual modelling consultant.

Figure 3 shows top view OPD and OPL of one of the OPM system models created by one of the teacher teams as part of the science or engineering education article synthesis assignment, in this case for science education on the topic of learning assessment. For the detailed view and for an explanation of how we scored this model, see Figure 6 in the 'Findings' section.

In total, the teacher teams produced 34 OPM system models: 16 for the adapted scientific text assignment and 18 for the article synthesis assignment. The discrepancy in number of models arose due to having more teams participating in the adapted scientific text assignment than in the science or engineering education article synthesis assignment.

Semi-structured interviews. Since conceptual modelling with OPM was a novel activity for every participant of the present study, we were interested in learning about the teachers' experiences of the conceptual modelling assignments they carried out. We used the information collected in these interviews to supplement our conclusions from the

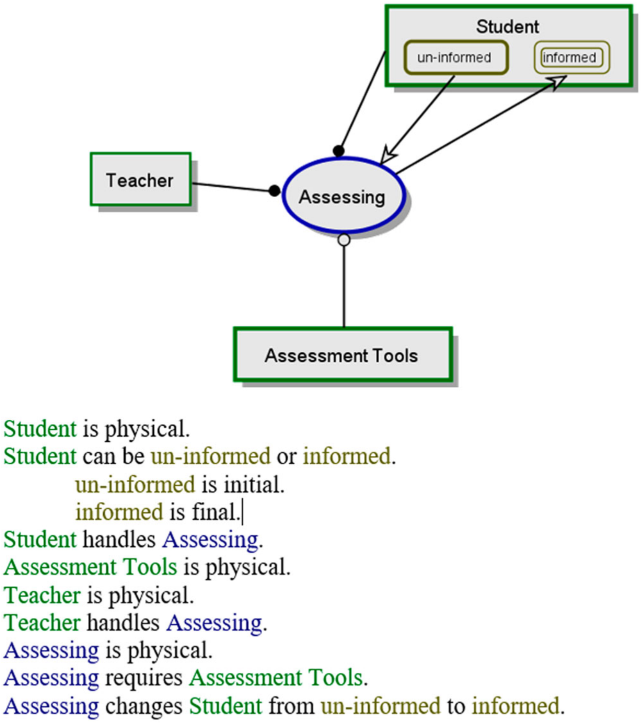


Gecko is physical.
Gecko can be stuck or unstuck.
    stuck is final.
    unstuck is initial.
Surface Area is physical.
Surface Area can be Hydrophilic.
Surface Area can be Hydrophobic.
Intermolecular Force is physical.
Hydrophobic is physical.
Hydrophilic is physical.
Gecko-Surface Footing is physical.
Gecko-Surface Footing requires Intermolecular Force and Surface Area.
Gecko-Surface Footing changes Gecko from unstuck to stuck.

Figure 2. Top view OPD and OPL created during the adapted scientific text assignment – Gecko-Surface Footing.

present study. We conducted semi-structured interviews with four teachers who participated in the study. Two teachers were pre-service and two were in-service. Three teachers had science background and one had engineering background. The interviewer conducted the interviews by telephone. Each interview lasted approximately 25 minutes. Interviews were recorded with approval of each interviewee. Each interview included the same three questions, expanded upon through the interview. Before each of the questions one and two were asked, the interviewer walked the participant through the corresponding models the same participant had created with his or her teammates.

(1) What were the opportunities and challenges of the adapted scientific text assignment?
(2) What were the opportunities and challenges of the science or engineering article synthesis assignment?
(3) Do you think systems thinking via conceptual modelling can be taught by teachers? If so, how? If not, why not?



Student is physical.
Student can be un-informed or informed.
un-informed is initial.
informed is final.
Student handles Assessing.
Assessment Tools is physical.
Teacher is physical.
Teacher handles Assessing.
Assessing is physical.
Assessing requires Assessment Tools.
Assessing changes Student from un-informed to informed.

Figure 3. Top view OPD and OPL created during the article synthesis assignment – Assessing in science education.

Data analysis

Conceptual modelling assignments. We assessed the conceptual models created by participants using the systems thinking assessment rubric developed for the present study. We assessed differences between conceptual modelling assignments using Mann-Whitney U test for independent samples. Our hypothesis was two-tailed with 95% confidence level.

Semi-structured interviews. Following submission of the second assignment by every team of teachers, we conducted interviews with four participants. We transcribed the four interviews and conducted free content analysis on the text. We identified categories in the transcripts and had three experts in science education allocate 57 statements from the interviews into each category. In addition, we had each expert ascribe either a ‘positive’, ‘negative’, or ‘ambiguous’ description to each statement, to describe whether he or she supported the statement, objected to it, or were not sure, respectively. We assessed interrater reliability for both category allocation and descriptions using Kappa. We then allocated the remaining eight statements into the categories we identified and gave each one an affective aspect: either positive, negative, or ambiguous. We had 65 statements in total.

Findings

The present section is divided into two sub-sections, according to our research objectives: the first sub-section describes our systems thinking rubric, which is meant to create the basis for a common language of systems thinking in science education and in engineering education, while the second sub-section describes the results of our assessment of science and engineering teachers' systems thinking.

Findings for creating a common language for systems thinking

The present sub-section describes (a) the results of our literature review, (b) the systems thinking rubric we developed based on our literature review, and (c) the results for the reliability and validity assessments of our rubric.

In our literature search, we found articles concerned with systems thinking or related topics in science education (e.g. Ben-Zvi-Assaraf & Orion, 2005; Batzri et al., 2015; Brandstädter, Harms, & Grosschedl, 2012; Hmelo-Silver et al., 2007; Tripto et al., 2013), technology education (e.g. Barak & Williams, 2007; Frank, 2006; Hung, 2008), and engineering education (e.g. Dym, Agogino, Eris, Frey, & Leifer, 2005; Frank, 2006; Gero & Zach, 2014). We added to these papers two widely cited books on systems engineering (Crawley et al., 2015; Dori, 2016) and two widely cited articles on instructional design related to systems thinking (Jacobson & Wilensky, 2006; Jonassen, 1997).

Systems thinking rubric

We synthesised, adapted and divided the terms we found in our literature review into three *systems thinking aspects*, each with two *systems thinking categories*: (1) system function – divided into *general properties* and *emergent properties*; (2) system structure – divided into *structural components* and *structural relationships*; and (3) system behaviour – divided into *procedural relationships* and *change over time*. We derived two, three, or four attributes of systems thinking from each category, making nine attributes in total. These attributes were meant to be relevant for both science and engineering education, i.e. for both descriptive and normative conceptual models of artificial systems or natural phenomena.

We excluded the following attributes from the present study: *system boundary* and *temporary objects and decision nodes*. The former concerns the objects and processes affecting the system but unaffected by it, while the latter concerns objects created and consumed within processes. We considered these attributes irrelevant to the OPM system models created in the present study due to the short time afforded to training in OPM and its dedicated software, as well as the constraint for two levels of the system model.

Table 2 contains the seven attributes we found to be relevant to the present study.

Interrater reliability. We assessed interrater reliability between three experts for eight OPM system models produced by participant teams in the present study. We hypothesised all correlation will be positive: one-tailed hypothesis at 95% confidence level.

As Table 3 shows, most correlations between every pair of experts were significant and moderate or higher ($r > .70$). Twelve correlations were significant, and only two were insignificant, $p > .05$: A_6 (procedural links), $r = .56$ and A_7 (procedural sequence), $r = .50$.

Internal consistency. We assessed the internal consistency for our rubric using Cronbach's α for 34 models scored using our systems thinking rubric. Cronbach's α was .800, showing high internal consistency. As Table 4 shows, Cronbach's α when each item was removed was .800 or less, which means each item contributed to the rubric's internal consistency.

Table 2. Systems thinking rubric – aspects, categories, attributes, and attribute descriptions.

Aspect	Attribute	Attribute criteria: clearly and correctly identifying –
Function	A_1^a, expected outcome/ intended purpose	The expected outcome (science) or intended purpose (engineering) of the system vis-à-vis its beneficiary group
	$A_{2,}$ main function	Main process, main operand (transformed object or its attribute), agent operators and enablers
Structure	A_3, main object and its sub-objects	Object transformed by main process and its parts, features (attributes and operations), and specialisations
	A_4, structural links	Links between objects and between processes
Behaviour	A_5, procedural links	Links between objects and processes
	A_6, complexity levels	Number of detail levels; refinement of each diagram into lower-levels processes
	A_7, procedural sequence	Linear, divergent, convergent, and looping sequences

Table 3. Interrater Spearman correlations with systems thinking attribute scores.

Attribute	*r* minimum	*r* maximum
A_6, complexity levels	.90*	.98*
A_4, structural links	.87*	.96*
A_1, expected outcome/intended purpose	.83*	.88*
A_3, main object and its sub-objects	.80*	.93*
A_2, main function	.76*	.94*
A_5, procedural links	.56	.77*
A_7, procedural sequence	.50	.86*

$^*p < .05$

Table 4. Cronbach's *α* when removed, for each attribute of systems thinking.

Attribute	Cronbach's *α* when removed
A_3, main object and its sub-objects	.80
A_4, structural links	.79
A_1, expected outcome/intended purpose	.78
A_5, procedural links	.78
A_7, procedural sequence	.77
A_2, main function	.76
A_6, complexity levels	.73

Construct validity. We also assessed construct validity by way of confirmatory factor analysis using structural equation modelling. Figure 4 shows the model created by the SPSS-Amos 23 software based on systems thinking scores for 34 models and the seven attributes of our systems thinking rubric.

The model indicates a moderately good fit between the model and the observed data ($\chi^2 = 13.373$, $df = 11$, $p > .05$, TLI = .939, CFI = .968, RMSEA = .081). In addition, every standardised β and co-variance correlation in the model was significant ($p < .05$).

Findings of the assessment of teachers' systems thinking

The following section presents (a) examples of how we scored conceptual models created by teacher teams, (b) analysis of the teacher teams' systems thinking scores, and (c) content analysis results of teachers' interviews.

The scoring method we developed and used in the present study can be classified as holistic, since it concerns the conceptual model as a whole. Scores for each attribute of systems thinking ranged between 0 and 3, in accordance with our scoring instructions. Since there were seven attributes of systems thinking, the total possible score for any model was 21.

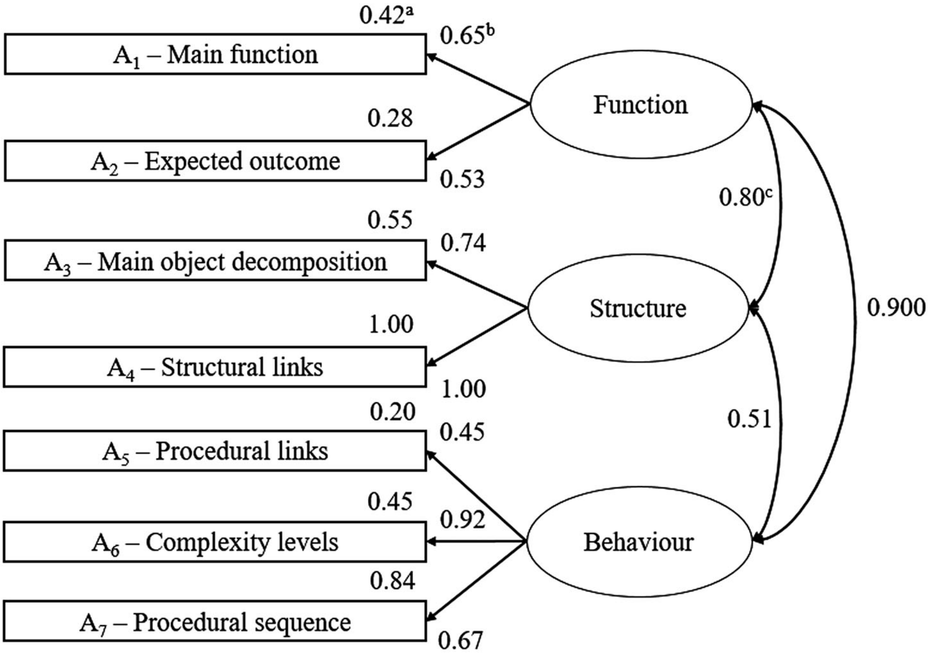


Figure 4. Confirmatory factor analysis for the systems thinking construct. [a]Explained variance. [b]Standardised β. [c]Co-variance.

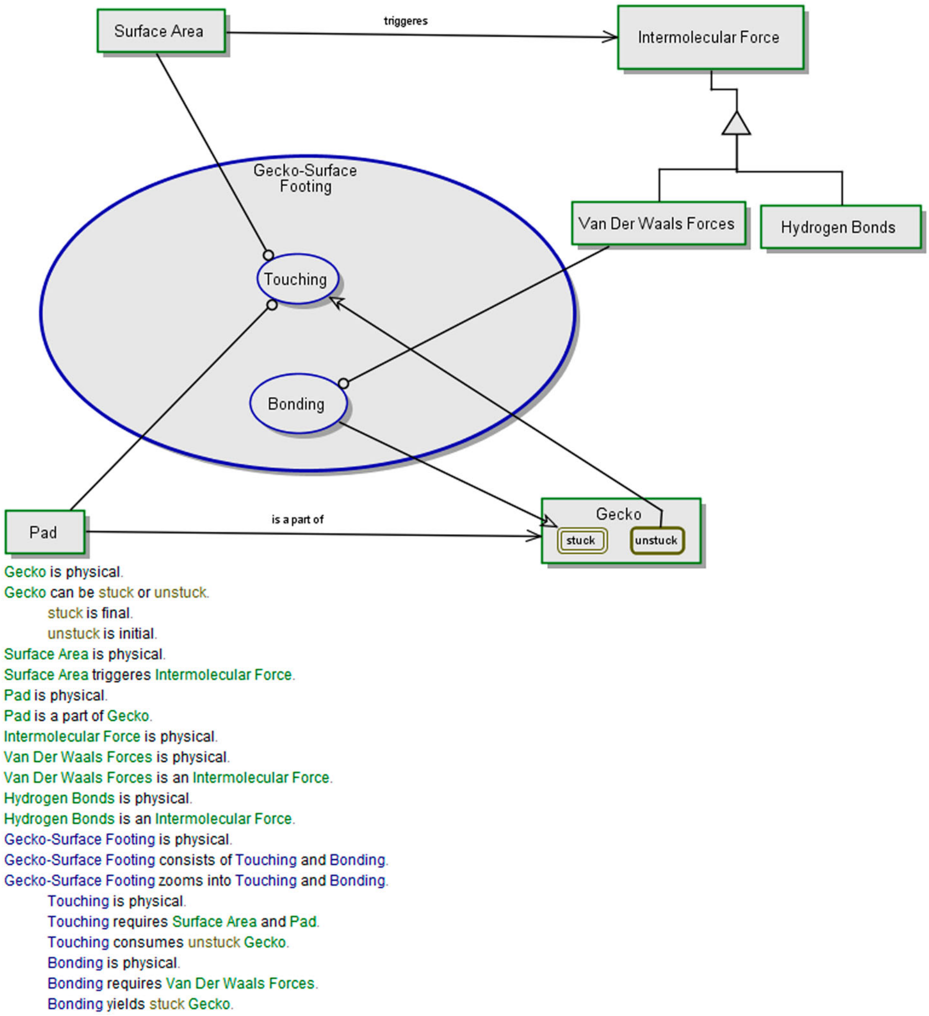
Figures 5 and 6 show a detailed view OPD and OPL for two OPM system models created by teacher teams: Figure 5 depicts the detailed view OPD and OPL of a model created for the first assignment – the adapted scientific text concerning the gecko's surface sticking ability, while Figure 6 depicts the detailed view OPD and OPL of a model created for the second assignment – science or engineering education article synthesis – for science education. Tables 5 and 6 summarise how we scored each attribute for the different models. See Appendix 2 for an example of the second assignment in engineering education.

Adapted scientific text assignment. Figure 5 depicts an OPM system model for Gecko-Surface Footing created by a teacher team, depicting part of the adapted scientific text on the gecko's adhesive ability. We gave this model a total score of 16 out of 21. Table 5 provides scores and explanations for each system attribute included in our systems thinking rubric. See Figure 2 for the top view OPD and OPL of this model and Appendix 1 for an explanation of OPM links.

Science or engineering education article synthesis. Figure 6 depicts an OPM system model constructed by a teacher team describing a system for assessing student learning in science education. We gave this model a total score of 17 out of 21. Table 6 provides scores and explanations for each system attribute included in our systems thinking rubric.

Analysis of conceptual models

We found the systems thinking scores were not normally distributed for any attribute. We therefore used non-parametric tests for analyisis of our data. Scores for systems thinking attributes in the adapted scientific text assignment ranged between .5–2.5 for each



Gecko is physical.
Gecko can be stuck or unstuck.
    stuck is final.
    unstuck is initial.
Surface Area is physical.
Surface Area triggeres Intermolecular Force.
Pad is physical.
Pad is a part of Gecko.
Intermolecular Force is physical.
Van Der Waals Forces is physical.
Van Der Waals Forces is an Intermolecular Force.
Hydrogen Bonds is physical.
Hydrogen Bonds is an Intermolecular Force.
Gecko-Surface Footing is physical.
Gecko-Surface Footing consists of Touching and Bonding.
Gecko-Surface Footing zooms into Touching and Bonding.
    Touching is physical.
    Touching requires Surface Area and Pad.
    Touching consumes unstuck Gecko.
    Bonding is physical.
    Bonding requires Van Der Waals Forces.
    Bonding yields stuck Gecko.

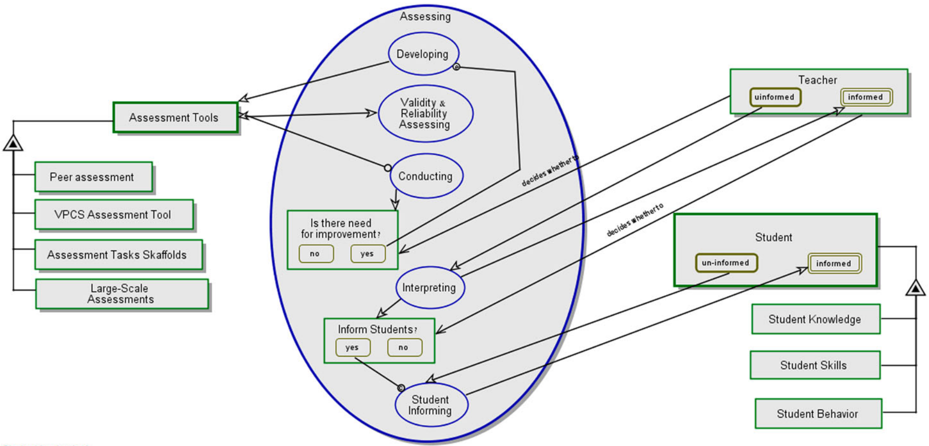
Figure 5. Detailed view OPD and OPL created during the adapted scientific text assignment – Gecko-Surface Footing.

Notes: OPL sentences duplicating those in Figure 2 are not shown. Any spelling or grammar errors were made by the modellers.

attribute and for the article synthesis assignment between 0 and 3.0 for each attribute. We assessed differences between assignments for each attribute of systems thinking using the Mann-Whitney U test for independent samples, with two-tailed hypotheses and 95% confidence level. Table 7 shows descriptive statistics and Z values for each assignment and systems thinking attribute. As Table 7 shows, we found differences ($p < .05$) between assignment scores, for two attributes: A_1, expected outcome/intended purpose ($Z = -2.05$, $p < .05$), and A_3, main object and its sub-objects ($Z = -3.00$, $p < .05$).

Semi-structured interviews

We analysed the content of the interview transcripts and identified 65 statements in total, which we allocated into four categories:



Student is physical.
Student can be un-informed or informed.
un-informed is initial.
informed is final.
Student exhibits Student Knowledge, Student Skills, and Student Behavior.
Assessment Tools is physical.
Assessment Tools exhibits VPCS Assessment Tool, Large-Scale Assessments, Peer assessment, and Assessment Tasks Skaffolds.
VPCS Assessment Tool is physical.
Large-Scale Assessments is physical.
Peer assessment is physical.
Assessment Tasks Skaffolds is physical.
Teacher is physical.
Teacher can be uinformed or informed.
uinformed is initial.
informed is final.
Teacher decides whether to Inform Students?.
Teacher decides whether to Is there need for improvement?.
Assessing is physical.
Assessing exhibits Inform Students? and Is there need for improvement?.
Assessing consists of Developing, Validity & Reliability Assessing, Conducting, Student Informing, and Interpreting.
Assessing zooms into Developing, Validity & Reliability Assessing, Conducting, Interpreting, and Student Informing, as well as Is there need for improvement? and Inform Students?.
Is there need for improvement? can be no or yes.
Is there need for improvement? triggers Developing when it enters yes.
Inform Students? can be yes or no.
Developing requires yes Is there need for improvement?.
Developing yields Assessment Tools.
Validity & Reliability Assessing affects Assessment Tools.
Conducting requires Assessment Tools.
Conducting yields Is there need for improvement?.
Interpreting changes Teacher from uinformed to informed.
Interpreting yields Inform Students?.
Student Informing occurs if Inform Students? is yes.
Student Informing changes Student from un-informed to informed.

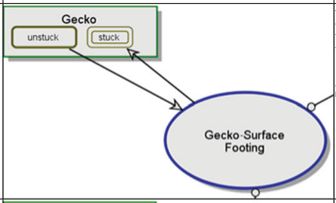
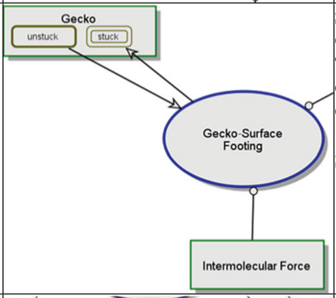
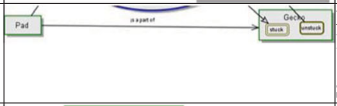
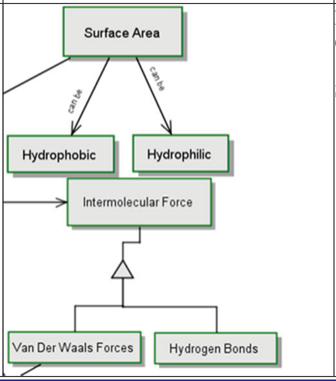
Figure 6. Detailed view OPD and OPL created during the article synthesis assignment – Assessing in science education.

Notes: OPL sentences duplicating those in Figure 3 are not shown. Any spelling or grammar errors were made by the modellers.

(1) Systems thinking via conceptual modelling in OPM can benefit teachers and students alike;
(2) The conceptual modelling assignments encouraged use of higher-order thinking, e.g. metacognition;
(3) The conceptual modelling assignments required a thorough understanding of the text/s involved; and
(4) The conceptual modelling assignments were challenging for participants.

For category (1), an example statement was S15 – 'I can now see what systems thinking is and I try to relate it to things I do'; for category (2) – S9b. 'Once you have to model something, you … really need to understand all the links, ask yourself all sorts of questions … there's a lot of … metacognition'; for category (3) – S9a 'To [conceptually] model something, you need to understand it really well' S11; and for category (4) –

Table 5. Scores and explanations for the OPM system model created during the adapted scientific text assignment – Gecko-Surface Footing.

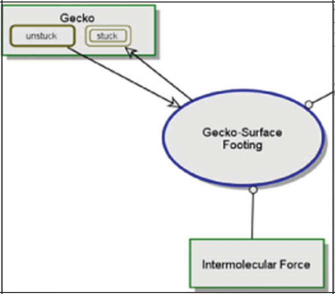
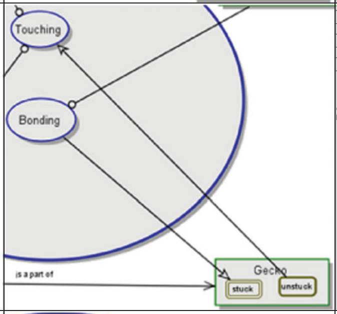
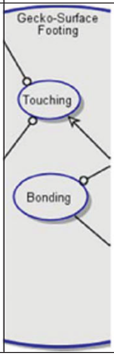
Attribute	Screenshot of relevant part of OPD	Scoring and explanation
A_1, expected outcome/intended purpose		**Beneficiary**: Gecko **Benefit**: specified and concrete **Score:** 2
A_2, main function		**Systemic process**: Gecko-Surface Footing **Operand**: Gecko **Transformation**: Gecko-Surface Footing changes Gecko from unstuck to stuck **Operator**: Intermolecular Force **Score:** 3
A_3, main object and its sub-objects		**Main object**: Gecko **N levels sub-objects**: 1 **Score:** 2
A_4, structural links		**N link types**: 2 – (1) Generalization-specialization; (2) Unidirectional tagged **Score:** 2

'When we submitted our final model we were still debating whether this was our final version or not'.

We gave three experts in science and engineering education two example statements from each category (eight statements in total) and asked them to allocate the remaining 57 statements into one of the four categories above. Kappa scores for all three experts ranged between .61–.63 ($p < .05$). As all Kappa scores were above .60, we can consider interrater reliability for our categories to be reasonable.

We then classified each of the 65 statements as either positive (+), negative (–), or ambiguous (=) with relation to its category. Figure 7 shows the total number of statements within each category as well as the distribution of positive, negative, and ambiguous statements we identified in each category.

Table 5. Continued

Attribute	Screenshot of relevant part of OPD	Scoring and explanation
A_5, procedural links		**N link types**: 2 – (1) Result/Consumption; (2) Instrument **Score:** 2
A_6, complexity levels		**N detail levels**: 2 **N subprocesses**: 2 **N transformative subprocesses**: 2 **Score:** 3
A_7, procedural sequence		**Procedural sequence**: Touching → Bonding **Score:** 2
Total score		**16 / 21**

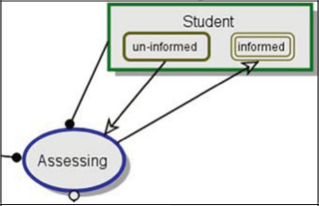
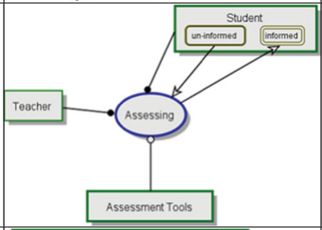
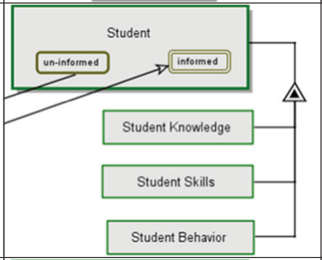
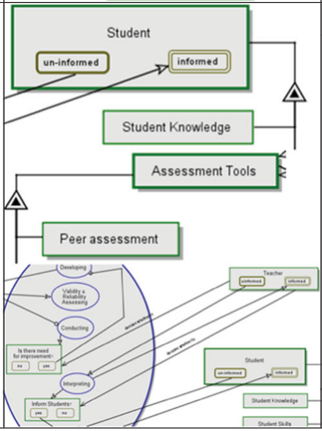
Discussion

In this section, we discuss (a) the common language for systems thinking we have created, (b) our assessment of teacher teams' systems thinking, (c) the systems thinking categories we found in interviews with teachers, (d) our recommendations for researchers and instructors, and (e) the contribution of our study to STEM education.

Creating a common language

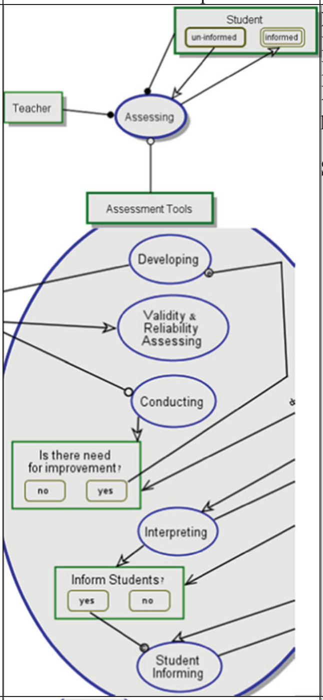
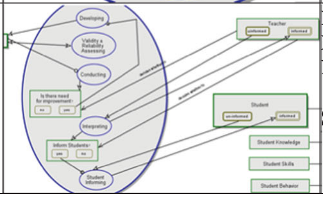
In line with the first study objective, we constructed a rubric which provides a basis for a systems thinking language common to both the science education and the engineering education communities. We compare our systems thinking rubric to two other systems thinking rubrics: the systems thinking hierarchy (Tripto et al., 2013) and the

Table 6. Scores and explanations for the OPM system model created during the article synthesis assignment – Assessing in science education.

Attribute	Screenshot of relevant part of OPD	Scoring and explanation
A_1, expected outcome/intended purpose		**Beneficiary:** Student **Benefit:** specified, but vague **Score:** 2
A_2, main function		**Systemic process**: Assessing **Operand**: Student **Transformation**: (1) Assessing changes Student from un-informed to informed **Operator**: Assessment Tools; Teacher **Score:** 3
A_3, Main object and its sub-objects		**Main object**: Student **N levels sub-objects**: 1 **Score:** 2
A_4, structural links		**N link types**: 2 – Exhibition-Characterization; Unidirectional Tagged **Score:** 2

systems thinking and model quality rubrics (Hung, 2008). Tripto et al. (2013) developed their rubric for assessing 11th-grade biology majors' hand-drawn conceptual models of the human body's respiratory system. Their hierarchy contains seven *characteristics* – as they called them – of systems thinking. Hung (2008) developed his rubric for assessing Master's students' computer-created conceptual models of learning theories, learning processes, or instructional design. His rubric contains eight *dimensions* – as he called them – of systems thinking. In Table 8, we compare the three systems thinking rubrics.

Table 6. Continued

Attribute	Screenshot of relevant part of OPD	Scoring and explanation
A_5, procedural links		**N link types**: 5 – (1) Result/Consumption; (2) Instrument; (3) Agent; (4) Condition; (5) Instrument Event **Mistakes:** Two states are not connected to any processes by procedural links **Score:** 3
A_6, complexity levels		**N detail levels**: 2 **N sub-processes:** 5 **N transformative sub-processes**: 5 **Score:** 3

While the rubrics of Tripto et al. (2013) and Hung (2008) do not include complexity management, our rubric contains A_6, complexity levels. The rubric of Tripto et al. does not specify the expected outcome of the biological system, but both Hung's rubric and ours do. In our rubric this is A_1, expected outcome/intended purpose, and in Hung's rubric – D_7, contextualisation. Hung's rubric does not specify structural relations, while our rubric and Tripto et al.'s do. In our rubric this is A_4, structural links, and in Tripto et al.'s – D_2, identifying simple relationships between components. Both Hung's and our rubric do not require identifying all the objects and processes in the model, but Tripto et al.'s rubric does, as indicated by C_1, identifying components and processes in the human body. We intentionally did not include attributes that necessitated assessing every model thing (object or process), in order to make the scoring of multiple models manageable. Finally, while Tripto et al.'s rubric was topic-specific, our rubric and Hung's were topic- and domain-independent.

To our knowledge, our study is the first in science and engineering education research that assigned the same teams with conceptual modelling assignments involving different topics. Previous studies in science and engineering education have involved the

Table 6. Continued

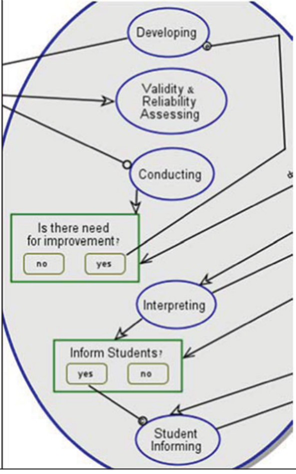
Attribute	Screenshot of relevant part of OPD	Scoring and explanation
A₇, Procedural sequence		**Procedural sequence**: clear sequence of sub-processes, with potential iteration (looping) following Conducting. **Score:** 3
Total score		**17 / 21**

Table 7. Systems thinking scores – descriptive statistics and Z values, by attribute.

	Conceptual modelling assignment scores				
	Adapted scientific text		Article synthesis		
	($n_1^a = 16$)		($n_2 = 18$)		
Attribute	*M*	*SD*	*M*	*SD*	*Z*
A2, main function	2.1	0.96	1.9	1.18	−0.48
A5, procedural links	1.8	1.00	1.4	0.92	−0.94
A3, main object and its sub-objects	1.6	0.50	2.4	0.86	−3.00*
A6, complexity levels	1.3	1.03	0.7	1.09	−0.96
A4, structural links	1.2	0.85	1.6	1.22	−1.12
A1, expected outcome/intended purpose	1.1	1.12	1.9	1.08	−2.05*
A7, procedural sequence	1.0	1.44	1.7	1.33	−0.94

[a]'n' denotes the number of conceptual models submitted.
*$p < .05$.

administration of conceptual modelling assignments on the same topic to the same group of participants (e.g. Assaraf & Orion, 2005; Hung, 2008), or the administration of different conceptual modelling assignments on the same topic to different teams of participants (e.g. Brandstädter et al., 2012; Hmelo-Silver et al., 2007).

We found our systems thinking rubric for assessing conceptual models in OPM created by science and engineering teachers to be reliable and valid. The rubric enabled us to score conceptual models in various topics and clearly differentiate between various performance levels of the assignments according to the rubric's systems thinking attributes. The rubric's general applicability provides indication that the function, structure, and behaviour system aspects and their respective systems thinking attributes can be applied to a large variety of topics in science education and in engineering education alike.

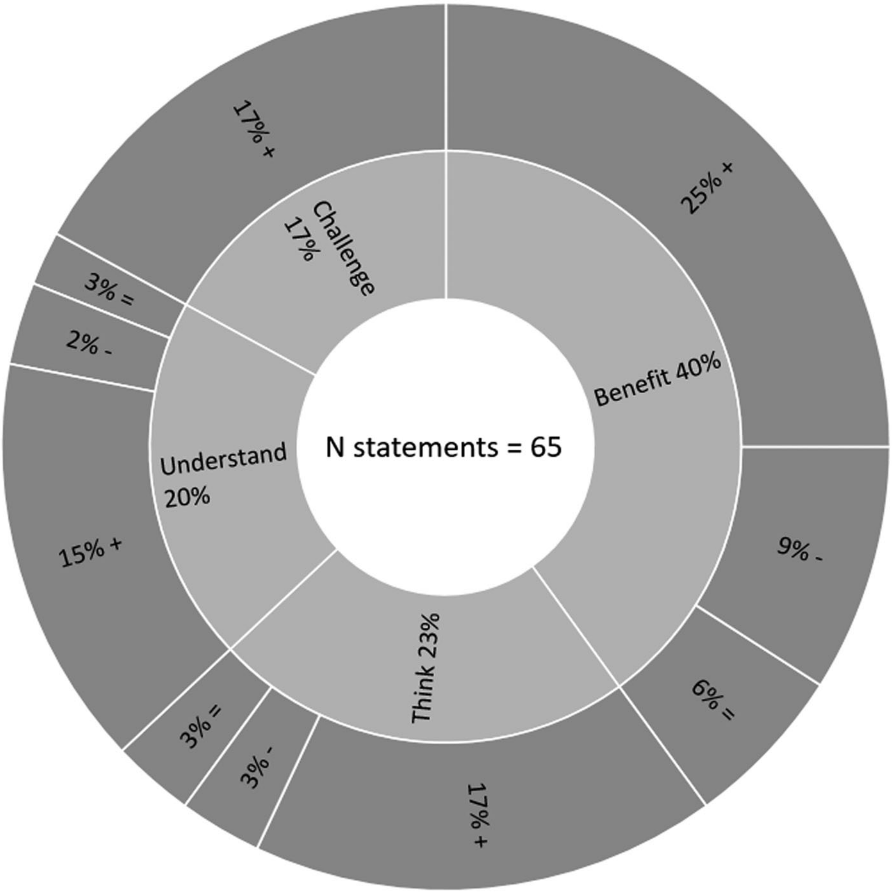


Figure 7. Teacher statements by category and percentage of positive (+), negative (−), and ambiguous (=) statements.

Notes. Each word in the inner circle corresponds to one of the categories of interviewee statements: (1) *Benefit* (40% of statements) – systems thinking via conceptual modelling in OPM can benefit teachers and students; (2) *Think* (23%) – the conceptual modelling assignments encouraged use of higher-order thinking; (3) *Understand* (20%) – the conceptual modelling assignments required a thorough understanding of the text/s involved; and (4) *Challenge* (17%) – the conceptual modelling assignments were challenging for participants.

Assessing systems thinking of teachers

In line with the second objective of our study, we applied the systems thinking rubric we had constructed for assessing systems thinking of teacher teams as expressed in the conceptual models of science and engineering phenomena they created. We found significant differences between the two kinds of modelling assignment, i.e. adapted scientific text and science or engineering education article synthesis, in two systems thinking attributes: A_1, expected outcome/intended purpose, and A_3, main object and its sub-objects.

The significant difference between article synthesis assignment scores and adapted scientific text assignment scores was for A_1, expected outcome/intended purpose, where scores for the latter assignment were higher than the scores for the former assignment.

Table 8. Comparison of our rubric with Tripto et al.'s (2013) and Hung's (2008).

Systems thinking attribute	Tripto et al.'s (2013) systems thinking hierarchy characteristics[a]	Hung's (2008) systems thinking dimensions[b]
A_1, expected outcome/ intended purpose	No similar characteristic found	D_7, contexualisation
A_2, main function	C_6^c, generalisation and identification of patterns; C_7, identifying hidden dimensions	D_8, underlying mechanism
A_3, main object and its sub-objects	C_1, identifying components and processes in the human body system	D_1, identification of crucial variables
A_4, structural links	C_2, identifying simple relationships between components	No similar characteristic found
A_5, procedural links	C_3, identifying dynamic relationships in systems; C_4, organising components and processes within a framework of relationships	D_3, interconnectivity; D_4, cause-effect relations
A_6, Complexity levels	No similar characteristic found	No similar characteristic found
A_7, Procedural sequence	C_8, temporal thinking	D_2, linearity; D_5, feedback processes; D_6, dynamic processes

[a] 'C' is for 'Characteristic'.
[b] 'D' is for 'Dimension'.
[c] Tripto et al. did not include a Characteristic no. 5.

We explain the difference in scores for expected outcome/intended purpose by the modelers' domain expertise: as teachers, the modelers were able to describe the purpose of the system more correctly for a science education or engineering education topic than for a science topic.

We also found a significant difference between article synthesis assignment scores and adapted scientific text assignment scores in A_3, main objects and its sub-objects, in which scores for the latter assignment were higher than scores for the former assignment. We explain the difference in scores for main object and its sub-objects by the domain expertise of the modeller and by the amount of information represented in the model. With regards to modeller's domain expertise, as teachers, the modelers were able to describe the main object and sub-objects of the system more correctly where a science or engineering education-based system was concerned than where a science-based system was concerned. Teacher interviews corroborated the difference in their domain expertise as modellers, saying they felt less familiar with the content of the first assignment (S15: 'It was difficult for us [the modellers team] to understand what the article was about'). With regards to the amount of information represented in the model, a much larger amount of information (five papers) was available for the article synthesis assignment compared to the adapted scientific text assignment (one page of text). This probably made it easier for participants to identify multiple sub-objects for the main object in the adapted scientific text assignment (Gecko or Pad) than in the article synthesis assignment (Student or Teacher).

The explanation we provided above regarding domain expertise echoes the findings of Hmelo et al. (2007) who had shown that conceptual models of biological systems constructed by experts exhibited higher systems understanding than models of the same system constructed by novices. An alternative explanation to the difference in both of the above attributes is that they are more easily fostered by training than the other attributes of systems thinking. However, exploring and potentially verifying these explanations would require further research with other populations.

Categories found in teacher interviews

In previous studies involving conceptual modelling assignments and systems thinking assessment in STEM education, interviews focused on participants' descriptions and explanations of their conceptual models (e.g. Hmelo-Silver et al., 2007). In our study, we focused on teachers' experiences of the conceptual modelling assignments we had assigned to them, as well as on their opinions regarding the potential of integrating systems thinking through conceptual modelling into science and engineering education. The teachers we interviewed expressed the overall opinion that while conceptual modelling using OPM may be beneficial for improving systems thinking, the assignments were challenging, and applying OPM in teacher training or in the classroom would require some adaptation.

Most of the interviewees found the conceptual modelling assignments using OPM to be challenging, requiring full understanding of the text and use of higher order thinking skills. However, their statements were more divided with regards to the benefit of and readiness for conceptual modelling with OPM. Being by far the most frequent, with 26 statements, the first category – *Benefit* – also had six negative impressions, as well as four ambiguous ones. This peculiarity can be explained by further dividing the statements in the first category into three sub-categories:

(1) 12 statements concerned with the potential of students to construct conceptual models with OPM, e.g. G11b. 'I think you have to choose high achieving students [for conceptual modelling with OPM] … ones with an analytical mind … otherwise they [not high-achieving students] will get lost'.
(2) 10 statements about the potential of teachers to construct conceptual models with OPM, e.g. G12a. 'The teacher really needs to … receive better training [in conceptual modelling using OPM]'.
(3) Four statements regarding the OPM software tool directly, e.g. A25. 'I would consider [developing] a "softer" version [of the OPM software tool] for students'.

In summary, while teachers seemed to recognise the potential of OPM and conceptual modelling for teaching science and engineering to students, they also identified potential challenges with applying OPM in the classroom.

Recommendations

For STEM researchers, we recommend expanding our study to other populations and topics in STEM education. Our rubric can be used to assess the systems thinking of students who are learning conceptual modelling of systems as part of their undergraduate or graduate studies. The results obtained in such a study can help discern differences in systems thinking between those with knowledge of systems and those without and help to ascertain which systems thinking attributes are domain-dependent and which ones are not. Before administering conceptual modelling assignments to teams, we recommend assigning such an assignment to each individual, and in this way, obtain a baseline score for systems thinking. This can be used to better understand and explain the scores obtained by teams composed of those individuals. Finally, for future study participants using the OPM software tool, we recommend extending their training in using the tool to a full day, in order to bring modellers to a level of skill where they can create conceptual models completely on their own without any assistance from the instructor.

In line with published NGSS-based guidelines for assessment (Schweingruber & Beatty, 2017), in the present study we have validated our rubric as indeed measuring systems thinking, and we administered the same training and same adapted scientific text under the same context of the place and time of the assignment to every team of students; however, the science or engineering education article synthesis assignment, being more open and long-term than the adapted scientific text assignment, arguably caused some change in context between teams of modellers, and we did not make sure that each student had his or her own individual opportunity to express what he or she had learnt. This opportunity can be provided by administering two conceptual modelling assignments and requesting students to change teams between each assignment.

We believe STEM teachers can use systems thinking for learning content knowledge and for facilitating students' systems thinking and conceptual modelling skills. We recommend teacher instructors use OPM as a tool to teach teachers content knowledge in science and engineering education. We also recommend teachers use OPM system models as a way to present complex information to their students regarding phenomena, systems and problems in science and engineering education. Finally, we recommend training science and engineering teachers in using the OPM software tool and our systems thinking rubric and raise their awareness with regards to the importance of fostering and assessing systems thinking.

Study contribution to STEM education

The theoretical contribution of the present study is in defining the systems thinking construct which can serve as a first step in establishing a common language between the science education and engineering education communities, helping to facilitate meaningful dialogue between the two.

With regards to the methodological contribution of the present study, our rubric can be used for formative and summative assessment of teachers and high school, undergraduate and graduate students, in a variety of STEM subjects where systems thinking is relevant. While previous studies have analysed students' systems thinking via conceptual models of scientific phenomena (e.g. Brandstädter et al., 2012; Hmelo-Silver et al., 2007; Tripto et al., 2013), our study is the first, to the best of our knowledge, to assess students' systems thinking in science and engineering education via conceptual models created using a model-based systems engineering methodology.

We set out to create a common language for systems thinking for science and engineering education and apply this language to assess systems thinking in pre- and in-service science and engineering teachers. We made the first step towards this objective and have shown that indeed, systems thinking can be described and assessed in both of these disciplines using the same language.

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Appendices

Appendix 1

Table A1. Object-process methodology structural links.

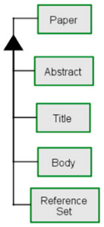
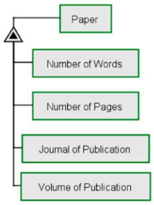
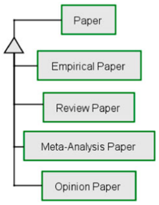
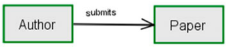
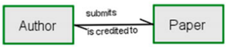
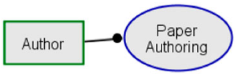
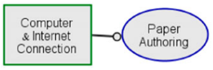
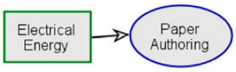
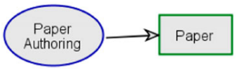
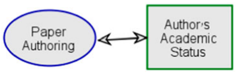
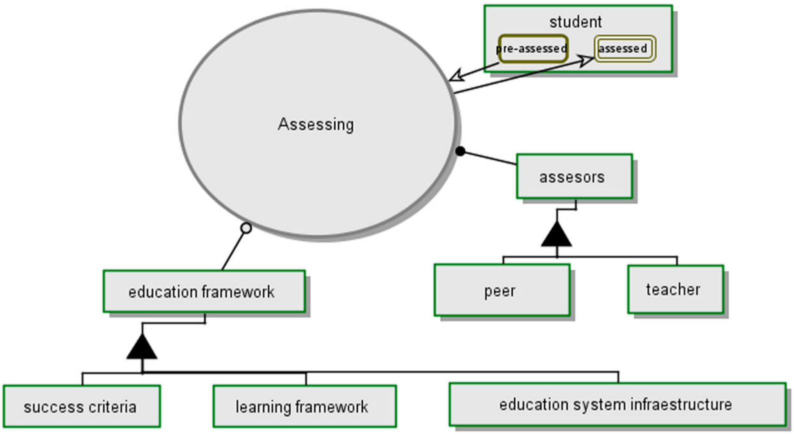
Link name and icon	OPL sentence	Example with objects
Aggregation-Participation ▲	[aggregator] consists of [part/s]	
Exhibition-Characterization ◬	[exhibitor] exhibits [character/s]	
Generalization-Specialization △	[specialisation] is/are a [generalisation]	
Unidirectional tagged →	Dependent on user input	
Bidirectional tagged ⇌	Dependent on user input	

Table A2. Object-process methodology procedural links.

Link name and icon	OPL sentence	Possible combinations
Agent	[Object] handles [Process/s]	
Instrument	[Process/es] require/s [Object]	
Consumption	[Process] consumes [Object/s]	
Result	[Process] yields [Object/s]	
Effect	[Process] affects [Object/s]	

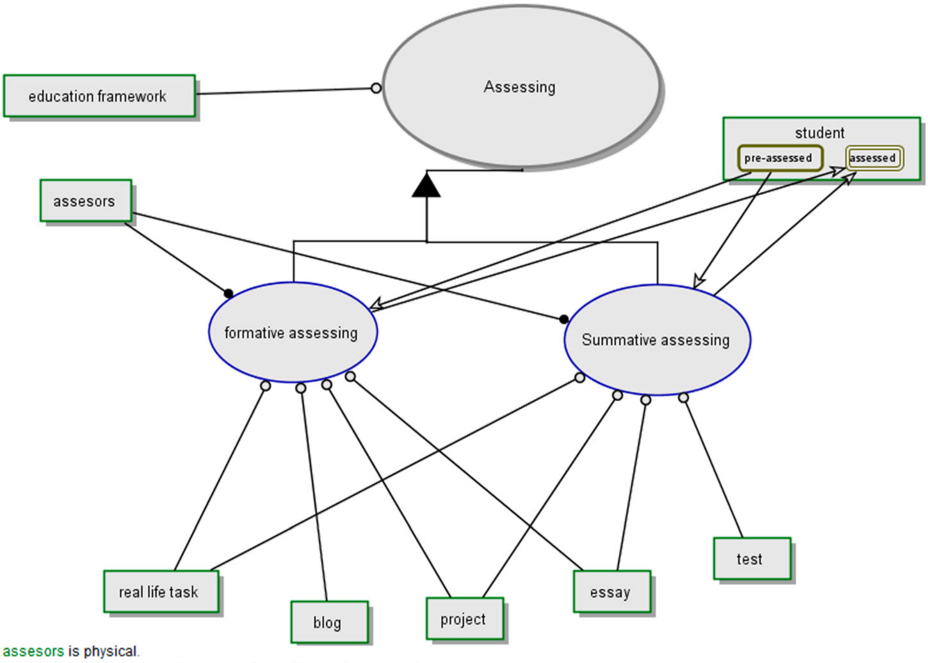
Appendix 2

Figures B1 and B2 depict an OPM system model created by a participant team for learning assessment in engineering education. Table B1 provides scores and explanations for each system attribute included in our systems thinking rubric. We gave this model a total score of 15 out of 21.



student is physical.
student can be pre-assessed or assessed.
    pre-assessed is initial.
    assessed is final.
education framework is physical.
education framework consists of success criteria, learning framework, and education system infraestructure.
    education system infraestructure is physical.
assesors is physical.
assesors consists of teacher and peer.
    teacher is physical.
    peer is physical.
assesors handles Assessing.
Assessing is physical.
Assessing requires education framework.
Assessing changes student from pre-assessed to assessed.

Figure B1. Top view OPD and OPL created during the article synthesis assignment – Assessing in engineering education.



assesors is physical.
assesors handles Summative assessing and formative assessing.
education framework is physical.
student is physical.
student can be pre-assessed or assessed.
pre-assessed is initial.
assessed is final.
real life task is physical.
blog is physical.
project is physical.
essay is physical.
test is physical.
Assessing is physical.
Assessing consists of formative assessing and Summative assessing.
formative assessing requires essay, project, blog, and real life task.
formative assessing changes student from pre-assessed to assessed.
Summative assessing requires test, essay, project, and real life task.
Summative assessing changes student from pre-assessed to assessed.
Assessing requires education framework.

Figure B2. Top view OPD and OPL created during the article synthesis assignment – Assessing in engineering education.

Note: OPL sentences duplicating those in Figure B1 are not shown here. Errors in spelling or grammar were made by the modellers.

Table B1. Top view OPD and OPL created during the article synthesis assignment – Assessing in engineering education.

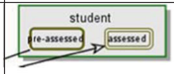
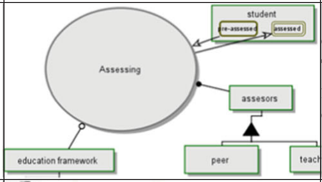
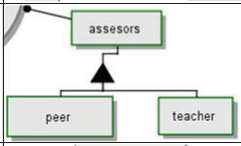
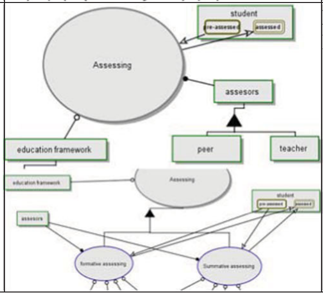
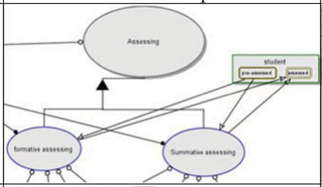
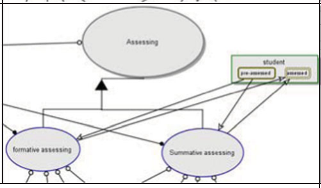
Attribute	Screenshot of relevant part of OPD	Scoring and explanation
A_1, expected outcome/intended purpose		**Beneficiary:** Student **Benefit:** specified, but relevance to beneficiary is unclear. **Score:** 2
A_2, main function		**Systemic process**: Assessing **Operand**: Student **Transformation**: (1) Assessing changes Student from pre-assessed to assessed **Operator**: Education Framework; Assessor **Score:** 3
A_3, Main object and its sub-objects		**Main object**: Education Framework **N levels sub-objects**: 1 **Score:** 2
A_4, structural links		**N link types**: 1 – Aggregation-participation **Mistakes**: sub-processes should be connected to main process in Generalization-Specialization link **Score:** 1
A_5, procedural links		**N link types**: 3 – (1) Result/Consumption; (2) Instrument; (3) Agent **Score:** 3

Table B1. Continued

Attribute	Screenshot of relevant part of OPD	Scoring and explanation
A_6, complexity levels		**N detail levels**: 2 **N sub-processes:** 2 **N transformative sub-processes**: 2 **Score:** 3
A_7, Procedural sequence		**Procedural sequence**: sub-processes are independent of each other. **Score:** 1
Total score		**15 / 21**