Articulating the role of models in science education: Exploring the use of models in effective science pedagogies

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Articulating the role of models in science education: Exploring the use of models in effective science pedagogies

1. Introduction

1.1 The aim of the study

The aim of the study is to articulate the role of models in Science education. Models have been used to represent phenomena in the natural world, to facilitate the understanding of abstract scientific concepts. How models make sense of the observed diversity of natural phenomena has been acknowledged in many science curricula and syllabi (OCR, 2016; NGSS, 2013). Visualizing models is important, as well as "understanding the natures of analogy and of metaphor, processes which are central to models and modelling" (Gilbert, 2004, p. 115).

This topic is important for me, because the role models serve in science education has not been communicated and emphasized to teachers in this context, resulting in teachers' limited use of models in classroom teaching. How models help in facilitating understanding in Science should be examined more clearly, so that teachers are confident of using models to teach abstract concepts to their pupils - to be able to make the 'unseen' and abstract entities visible (Francoeur, 2001). In addition, examining 'the why' of model use also helps to enhance the use of models for other purposes apart from content mastery in science education, such as bringing out the understanding of the Nature of Science (NOS) through model use. Gilbert (2004) agreed that students should arrive at an understanding of the nature of models and the key roles they play in developing science concepts. The Nature of Science (NOS) emphasizes science as a way of thinking and knowing, constantly subject to the critique of new evidence. As Bell (2009) acknowledged, the knowledge of the NOS (tantamount to the epistemic knowledge of science) is just as important, if not more important than content and process skills knowledge. These are

areas which are lacking in this context.

There are several reasons for the lack of use of models here. Firstly, in our context, time constraint is a concern for teachers. As content knowledge is often heavily emphasized here - syllabuses have a common slant towards being very specific in articulating learning outcomes in the form of content knowledge, as a result, teachers also have a very strong assessment-driven mindset that is geared towards mastery of content. This results in a time constraint for them to use a variety of pedagogies, including carrying out modelling and explicating the nature of models in class. Therefore, a balance is required to be struck between epistemic knowledge and content knowledge, and the use of models in the development and history of science can bring out this epistemic knowledge of science well – in emphasizing science not as a body of facts but a constant attempt at developing better representations of natural phenomena, through subjecting evidence to ongoing critique. Gilbert (2004) supported this in stating that students should be able to produce, test and evaluate models too. Consequently, Science not be presented as 'truth', but as most current scientific evidence of the natural phenomena. This is fundamental in understanding the Nature of Science (NOS) - with models at the heart of science as one of the most common ways of scientific representations. Although many science curricula contain NOS, a tradition working with NOS in the science classroom is not a common practice in many parts of the world (Lederman, 2007), especially in this context. A scan of science curricula documents (e.g. those of GCSE and Singapore-Cambridge 'A' and 'O' levels) also do not reveal much on modelling pedagogy. Therefore, bringing out NOS explicitly is needed in science education and how models can contribute to this will be explored in the study.

Consequently, this study aims to examine the 'how' and 'why' of model use, through a baseline study of how teachers use models in class. Appropriate scaffolding is needed with the use of

models – but what scaffolding is needed exactly? This requires considering a multi-faceted approach to viewing a model – "its nature, the types of entities it represents, the use to which it can be put, and its stability over time" (Justi & Gilbert, 2002). In addition, Gilbert et al. (1998) stated that models can explain and predict science phenomena, so examples of how teachers use models to explain science will be examined, and the impact of the use of models on science learning will also be discussed. A thorough investigation into the *how* and *why* teachers use models, together with details of the use of scientific models could possibly complement existing curricula and schemes of work (Gilbert, 2004), which have listed the use of models in science education but not articulated its use in varied classroom contexts. Justi & Gilbert (2002) concurred with the lack of initiatives to promote teachers' pedagogical content knowledge (PCK) in this area. Yet, models prove to be an effective tool for classroom teaching, and its potential in facilitating science inquiry is untapped – whilst inquiry has been the main pedagogical approach advocated here for more than a decade.

Moreover, in the history of science, models have also been used to develop scientific theories, through increasingly better representations of the studied phenomena by scientists. Hence, models not only facilitate the understanding of abstract concepts, they play a fundamental role in the development of science and the advancement of scientific knowledge; they enable scientists to 'make visible' their thinking through scientific representations that others can act on – to come up with better representations of phenomena. An example of a successive introduction of models in an historical sequence is the 'models of acidity/alkalinity' proposed by Oversby (2000). How models can thus be used to bring out the Nature of Science (NOS) in classroom settings, showing how science was 'developed' rather than 'discovered' in effective science pedagogies will be explored in this study.

Also, if inquiry lies at the heart of the science curriculum framework (MOE, 2004) in this context, how much more should this be reconciled with the use of models – which lies at the heart of the advancement of scientific knowledge. Therefore, this study aims to explore how models can be used in effective science pedagogies – including developing the epistemic knowledge of science.

This results in the following Research Questions (RQs) for this study:

RQ1) Why and how are models used in science classroom?
RQ2) How do teachers perceive they can better promote the effective use of models?

2. Literature Review

This review looks at literature explicating the role and use of models in effective science pedagogies. Firstly, I start with considering the complexities of the definitions of a model, and 2.1 goes on to outline the role of models in science education. The definitions of a model were used to inform the interview questions (see Appendix A Part 1) on teachers' 'perceptions of models', to find out how they perceive what models are, whilst the ideas in 2.1 will be revisited again in '5.2 Professional development intervention' to inform teachers' practice.

Secondly, this literature further elaborates on how teachers use models in science education, focusing on enhancing students' understanding of abstract ideas and their understanding of the nature of science (NOS). In section 2.2, how science models are used in the learning of science is described, to attain conceptual visualization and facilitate a structured approach to learning science. This section was also used to inform the interview questions (see Appendix A Part 2) on teachers' "use of models", to find out how they use models in science education, based on how science models contribute to the process of science learning.

Section 2.3 then expands on how models are used in relation to model critique, which leads to the consideration of models' limitations - including the different pedagogical approaches which need to be employed in model use based on discipline-related differences. This section on model critique was used to inform the interview questions (see Appendix A Part 3) on teachers' 'evaluations of lessons using models' too. Finally, in section 2.4, the review looks at implications for teacher education, examining model-based teaching in teacher training. This section involves two sub-sections: *i) Addressing students' misconceptions when using models* and *ii) Using Models for formative assessment to enhance Conceptual Understanding,* which help to elucidate the role of

models in effective science pedagogies, and literature review in this area will greatly informed the subsequent intervention.

What is a model

A model consists of representations taking various forms – mental, expressed, consensus and historical (Gilbert, 2004), and in multiple modalities. According to Gilbert (2004), "a 'mental' model is a private and personal representation formed by an individual – either alone or in a group" (p. 117), and this can be 'expressed' and communicated to others, with the potential to be developed into a 'consensus' model, which translates to an agreed upon model by various individuals in a group setting. Also, 'historical' models hold significance for science, in which newer models are built upon older models to result in the development of science, on theoretical and experimental grounds.

There are different uses for the various forms of models. This section addresses the 'how' of different forms of model use. Gilbert (2004) argued that the 'mental' model exists across the science disciplines - all students of chemistry "must have a 'mental' model of an 'atom', whilst all those of biology of a 'virus', and all those of physics of a 'current of electricity' (p. 117)." Through these illustrations of a mental model within the individual science disciplines, a mental model is consequently by its nature inaccessible to others, whereas "a version of that model can be placed in the public domain and can therefore be called an 'expressed' model" (p. 117). Consequently, this resulted in another form of model, the 'consensus' model which can be viewed as an agreement on the 'expressed' model. Gilbert (2004) further introduced the term, 'scientific' model - that is often present in school science as our curricular model, and claimed that such a model usually arises from a group of scientists working with a 'consensus' model at the frontier of science, and some examples of these 'scientific' models in the three disciplines of science (physics, chemistry and biology) include the Schrodinger model of an atom, p-n junction in a semi-conductor, or the AIDs virus. Gilbert (2004) also defined that a "superseded scientific model can hence be called a 'historical model', e.g. the

Bohr model of the atom" (p. 117) which was what we discussed earlier in terms of the development of science through building upon 'historical' models – present in model revision. In addition, there are 'iconic' models such as the DNA model built by Watson and Crick, and as the name suggests, it is iconic and synonymous with unravelling the 'mystery of life'. Hence, literature has shown that how a particular form of model arises is closely related to its use.

What then are the existing modes of models? From literature, models in various modalities include physical, analogical, mathematical and computer simulation models. Physical models are concrete ones which can be seen and are often synonymous with 3-D models. According to Harrison & Treagust (2000), "analogical models comprise scaled and exaggerated objects, such as symbols, equations, graphs, diagrams, maps and simulations" (p. 1012) that serve a purpose of facilitating communication. Hesse (1966) further argued that these models arise when two things are compared (target vs. source) in analogies, to provide the framework for model building. Chamizo (2013) claimed that analogies are also the originators in the construction of many models (p. 1619).

In sum, a multi-faceted approach is useful in viewing modals with their varied forms of representations and modes. Justi and Gilbert (2002) aptly advocated this approach in considering a model's nature, the types of entities it represents, the use to which it can be put, and its stability over time. Some of these facets will be explored in-depth in this literature review, in the context of science education.

2.1 Role of models in science education

This section articulates the twin roles of models in science education, to build a conceptual understanding as well as to facilitate the development of NOS. The addresses the 'why' of model use.

Models are part of many classroom pedagogies in science education, and one of the most important aims in science education is to build conceptual understanding, and models play a fundamental role in this. What then is conceptual understanding? Conceptual understanding is defined as "comprehension of the principles and concepts of a given domain or subject, and the interrelationship between the different concepts" (Corradi et al., 2015, p. 686). From literature, it seems that conceptual understanding entails making links between concepts to result in essential understandings which transcend content knowledge. Clement (2000) concurred with this idea in emphasizing the transferability of knowledge, by stating that conceptual models can help students "make sense of science via satisfying explanations, embodying a flexible kind of transferable knowledge" (p. 1042). Vries (2006) refers to a paper by Gilbert et al., which examines what 'satisfying explanations' are. According to them, there are "different types of explanations - descriptive, causal and predictive explanations…" (p. 3). To illustrate this in our context, descriptive versus causal explanations can be applied to the construction of structural versus teleological explanations respectively in the field of Biology (Yip, 2009), and different conceptual models may be used for the attainment of varied explanations.

The second role of models in science education is to facilitate the development of NOS. In support of this, Coll et al. (2005) articulated that using models as well as analogies meta-cognitively constitute "an appropriate choice of pedagogy to integrate the development of science concepts while developing students' understanding of the 'Nature of Science' (NOS)" (p. 195) – in a way balancing conceptual and meta-conceptual learning (Delgado 2015). The following paragraphs explicates how models and modelling support the development of students' understanding of the NOS.

What then is NOS? According to the NOS under the Next Generation of Science Standards (NGSS, 2013), science is described as ever-changing and "the only consistent characteristic of scientific knowledge across the disciplines is that scientific knowledge itself is open to revision in light of new evidence" (p. 2) – this implies that the only constant is change for science. This articulates how NOS

should widely be understood, and as science constantly seeks to explain the natural world, the implications for science models are that they should be consistently fine-tuned and subjected to change – in model revision, just as how science is open to change against new evidence. However, Hansson & Leden (2016) pointed out that most models used by scientists today will still be in use when students age, so this also captures the irony in scientific knowledge in that they take a long time to evolve and materialise.

2.1.1 Model revision

Model revision is key in enhancing students' understanding of the NOS. Sorensen et al. (2012) argued for developing scientific literacy and public understanding of science (p. 44) to enhance the understanding of the NOS, which is achieved through model revision, as the key to developing scientific literacy. Public understanding of science is really to "generate a source of new questions, enable a cycle of criticism and improvement important for NOS" (Clement, 2000, p. 1044). Moreover, model revision can also be advocated using historical models as intermediate models in the curriculum for students to appreciate the ever-changing nature of scientific models – a key idea in the NOS (Justi & Gilbert, 2000).

Furthermore, one of the central goals of science education is to promote model-based reasoning in students (Clement, 2000). When students reject or revise models to fit new empirical data, they are developing a kind of reasoning that helps them to use models to simulate natural phenomenon through the best representation. Hooper (1974) supported this view in articulating that "the model and its mode of construction are at the heart of the higher education scientific curriculum" (p. 364), and understanding this contributes to enhancing students' understanding of the NOS.

Also, within model revision, Mathewson (2005) further argued that multiple models are useful in clarifying misconception caused by single models. Students will then understand that each model demonstrates only limited aspects (Millar, 2005) of the target phenomenon (Harrison & Treagust,

2000). Grosslight et al. (1991) also substantiated that multiple models can provide "different spatiotemporal views of the target and feature different conceptual vantage points" (cited in Gustafson et al., 2010, p. 104). By getting students to reason and argue produced models and how these relate to the 'standard model', this gives credence to models being a pedagogical tool for bringing out the nature of science. To summarize, the use of model revision and multiple models can enhance the understanding of the NOS. Furthermore, understanding the NOS also helps students to carry out scientific inquiry in their daily lives (UCMP, 2016) – which is at the heart of the science curriculum framework (MOE, 2004); consequently, it is important that science education brings out the NOS through model revision.

2.1.2 Modelling

In addressing models, we should consider 'modelling' too – which is key to model revision. A model seems to be the 'product' which arises from the process of modelling. Chamizo (2013) refers to Bruner, who clarified that modelling is so deeply interwoven into the fabric of our thinking that, like walking, we do it without having to analyse or be aware of the mechanism, but how a model arises is as fundamental as the model itself. This seems to link model (product) and modelling (the process) in a truly dialectical way. To further develop on this, some researchers put forth that the process of modelling could be a kind of model too, for example, refer to the "model-based reasoning" figure proposed by Anderson (2003) as follows (subsequently listed as Fig. 3 in this study):

The figure originally presented here cannot be made freely available via ORA because of copyright. The figure was sourced at Anderson, C.W. (2003) ***Teaching science for motivation and understanding***, East Lansing, MI: Michigan State University

This diagram will be referenced for categorizing teachers' findings in section 4.0, as most of the emergent themes there are highly coherent with this diagram that Anderson (2003) proposed.

Similarly, in the development of NOS, modelling is also fundamental in the testing of science. What exactly is modelling? Modelling includes the derivation of science concepts from investigative approaches. In the testing of science using modelling, variables are changed and hypotheses are formulated for testing in the process. According to the National Council for Educational Technology (NCET, 1994), software support also enables this process through using well-defined and structured simulations, which can progress to more open-ended modelling. This form of modelling can support the understanding of the NOS in tandem with the development of science concepts. The result is the creation of a model as a representation of a real or imaginary situation (through technological affordances) that will enable students to explain and explore different scientific concepts (NCET, 1994).

In sum, this section elaborated on how teachers use models in science education, focusing on enhancing students' understanding of the Nature of Science (NOS). Lastly, a scan of different pedagogical approaches to facilitate the development of the NOS using models was also done and these include:

- Critiquing models help student to learn science while developing an understanding of NOS as they acquire content knowledge (e.g. New Zealand curriculum, MOE, 1993).
- Facilitating collaborative talk is effective for students to build and defend their models, critiquing their models in the process of explaining phenomena (Boulter & Buckley, 2000).
- Focusing on science as a social practice – focusing on the interactions of doing science (Duschl & Hamilton, 1998).
- Using analogies – considered a subset of models, which not only explain science concepts but are also used to develop the complexity of mental models (Coll et al., 2005, p. 185).

A combination of specific pedagogical approaches could be considered to bring about the desired outcomes of bringing out the NOS using models. Finally, literature also states that models and modelling can be used as an important constructivist teaching strategy (Harrison & Treagust, 1996), and according to Harrison & Treagust (1996), teachers know that students enjoy playing with them. These ideas will be further explored in '5.2 Professional development intervention' to inform teachers' practice.

2.2 How science models are used in the learning of science

This section discusses how science models are used in the process of science learning, to attain visualization of concepts or even a structured approach to science learning. This section develops the 'how' of model use in effective science pedagogies.

Science models can be used to facilitate visualization processes required to grasp science concepts. This is exemplified in the history of science, where certain phenomenal breakthrough achieved in science resulted from model making. For instance, it is noteworthy that Watson and Crick reported reaching a point where they had to make models, as having mental images about DNA's structure was insufficient. Watson subsequently claimed that their success rested on model building (Harrison & Treagust, 2000, p. 1012).

Science models can also be used to develop a structured approach to learning science. As science is a rigorous subject requiring the logical sequencing of understanding and science experimentation – from which knowledge of science is uncovered, it therefore follows a structured way of delineating the problem to be studied and formulating relevant questions to investigate. It is thus important to raise awareness of this implicit process, and Suckling et al. (1978) further developed this as "recognising the existence of a problem; delineating the system to be studied; and formulating questions to be asked, including constructing the model and running the model" (p. 26).

Consequently, it is useful to develop a structured approach to modelling to raise awareness of this implicit process, and this maps out how models are used in science learning in a precise way. This is related to teachers viewing models as 'tools' to learn science (in 3.6).

This section has implications on how teachers use models, whether for visualization of concepts or delineating a structured approach to science learning, and this is contingent on what they want to achieve in science learning. This will be further explored and verified in 4.0 Key teacher findings.

2.3 Model critique which leads to the consideration of the limitations of models

Model critique is fundamental in the progression of modelling in science, especially in KS3/4, to develop understandings of NOS. The stages of progression are articulated as such: using others' models, creating own models with guidance, analysing and modifying other peoples' models, and creating and evaluating own models (The National Curriculum, 2004). Empirical studies have detailed that how students critiqued models depended on the different aspects of models. For instance, the aspect of features of models can help to facilitate a deep understanding of models. In a study examining elementary children's shifting views of models and the nature of matter in a grade 5 class (Gustafson et al., 2010), it was found that the extent to which they exhibited a naive or evolving understanding of models varied with the features of the model under consideration, as did their understanding of the subject matter in question, e.g. the particle nature of matter. It is thus important to scaffold their ability to think critically about models, and then to explore the use of various models to help them understand the particulate nature of matter.

In sum, model critique is important not only in science classroom to achieve important purposes of science education such as developing the NOS as detailed by The National Curriculum (2004), but also to develop students' and teachers' higher-order thinking about models. This will inform teachers' use of models and develop their practice in this aspect. Following this, literature reporting

on model critique, specifically some limitations and challenges with the use of models in science classrooms will be discussed here, together with some of the ways these might be overcome.

Firstly, models are focused on different attributes of representation (Boulter & Buckley, 2000) or chosen behaviour of a phenomenon, and due to this, they have their limitations in not being able to demonstrate a phenomenon fully. Consequently, most models are 'wrong' or 'limited' in some key aspect and it takes a skilled teacher to portray this - the "pragmatic use of models that are known to possess limitations is one of the characteristics that differentiates the expert from the novice" (Grosslight et al., 1991, p. 4).

Secondly, apart from understanding the nature of models, global research also corroborates the existing limitation in the current use of models – due to a lack of articulation of the role of models and modelling in science education. For example, chemistry teachers tend to focus on the content of models rather than on the nature of models (Van Driel et al., 1998).

How this may be overcome is cited in an example by Chamizo (2013), through portraying issues in chemistry using models-constructed 'situations' of a political, historical or cultural context – with the intention of explaining and/or predicting the behaviour of objects, phenomena or systems" (p. 10). In this case, the focus is on the nature of models and how they are used to facilitate contextual understanding rather than on the content of models. He argued that in such context-based teaching in chemistry education, epistemology on models and modelling was further analysed and modelled in the curriculum unit. This portrays that the practices of science can also be highlighted using models in contextual learning. As a result, Chamizo (2013) stated that students could "experience their learning as relevant to some aspect of their lives and be able to construct 'mental maps' (or mental models) of the subject" (Gilbert, 2006, p. 960). These benefits are ideal as they develop interest and meta-cognitive skills in students and provide teachers with the 'relevance' of bringing in

models. This also expands on the use of models and overcomes the limitations of model being used only for content knowledge teaching. To summarize, limitations of models must be considered carefully in the use of models, and articulated explicitly where possible.

In addition, this section on model critique was used to inform the interview questions (see Appendix A Part 3) on teachers' 'evaluations of lessons using models', to find out how (if) they evaluate the instances of using science models in class, and whether this will benefit them. The findings from the interview will inform the subsequent **questionnaire intervention** focusing on **Professional development (PD)** for teachers, in consideration of the literature review in Section 2.4 on implications for teacher education.

2.4 Implications for teacher education: Model-based teaching in teacher training

Finally, in this last section, this review looks at implications for teacher education, examining model-based teaching in teacher training. This is firstly focused on facilitating models and modelling as key thinking tools for students and teachers learning science (Coll et al., 2005); secondly, issues surrounding the use of models for enhancing conceptual understanding.

2.4.1 Models and modelling as key thinking tools

Firstly, models and modelling are key tools for scientists, science teachers and learners and this involves students' constructing and critiquing their own models. According to Coll et al. (2005), "pedagogies that involve modelling are most effective when students are able to construct and critique their own models" (p. 183). Gilbert (2004) concurred that students should be able to produce, test and evaluate models; consequently, this fosters a thinking that science is not a fixed body of knowledge, but based on current evidence which are but representations of the natural

phenomena. This results in models being used as a key tool for fostering specific thinking about science, with the potential to contribute to the understanding of the NOS.

Other types of thinking also exist, e.g. meta-cognitive thinking. Can modelling then be used as a tool to enhance this type of thinking? As research suggests that group work and peer discussion are important ways of enhancing students' cognitive and meta-cognitive skills (Coll et al., 2005), this meant that to use models as key thinking tools for students, other factors such as collaborative learning present in group work and peer discussion are also important. In line with this, teachers can promote the constructivist approach, tapping on students' enjoyment from playing with models (Harrison & Treagust, 2000) – modelling thus becomes an important constructivist teaching strategy.

Some other issues to consider would be how teachers reflect on the use of models. Do they reflect on the pedagogical use of models? What do they reflect on – their performance or students' difficulties (Drechsler & Van Driel, 2008)? In sum, teacher training should encompass various aspects of exemplary model use, identified from literature and the practice of expert teachers.

Lastly, France (1997; 2000) articulated that teachers should not only possess sound pedagogical content knowledge to use and develop appropriate models, but also be conversant with the use of models within the community of experts that use them. Where possible, model-based teaching in teacher training should provide such opportunities.

Other considerations of model-based teaching in teacher training include enhancing conceptual understanding of students; addressing students' misconceptions when using models; and using formative assessment for enhancing conceptual understanding.

2.4.2 Issues surrounding the use of Models for enhancing Conceptual Understanding

For conceptual development in the understandings of e.g. laws and theories, teachers could highlight explicitly to students "the assumptions, limitations and contexts in which laws, theories and scientific models apply" (Stains & Sevian, 2015, p. 836), so that conceptual models can help "attain 'conceptual understanding' in science at a level that goes beyond memorised facts, equations, or procedures…that science can 'make sense' via satisfying explanations (Clement 2000, p. 1042), and be used flexibly to solve other problems.

i) Addressing students' misconceptions when using models

Research has shown that a common misconception among most secondary students is that they believe there exists a 1:1 correspondence between the models they use and the targeted reality (Clement, 2000), in terms of 'model-target correspondence'(Gustafson et al. 2010). Another issue is that some students believe that there is only one scientific method that all scientists follow – an existing prevalent misconception (Hodson, 1988; Abd-El-Khalick and Akerson, 2004). This impedes the development of the NOS that models seek to bring about. It is also a common misconception that science progresses because of observation, and then theories are produced to agree with the observed. This is a common way of progression in historical models, but it is vital to note that science does not always proceed inductively.

ii) Using Models for formative assessment to enhance Conceptual Understanding

Models are important for teachers to elicit information on formative assessment (Cowie & Bell 1999), to elicit information on students' ongoing understandings, and scope and depth of their prior knowledge. Clement (2000) also explicated this process in his 'Preconceptions to expert consensus model' (see **Fig. 1**), thus wherever possible, teachers should employ formative assessment and note the preconceptions of their students in the use of models.

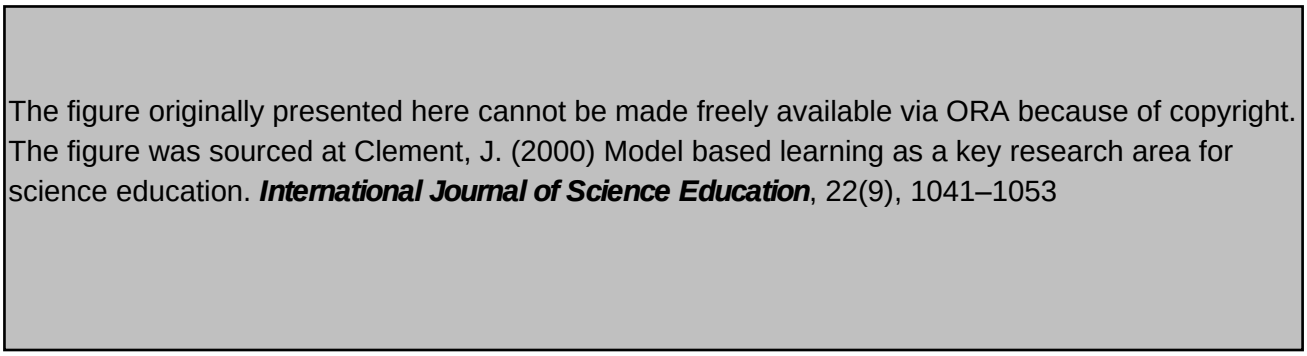


Fig. 1 A map of the student's preconceptions and natural reasoning skills (Clement, 2000)

Fig.1 shows that conceptual change is highly coherent with the use of models as a thinking tool. In this regard, modelling can be employed to disprove predictions, or provide insights into students' understandings of models – including the nature of models, multiple models and their use in science (Grü Nkorn et al. 2014).

3. Methodology (Data collection)

Chapter 3 describes and justifies the research design and methodology by which the key research questions were addressed:

RQ1) Why and how are models used in science classroom?

RQ2) How do teachers perceive they can better promote the effective use of models?

Section 3.1 justifies why an action research methodology was adopted. Section 3.2 looks at action research cycle 1 and the use of interviews as a data collection method. Section 3.3. then looks at the baseline findings from the interviews in action research cycle 1 and uses these to inform the intervention in action research cycle 2.

3.1 Why Action Research?

This study takes place in two cycles:

Cycle 1: A baseline study is necessary to understand the current situation of how teachers perceive and use models in science classrooms, using teacher interviews to collect data in these focus areas.
Cycle 2: The outcome of these interviews and analysed data will shape my intervention project of using a Professional Development (PD) questionnaire and collaborating with teachers to further inform the ways they perceive they can better promote the effective use of models in science pedagogies.

In Prins et al. (2011) evaluation study on fostering students' epistemological views on models and modelling through the use of contexts for learning, he collected data through means of classroom observations, interviews, audio-taped discussions, completed worksheets, and written questionnaires throughout the field tests (p. 2). Similarly, in this study on models and modelling to articulate the role of models and explore the effective use of models in science pedagogies, data was collected through teacher interviews (cycle 1) as baseline study, and findings from cycle 1 led to devised teacher questionnaires in the professional development (PD) intervention (cycle 2).

Action research was decided on as I was developing the practice of two target groups of teachers in cycle 2 on their use of models, in the STEM Applied Learning Programme (STEM ALP) in schools – which is part of the informal curriculum in this context, as well as another group of teachers – who are mainly chemistry teachers – part of a school which I provided consultancy for their formal chemistry curriculum review. As the nature of the research was highly contextualised for each group of teachers and built upon findings attained from previous research cycles to further develop their practice, hence action research was selected as it follows a key methodology through the following 'action research diagram' (in **Fig. 2**) rather than practitioner research.

This action research diagram was thus referenced in guiding my methodology throughout this research. Various phases of my research will be tied to this reference from Altrichter et al. (2013) work on "Teachers Investigate Their Work: An Introduction to Action Research across the Professions" where appropriate.

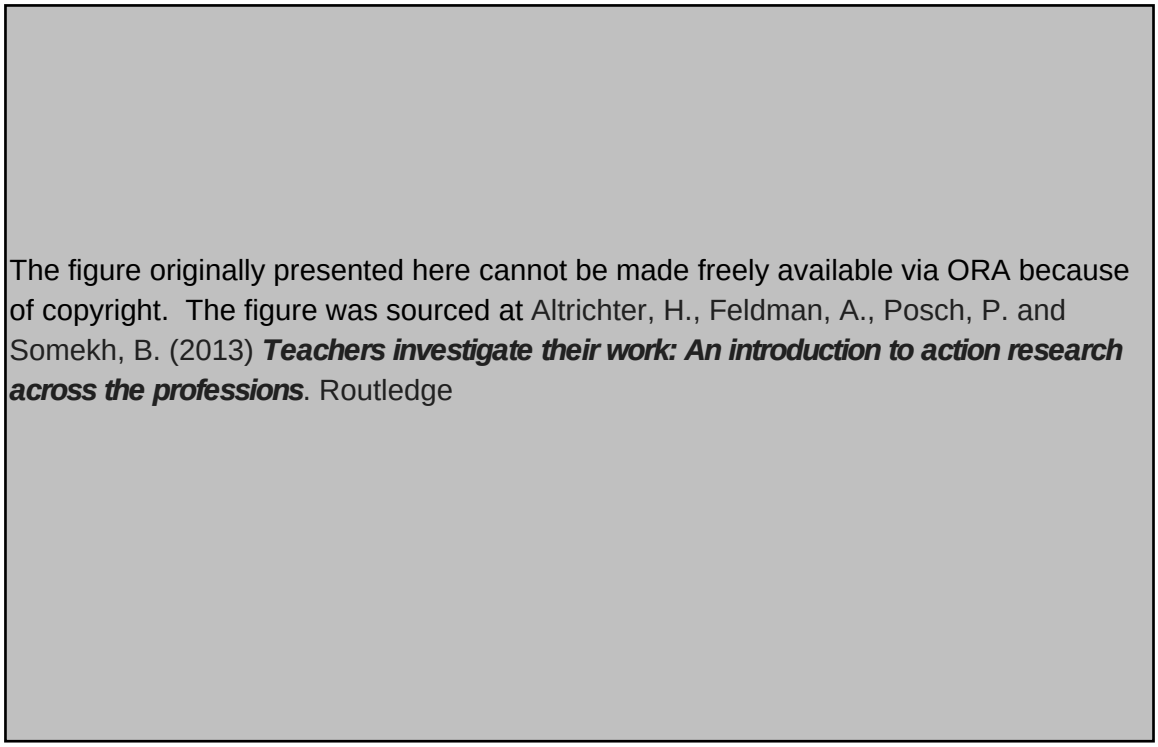


Fig. 2 How teachers investigate their work (Altrichter et al., 2013)

With reference to **Fig. 2** above, the literature review – which informed the RQs – was tapped on for addressing "chapters 2 & 3" in **Fig. 2**. This established the starting point for research (corresponding to "stage A" in **Fig. 2**), and the starting point was further clarified through the outcome from the interviews ("stage B"). The interviews were conducted (in cycle 1) and addressed "chapters 5 & 6" in **Fig. 2** through collecting and analysing data, and in the analysis of the interview data, baseline findings were determined for the further development of action strategies to tackle the findings from cycle 1. These action strategies in **Fig. 2** ("stage C" and "chapter 7") were put into practice in the questionnaires (in cycle 2) situated within the professional development (PD) intervention, and teacher knowledge was formulated and shared through the PD intervention (corresponding to "stage D" and "chapter 8"), where teachers' reflection was facilitated through the questionnaires.

3.2 Methods of data collection

Table 1 matches the data collection methods to each research question and cycle.

Research questions (RQ)	**Data collection method I used to answer the research question**
RQ1) Why and how are models used in science classroom?	**Teacher interviews (Cycle 1)**
RQ2) How do teachers perceive they can better promote the effective use of models?	**Questionnaires (Cycle 2)** **From the baseline study of teacher interviews, professional development (PD) intervention was carried out.**

Table 1

3.3 Cycle 1 (Interview) methods

3.3.1 Description of interview sample

Decisions on the selection of sample was made based on the following considerations. The 3 science teachers are representative of the teachers in Singapore at secondary level due to the varied composition of the group – ranging from beginning teachers to expert teachers. Their differing school experiences will account for a range of school practices and student profiles. Also,3 teacher interviewees, L, H and C with teaching experience from different science subject disciplines will articulate different ways in which models are used to engage students in different science subject disciplines, as there are varied ways of using models in science disciplines.

L is an experienced teacher with more than 35 years of experience. She had taught in various schools throughout her career, starting off as a high school chemistry teacher specialising in teaching the A

level curriculum, then going to teach middle school students specialising in teaching the GSCE curriculum.

H is a teacher with approximately 7 years of teaching experience. He is currently in his second school, and teaches GCSE Chemistry and Biology. Both H and L are currently teaching lower attainment students compared to the national average, though L had experience teaching higher attainment students at the start of her teaching career.

C is a physics teacher who had taught at both high school and middle school, and had experience working in the curriculum planning and development division, where he stayed almost a decade and was a strong supporter of the inquiry framework - which guided the 2004 and 2013 science curriculum in Singapore. He was involved in driving inquiry as the main science pedagogical framework in Singapore, taking a leaf from the National Research Council (NRC, 2012) in the United states. Towards the end of his career, he was a vice-principal in a local middle school, and went on to assume a role in teacher training. Given his vast experience in pedagogical and curricular development work, including the leadership of schools, he could articulate the role of models in the broader sense, including opinions on whether models could be incorporated into the curriculum, informed by his interactions with teachers - based on his current work in professional development (in-service teacher training) and as an ex-school leader.

Indeed, considerations of the selection of teachers included whether they had taught different curricula e.g. GCSE and A levels; students of different age groups learning science; students with varied abilities and learning needs; or helmed leadership positions, including in schools or in the curriculum field. C fulfilled all these considerations; L and H fulfilled mainly teaching different curricula, and different profiles of students. Also, to further nuance the data collected, L and H were selected based on their different years of teaching experiences - L (>35 years) and H (>6 years), both respectively are representative of varied perspectives ranging from those of a highly-experienced

teacher (having witnessed 3 decades of curricular reform) to a relatively new teacher (who had attained stability in his teaching career). In terms of personal development such as postgraduate studies, L has recently embarked on one after almost 3 decades of teaching, while H has yet to embark on any postgraduate studies.

Also, for the various science subject disciplines offered here – chemistry, physics and biology, which could influence how models are used in suitably varied science pedagogies, my interviewees collectively are representative of teaching different science disciplines for me to attain a more holistic view of how models can be used in sciences pedagogies within the various disciplines.

3.3.2 Reasons for choosing interviews to answer RQ1

3 secondary science teachers from Singapore were interviewed for approximately an hour and their responses were elicited, on areas of the research questions, focusing on how teachers perceive and use models, and whether its role was articulated in science learning and teaching. Interviews were chosen as explicit examples of teachers' use of models and their limitations (if any) will be recorded through this research method at length, so that good practices - arising from the differing ways in which models are used - can inform ways of further developing teachers' use of models. This results in rich, qualitative data being unearthed.

A semi structured style of interview was chosen as it allows for teachers to be more forthcoming with me. Also, this style was suitably chosen as I was acquainted with them, and they have worked with me in different capacities, and L had even mentored me before. This semi-structured interview style balances any power differential and puts the interviewees at ease so that I could ask more probing questions, in the process allowing them to elaborate freely where they want to.

Questions that I asked in the interviews and why these questions were asked to answer the overall research questions will be elaborated in this section. This ties in with section 3.6 on teachers' responses to these questions. The questions I asked in the interviews are listed in **Appendix A**.

Interview questions were divided into 3 parts (see **Appendix A**) - (Part 1) Perceptions of models; (Part 2) Use of Models; (Part 3) Evaluation of lessons using models. As the RQs were focused on why and how models are used in science classroom (RQ1), and how teachers perceive they can better promote the effective use of models (RQ2), consequently, interview questions on perceptions of models (in Part 1) were designed so that teachers' current perceptions of models can be clarified as the 'starting point' (see **Fig. 2**), and their perceptions of the 'use of models' (in **Appendix A** Part 2) were built upon through asking them if they carry out any form of 'evaluation of lessons using models' (in Part 3). Asking these questions will constitute baseline findings that allow us to address RQ1 - Why and how are models used in science classroom, and the baseline findings obtained from the interview could be further used to inform RQ2 - How teachers perceive they can better promote the effective use of models.

In addition, the reasons why these questions were asked are based on literature review. From literature review, definitions of a model and '2.1 role of models in science education' inform Part 1 of the interview questions – Perceptions of Models. Questions such as how teachers classify models and what science models are to them were explored in literature and hence posed to teachers. Similarly, '2.2 How science models are used in the learning of science' informs Part 2 of the interview questions – Use of models. For instance, questions such as how models have been used in science teaching and how they have been set up in lessons were asked. Lastly, in literature section '2.3 Model critique which leads to the consideration of the limitations of models' and '2.4 Implications for teacher education: Model-based teaching in teacher training inform Part 3 of the interview questions – Evaluations of lessons using models. For instance, questions such as whether teachers

used pre-/post- tests to evaluate the success of models or examine various ways of using models were posed here too.

Also, questions asked were mainly open questions – e.g. “do you think”, prompting them to elaborate as far as possible. Questions that require elaboration include “why” questions. Through this approach, assumptions were minimised, allowing me to capture their authentic opinion. The interviews were conducted in quiet public places, and typically lasted for 1.5 hours for each interviewee. Permission was sought from them to audio record their responses at the start of each interview.

Some potential biases of my data include a closer examination of the types of questions asked to the participants and the way my interview was conducted, in addition to any existing power differentials. Power differentials were not significant, as one of them was an ex-mentor who is currently semi-retired and teaching in a different setting from me. Regarding the second interviewee, he was an ex-colleague and is currently working in a different school from me. Also, though another had assumed leadership positions before, he was not in any way my superior at work. I had decided to interview him as he had portrayed mastery of his disciplinary content knowledge, as well as an understanding of the nature of science and the inquiry process of science. I had attended his workshop and so he was willing to share with me as much as possible. At work, he is a teacher trainer and is keen on developing teachers’ practice through this research.

3.4 Cycle 2 methods – Description of the intervention in the form of a questionnaire

3.4.1 Description of questionnaire sample

In the intervention with the teachers in action research cycle 2, the questionnaire was both designed as the intervention and the data collection tool - to assess the effectiveness of the questionnaire as an intervention. Hence, the questionnaire as the intervention was designed to begin a process of changing practice and how the questionnaire serves this purpose will be further discussed in 3.4.3.

How I selected the teachers to be involved are described here. The questionnaire sample size comprised 6 teachers from 2 schools – 3 teachers per school. They were selected largely based on access - my established working relationship with a school on STEM projects, and for the other school, I also had a working relationship with them based on a consultancy project where I assisted the school in the review of their chemistry curriculum. The first group of teachers that were teaching STEM had interdisciplinary backgrounds in science – physics, chemistry and biology. They were also teaching science to 13 and 14-year olds (Lower Secondary Science teachers). The second group of teachers (from the school that I provided consultancy to) was a group of chemistry teachers teaching students across a range from age groups (13-16-year olds) but largely focused on GCSE chemistry. They were selected not only due to an existent working relationship, but also for the subject discipline they teach, as chemistry was a subject that required much modelling so they were already somewhat conversant with the use of models but were looking to further develop their practice in this aspect too – which was a perfect fit with the aim of my research.

Biases in data were not evident, except in the consultancy case where they might have been more prone to give data that did not criticise the curriculum (in consideration of my background at the curriculum planning and development division); however, within the responses there was actual

contrasting evidence to this – as they highlighted how better the division could have designed the curriculum. Moreover, it was not due to sheer access that they were chosen as the teachers' responses from the STEM ALP school that I worked with were chosen to nuance the collected data further based on the informal (STEM ALP) versus formal (chemistry) curriculum. The result of this could allow for follow-up as future work on models nuanced for different curriculum.

Before introducing the questionnaires to the chosen teachers and engaging them in this cycle 2 research, the aim of the research was explained to them, building upon cycle 1 baseline findings – which were shared with them. Through the research, it was explained that in getting them to consider their own use of models based on the findings in cycle 1, they would perceive how they might further develop their practice in the effective use of models. Hence, cycle 2 intervention in the form of the questionnaire helps them to reflect on their own contextualized practice, and finally lead them to perceive how they can promote the effective use of models. Their consent in filling up the questionnaires was then sought in subsequent meet-ups with them (the two groups of teachers) and then a consensus was reached to disseminate the questionnaires to them and they were given time to deliberate on them. A coordinator in each group would then send back to me the completed questionnaires via email.

3.4.2 Why chose questionnaires to answer the research questions for cycle 2

In the research on the use of classroom models in various science pedagogies, various methods should be considered since relying solely on one instrument, e.g. interviews – that research on mental models have traditionally relied upon can be time-consuming, in terms of in-depth analyses that interviews require. Thus, an open-ended survey (qualitative instrument) could also be

developed (Stains & Sevian, 2015), which supports our use of questionnaire in cycle 2. Shwartz et al. (2006) reported this instrument to have good construct and concept validity.

Moreover, classroom observations were not possible to conduct to get first-hand data on teachers' use of models in lessons as the teachers' schedules were diverse and their use of models (for certain topics) was already concluded in the previous terms. Extended interviews to be conducted with teachers were not feasible in cycle 2 due to their busy schedules, hence it was agreed upon that questionnaires would be explored, though admittedly, if teachers had more time, questionnaires complemented with teacher interviews would be ideal for the PD intervention in cycle 2.

However, even with the limitations of questionnaires not being able to provide first-hand observational data – that an interview or classroom observation could provide, the questionnaires turned out to have some benefits over the other research methods. They could facilitate teachers' reflections better, as evidenced through the questionnaire responses – which were long and reflective. Due to the questionnaire research method, teachers could ponder upon the questions more, as they had time (to ponder over the questionnaire) as opposed to immediate responses required in interviews. Also, time was sufficient for teacher respondents (in cycle 2) to think through the responses of the teacher interviewees (in cycle 1) - which were made available to them in the cycle 2 research phase. This was a deliberate attempt to build on baseline findings from cycle 1, to get teachers to reflect upon those findings (in their own practice and context) for professional development – fulfilling the aim of cycle 2. Through this method, they critically considered the research in cycle 1 based on their contexts.

3.4.3 Why devise these questions in the questionnaires to answer the research questions for cycle 2

The questions in the questionnaire have been informed by the following action points - derived from literature and considering the *action strategies derived from cycle 1 (refer to **Table 2**).

Action points:

1) **Making models explicit; and using models to illustrate the process of doing science**

   Chamizo (2013) refers to a book by Bruner (1966) and argued that it is useful to develop a structured approach to modelling to raise awareness of this implicit process, such as "recognising the existence of a problem; delineating the system to be studied; formulating questions to be asked; and constructing the model and running the model" (Suckling, 1978, p. 26). This added credence to making models explicit and using them to illustrate the process of doing science.

2) **Model revision (using Justi & Gilbert's (2002) "a model of modelling" framework)**

   Justi & Gilbert's (2002) figure of "A 'Model of Modelling' Framework" (p. 371) is referenced (in Appendix C) to guide teachers in directing them to think about model revision in the questionnaires.

   **For elaboration on the developed action strategies – refer to Section 5.1.*

Refer to the questionnaire (Appendix B) for this explanatory section on the questions. **Table 2** below shows how each part of the questionnaire links to each of the action points 1 and 2 above.

Action point	Questions in questionnaire asking teachers to reflect on this action point (referencing questionnaire Appendix B)
1) Making models explicit; and using models to illustrate the process of doing science	Questions devised under "how you see the subject" on models aim to make models explicit to teachers through asking about their perceptions of models (including those within the curricula). Teachers were asked if they "make distinctions in their teaching between models vs. theories", and how they "think these are linked", to find out how competent they are in making models explicit to their students – affecting how confidently they can make the distinction in their teaching. Furthermore, finding out about their making models explicit in class is seen in the following question, "do you get students to present, specifically including differentiating representations from phenomena?" In considering when models were made explicit in class, questions in the questionnaire were further split according to the pre- and post-activity phase, and teachers were asked to deliberate on them. Their responses were recorded via the questionnaire, which serves as a data collection tool for professional development purposes. Also, teachers were asked to deliberate on the process of a current 3-D modelling activity (within their scheme-of-work (SOW)) where students built 3-D models, and to further develop how they perceive they can promote the effective use of models, teachers considered the "pros and cons" of the models they get students to build – this involves making model explicit, even to the extent of getting students to explain if their model is better than the textbook explanation. In devising these questions, this develops teachers' awareness of the limitations of models. These questions were also informed by literature, which concurs with 3D models being useful. In Biology, hands-on aspect of models also enhances students' understanding, e.g. making of three dimensional (3D) cells. In a study that included 669 9th grade students from 25 classes taught by 22 Biology teachers - with random assignment of teachers to three different instructional methods, it was found that the 'hands-on' learning group who built 3-D models "achieved significantly higher on academic achievements, and on the high and low cognitive questions levels than the other two groups" (Lazarowitz and Naim, 2013, p. 500).
2) Model revision (using Justi & Gilbert's (2002) "a model of modelling" framework)	Beliefs of teachers on science education undergird model revision, as they can impact teachers' enactment of carrying out the models-based process as a modelling approach, and how frequently teachers carry out model revision. This is translated to questions where teachers were asked if they believe in 'discovered knowledge' or exploring the process of discovery more. For model revision, questions on "critique, especially to think of limitations of their models" and "model revision" were devised, as

	these are prerequisite skills required in model revision. Addressing these questions is essential in answering the second role of models in science education (addressing 'the why' of model usage) to facilitate the development of NOS - as expounded on under section 2.1. This addresses RQ2, by simultaneously tackling 'the why' of model usage (in RQ1). Literature also highlights the importance of encouraging teachers to teach model revision skills to students. This is portrayed through an empirical study by Grosslight et al. (1991), who proposed that students seldom attained the highest level of understanding of models ('level 3') - where models are tested and changed to inform the development of ideas in the process of supporting students' understanding of the NOS.

Table 2

Some questions cut across both action points. For instance, under "how you see science education", questions were asked on teachers' perceptions of science education, their beliefs of science education as aims of science education, which potentially impact their enactment of both action points. For instance, under "teachers' reflection" in the post-activity phase, teachers were asked if students' models can be extrapolated for teachers' use; this can potentially bring about model revision (addressing action point 2) and students' reflections on the process of doing science, through teachers' explicit use of models and modelling (tapping on action point 1).

3.5 Ethical issues

Participants were informed of how the data will be used and assured of their full anonymity throughout the research processes. Participants were granted full volition of their participation in the interview process, and were told that they could withdraw themselves from this research project at any time. Permission was sought to audio record the interviews. Similarly, for the questionaires, similar ethical considerations apply and participants' schedules were accomodated and granted the benefit of responding according to their schedules – for most, after the exam period so that they were given at least 3 weeks to respond. This allowance ensures that they were not unduly stressed and their well-being was a foremost consideration.

3.5.1 Risk involved and mitigation of potential risks

Possible risks involved in taking part in the study with the consultation of proper channels were acknowledged, in the event of personal information being divulged during the interview. Furthermore, it was made known to the participants clearly in the information sheet, that in dealing with recordings where participants' confidentiality may be breached (such as audio recordings), only the researcher and the supervisor will have access to such data. Nevertheless, to mitigate any potential risks, all data will be locked up and access will only be granted upon explicit written consent from the research participants. In addition, a storage and disposal plan was devised for all materials involved in the research.

3.5.2 Use of data:

Participants were informed that the research, written up as a thesis and on successful submission of the thesis, will be deposited both in print and online in the University archives, to facilitate its use in future research. The thesis will be published open access.

3.6 Analytical procedures

In analysing the interview data, I listened to the three interview transcripts and recorded down notes of key themes that the teachers mentioned, in response to RQ1 and RQ2, including the many specific examples they gave. Subsequently, I grouped these into elaborations of key themes, and as far as possible, cross-compared the interviewees' responses to each theme. I ended up with these 3 sections, according to three key identified themes.

Method of analysis for the interview Findings from Cycle 1 (Teacher interviews)

Findings from the teacher interviews (cycle 1) were organised into two sections – 3.6.1 and 3.6.2, which examine the how and why of teachers' model use (RQ1), thereby constituting baseline findings for informing RQ2 (the subsequent professional development intervention). First and foremost, these 2 sections with their sub-sections are:

3.6.1 Teachers varied uses of models:

(i) as 'products' of science to be learnt (often presented in curricula as part of content knowledge to be acquired, e.g. model of the atom etc.)

(ii) as 'tools' to learn science in a process-based approach

3.6.2 Purpose of models:

(i) To facilitate conceptual understanding

(ii) To develop the Nature of Science (NOS)

On 3.6.1 Teachers varied uses of models

Teachers' responses on how they use models are analysed according to whether they describe the models in a process-based approach of modelling (as depicted in Anderson's (2003) 'model-based reasoning' model in **Fig. 3**) – as 'tools' of learning science, or as 'products' of science to be learnt (seen as an outcome of the 'model-based reasoning' model in **Fig. 3**). When models are 'products' to be learnt, these are usually embedded within the curricula, e.g. model of the atom etc. Also, as 'products' of science, the modelling process is not always present in science education – which is often more evident in scientist science than school science.

The disparities in teachers varied uses of models are shaped by their views of school science (versus scientist science), which play a fundamental role in influencing teachers' use of models – in a 'product-based' or 'process-based' approach. The difference between school science and scientist science can be illustrated by the "model-based reasoning" model of Anderson (2003) and thus this model was chosen to largely summarize the differences in teachers' use of models in a 'process-based' model approach versus a 'product-based' model approach which emerged from the interview data.

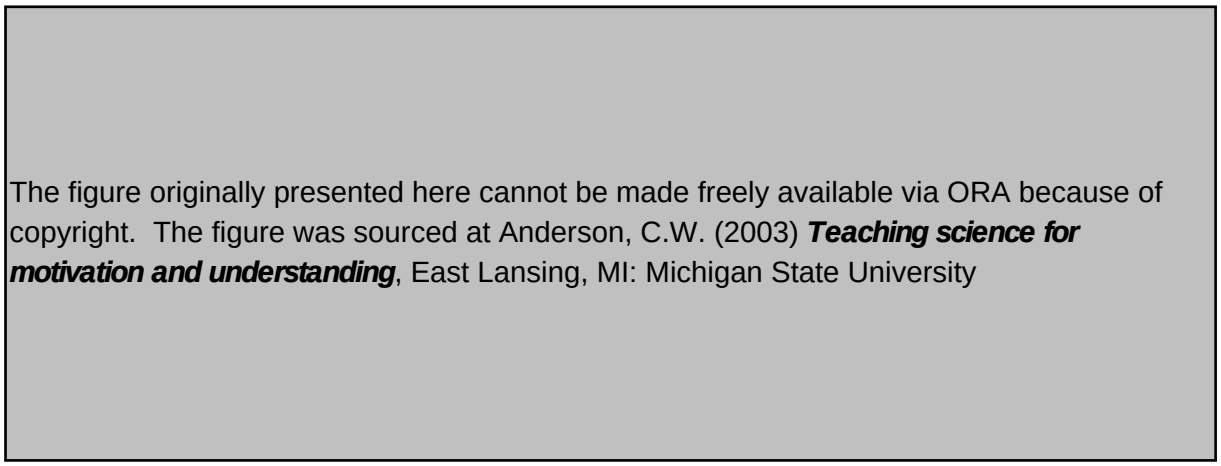


Fig. 3 Model-based reasoning model (Anderson, 2003)

This section relates strongly to RQ1 by recording how teachers use models – relating to the 'how' and 'why' of their model use.

Analyses of the findings show that teachers either use models as 'products' of science or in a 'process-based' approach, depending on their purposes. If they use models as (i) 'products' of science to be learnt, they will mainly facilitate conceptual understanding. However, if they use models in a process-based approach in (ii) as 'tools' to learn science in a process-based approach, there is a higher likelihood that they will go on to facilitate understanding of the NOS.

(i) *as 'products' of science to be learnt*

The varied ways in which L, H and C use models largely as 'products' of science to be learnt will be discussed and contrasted here. Analysis of the data showed that teachers had many ways of using models in the classroom (the 'how'). This includes L using models as visible representations of mental ideas, fundamentally as abstract 'products' of science to be learnt. She defined that models are used as representations to enhance understanding of an occurrence, which involves some change or process that had taken place – whether initiated by human beings or the natural world, e.g. moving leaves or a cooked meal. The process is usually more invisible, and the result is more visible. Therefore, models can be used to simulate this process or more commonly show the visible result. Consequently, L demonstrates that models can be used as visible representations of mental ideas. L also cited other examples of models including molecular model sets that make the visualization of shapes of molecules concrete; unfortunately, she articulated that many teachers have stopped using them, so students end up not being able to visualize molecules such as methane, propane etc. In this case, L would like other teachers to use models as visible representations.

Analysis of the data also showed that the teachers had different ways of using models in the classroom (the 'how'). The first way identified by teachers in using models was to use them as approximates. For example, H cited that models are useful to approximate 3D structures for visualization, demonstrating the 3D nature of physiological structures in biology, such as the model of the eye, or the cross section of a leaf. On this point, L elaborated further that models are being built to illustrate a change in diagrammatic representation from one form to another – this is essential to help students attain a 3D model. When asked if pictures can be given, L expressed her vehement opposition, "No! Those are 2D! Must give them 3D representations, must! (in a high-pitched emphatic voice)".

Apart from approximating 3D structures (addressing the 'how' of using models in class) – more common in chemistry and biology due to the nature of the subjects, C articulated that models can be used to approximate science phenomena too. In response to "why does physics employ models?", C explained that it is due to the nature of the subject, trying to use models to explain complicated phenomena using idealized situations. The largest difference in physics, in C's opinion, would be the importance of deriving a simple model, through approximation, to "get into the laws of nature". For example, he cited the example of understanding motion, to examine a lift falling to the ground. The lift needs to be represented as an object, as it is more complicated in real-life – the object doesn't just fall, but spins and floats around, so setting a frame is paramount. Thenceforth, to understand a phenomenon, it should be simplified to get to the real concept - analogous to how scientists derive a law from observations of complex phenomenon. It is crucial to examine an ideal situation and use it to examine the real world, otherwise, "you are not getting into the laws of nature"; according to C, this is the aim of approximation with simplification, to predict for other situations. Literature lent credence to this view, as Bortolotti (2008) stated that "such a hypothesis would refer to an abstract and often suitably simplified replica of reality (an environment in which some variables would be better controlled) that could serve as an idealized model in which to observe the basic relations between, say, the velocity of a body falling and the (amount of) force impressed upon that object" (p. 57). Furthermore, Suckling (1978) articulated that modelling consists in constructing alternative, usually simpler forms of objects or concepts, in the expectation that the study of the model will shed light on the nature of those objects or concepts" (p. 5). Both C and L seemed to have described 'product' models more to facilitate conceptual understanding of science phenomena as replicas of reality.

C summarized that models can be used in two different ways:

1) Physical model – used to provide students with some visual understanding

2) Process model (e.g. Simulation) – used to model certain processes in science over time, illustrating and predicting what will happen

Having looked at how models are used in class, this section also explicitly addresses RQ2 - "How do teachers perceive they can better promote the effective use of models" - by first looking at the limitations teachers perceived of 'product-based' models in the representational form. It then goes on to report on how teachers overcame these limitations – informed by baseline findings of cycle 1. In recognising teachers' current baseline practice, this will inform the intervention in cycle 2 aimed at addressing the effective use of models in RQ2.

Limitations of product-based models

Analyses of the interviews showed that teachers articulated several limitations in their use of models. This is related to models being used as 'approximates' as previously discussed, which results in various limitations as they do not fully represent the phenomena. Firstly, accordingly to L, models are only useful for certain examples. For example, in chemistry, models are useful for single ions, and not for more complicated ions, e.g. sulphate. For biology, H argued that concrete models as the representational mode lack the labels and the functions, exemplifying mainly anatomical structures rather than their physiology. Physical models can be imperfect too as they are static and do not illustrate processes (occurrence) well.

How teachers perceived they overcome the limitations

Having identified key limitations of models, the following describes how teachers deal with these issues in their teaching. Teachers had many strategies they perceived they used to overcome the limitation that they expressed about the use of models.

Firstly, to overcome the limitations of models used, H will tell students that e.g. the model of the atom is not static (as electrons move), and highlight that protons and neutrons do exist in the nucleus (although the nucleus shows up simply as a sphere in the model). H will even tell student that the dots and crosses in diagrammatic representations do not exist. They are just

representations to distinguish electrons (from different atoms). Finally, he will highlight that there is no actual electron path too. What H is doing is essentially recognizing what literature stated about pupils lacking awareness of the boundary between the model and the reality the model is representing (France, 2000), and he is enacting what Clement (2000) referred to as "epistemically guided lessons on how to construct and interpret analogical models" (p. 1047). Regarding how H acquired this knowledge, he attributed it to watching videos as part of his own professional development.

H summarized that "ultimately, the selection of a model depends on what you want to elucidate" and every representation has its basic pros and cons. This is analogous to Erdogan & Duschl (2004) articulation of models being limited by their 'properties'. According to H, he often considers how the model compares to the textbook explanation and this constitutes a key question for him on whether he should use the model. Currently, good models are not easy to find (to show all aspects of what students are to learn). This point is also picked up as a question incorporated into teachers' questionnaire in cycle 2, as it is a question worth pondering about when using models in class.

Secondly, C articulated that at times, the limitation of a model is its use, i.e. a model may not be sufficient to illustrate certain concepts, e.g. a current model may be insufficient to explain the concept of potential difference (p.d). C stated that there are series of activities designed to reach a stage, when you realise that your model is not very useful anymore. At times, using the current model is sufficient to explain phenomenon, however, at other times, students need the concept of potential difference. Though the concept of current can explain many circuits, however, once current (as a model) cannot be used to explain circuits, then something else should be used to circumvent this limitation. This leads us to the next section, the use of models in a 'process'-based approach way to address this issue.

(ii) as 'tools' to learn science in a process-based approach

Models used in a 'process-based' approach often involve the use of several 'product' models (the 'how' of model use), in terms of model revision or comparing models, as well as adopting model-based reasoning as a way of thinking. These include focusing on using models as a thinking tool, to achieve model-based reasoning in science. This addresses the purpose of using models (the 'why') in RQ1.

Firstly, in support of this 'process-based' view, C elaborated that a model is a way of thinking, and should rightfully be used to achieve such purposes, e.g. acceleration as a model is a way of thinking through graphical representations and/or formulae. C agreed with H and L that science is to explain a physical phenomenon to understand the physical world. But from his perspective, science models often involve conceptual thinking which could hardly be separated from their representational forms such as graphs and mathematical formulae – that illustrate science concepts.

Furthermore, L agreed with H that Science is a rigorous subject that relies on precision, strong observations and logical thinking, and this reinforces the need to use models as 'thinking tools' in science (addressing the 'why'). L articulated that many students struggle with learning science, as they do not possess a meticulous and precise nature required to handle science. C supported this view in stating that school science is abstract, and may not be aligned to students' experiences, therefore this makes grasping science concepts difficult. In addition, C acknowledged that science models are not intuitive by nature – and are derived through an experimental process of many years. It is thus difficult for a young learner to formulate science models themselves, therefore, C articulated that it is vital that models are also used as 'thinking tools' of learning science and demonstrated as a way of thinking, to help learners overcome the difficulties inherent in the subject.

In sum, teachers largely use models to facilitate conceptual understanding – which taps on models as 'products' more than as 'thinking tools' used in a 'process-based' way, the latter would be useful for promoting understanding of the NOS. This leads on to the next section (the 'why') of model use – purpose of models.

On 3.6.2 Purpose of models

This section explicitly addresses RQ1, the why of using models. This section elaborates on the two emergent categories of the purpose of models found from the interviews. Comparatively, models were largely used to develop conceptual understanding by the teachers rather than to develop understanding of the NOS. This reveals a gap and hence paves the way for investigating into how teachers perceive they could promote the effective use of models - beyond conceptual understanding, and for facilitating understanding of the NOS in the intervention phase (to address RQ2).

(i) To facilitate conceptual understanding

Analysis of the data showed that the three teachers described a main purpose for the use of models in science teaching, i.e. to facilitate conceptual understanding.

In C's discipline of physics, C identifies that models are largely conceptual. He explained that models illustrate concepts in science and he uses them to facilitate conceptual understanding in science (the 'why'), and even to the extent of addressing the NOS.

> So, I think it is just how you want to present it, of course you can present it like, the concept acceleration is a model, for you to be able to explain the physical phenomena. But very often, we present it like graphs, formulas, and some understanding of knowing when you have acceleration etc.

He added too that for physics, models are often abstract and seldom concrete, unlike the concrete examples of molecular models which L cited in chemistry.

Analogues are another type of model used to facilitate conceptual understanding (the why). C exemplified the difference between analogue and other models through an example. He explained this at length:

> Analogies are not really models. Analogies are useful to relate ideas into something more familiar to the student. But they do not fully describe the model that we want students to learn.

He went on to elaborate that the analogy for electricity – and/or electric circuit, could involve using water and a pump. But he highlighted that analogues do not represent the full conceptual model that students should acquire. He further cited another analogy of the solar system for the model of an atom, which is used to facilitate conceptual understanding of the model of an atom (the why). This analogy of the sun and planets is used to explain the model of an atom. But the ideal model of the atom is different - a small nucleus with electrons going around. Literature concurs with what C said, as Bortolotti (2008) stated that using the solar system as an analogy does not provide an accurate description of the nature of the atom, as "the relation between the nucleus of the atom and the orbiting of electrons is dissimilar from the relation between the sun and the orbiting of the planets" (p. 57). He further summarized that the planetary orbits and gravitational forces are dissimilar to the electron orbits and nuclear forces within the atom too. This gives credence to what C articulated. On the other hand, L and H were not able to articulate the differences between analogies and models.

Further to this, empirical evidence here seems to support what literature articulates about a feature indicative of expert model use – the ability to compare and critique analogues and models. This

relates to teachers using models in many ways (the how), including how they use analogies. Coll et al. (2005) argued that exemplary teachers share this strategy of using analogies with scientists in expressing complex ideas. C is an exemplary teacher in this respect. Nonetheless, C's view is contentious, as though models may be conceptually more 'complete' than analogues, they have their limitations too in explicating the many facets of a science concept, and are not as conceptually sound as C described them, having their limitations of focusing on attributes of representation (Boulter and Buckley,2000).

(ii) To develop the Nature of Science (NOS)

According to C, one of the purposes of using models (the why) in teaching in school is to facilitate the understanding of the NOS and the use of models in science. The purpose of modelling as a process skill leads to the understanding of the Nature of Science (NOS), when students understand how science is done. Therefore, to advocate students' understanding of NOS, models should be used in a process-based approach. However, H and L do not think this way, and this reveals a gap in the use of models to develop the understanding of the NOS, which should thus be tapped upon in the intervention in Cycle 2.

C further added that he is uncertain if it is advisable to infuse NOS into content - where students learn at face value; according to him, this has implications on the modelling ('process-based' models approach) used to bring out the NOS. "Not too sure if curriculum is the main thing you would change…more of getting teachers to accept that the modelling approach is very important…the process of getting students to understand the NOS." C also reiterated that NOS is not something that you pick up after one lesson, but the learner must be given chances and opportunities to go through such processes.

He also cited examples of models (as 'products' of science) but still used in a process-based manner to bring out NOS:

> Nuclear model (standard model), which is still changing and so it is a good example, like the model of the atom; certain models are the best representation at a certain time, e.g. the electric circuit model.

However, all these had to be taken in the light of C being a curriculum planner before, thus his enlightened' viewpoints are not shared by the clear majority, thus the gap in the facilitation of NOS still stands.

He further added that the investigation process can bring out the NOS when he said:

> you allow a student to do investigation and you give guiding questions to allow them to realise that certain things they can infer for themselves...that they can formulate representations. This is not content-centric, but it is a process, an approach that the teacher can learn and use. Depending on how much they believe – as teachers are very practical, it is vital to focus is on what the student needs to know.

In sum, he is of the view that modelling is a process approach to facilitate NOS - which shows that he subscribes to the approach stated by Anderson (2003), but should not be hardcoded into the curriculum as content – and he is not in support of assessing NOS. This shows that models used as tools of science in a process-based approach could possibly help to facilitate the development of NOS.

As aforementioned, C has had extensive training in curriculum development and is currently a master teacher at the academy of Singapore teachers, hence he has more knowledge in NOS than most of the teaching fraternity. From my professional experience of working with teachers in schools, H's view of models being rarely used for facilitating inquiry into the NOS in actual classrooms is pervasive. His view is that teachers' main purpose of using models is not to facilitate inquiry into the NOS, but mainly to prevent misconceptions in conceptual understanding. This contrasts with C's view and is representative of most teachers' views in this context and thus gives credence to C's view of models being uncommon – to facilitate the NOS.

4. Key teacher findings (referencing the Analytical procedures in 3.6)

4.1 First finding – Importance of using models in a 'process-based' approach

Teachers use models as 'products' more than in a 'process-based' approach. Why is this an issue? Models, as 'tools' of science, can be used to achieve larger aims of science education apart from content mastery – often achieved by using models as 'products' of science - in a process-based approach, through investigation, model-based reasoning skills and a critiquing mindset.

The key difference between school science versus science in society would involve investigation – a way of using models in a 'process-based' approach, which is more evident in science in society. Wherever possible, students should be given opportunities to investigate phenomena beyond school science, as students can engage with the phenomenon and 'discover' science – verifying the models of reality. Bortolotti (2008) gives credence to this, "the relation between the statements of a theory and the world of experience is no longer hostage to the identification of correspondence rules, but relies on the scientists' creation of abstract *replicas* or *models* of reality that fit the provided theoretical definitions" (p. 56). Consequently, this way of doing science is more closely linked to the process-based approach under using models as 'tools of science'. On the contrary, for school science, theory is often taught first in such contexts, with some or no leeway for investigation provided to students.

Also, students can acquire the model-based reasoning skills from the use of models in a process-based approach. Clement (2000) stated that the central goal of science education was to promote model-based reasoning in students. This entails understanding that models are primarily a representation of ideas about phenomena and can be rejected. He stated that "students should understand that models are primarily a representation of ideas about phenomena and can be

rejected, replaced, or modified to fit new (empirical) data. Through this process of model revision, the critiquing process is brought forth. The focus of model-based reasoning skills is thus on the critiquing mindset. Consequently, we could argue that another aim of science education is for students to possess model-based reasoning skills that encourages a critiquing mindset. In bringing forth the critiquing mindset, the key is for students to reason their way through model revision rather than learn models merely as 'products' of science.

To summarize, from my professional judgement, the critiquing skill has the potential to transcend both school science and science in society. C lent his support to this in articulating that if the focus is on experimentation (evident in both school science and science in society), this allows for students' critique and teachers will emphasize the use of models in a process-based approach. However, there is a contrasting viewpoint to this. Even within experimentation, students may critique or not, depending on the teacher's facilitation. For instance, sources of error in experiments may become 'standard' answers for students to cite, which is an existent problem, so how can we tackle this? C replied that certain errors for the experiment are more valid, but when teachers 'short-cut' by stipulating standard answers for errors within students' experimentation, this may not be aligned to students' actual errors. Though it is not easy for students to identify errors in experimentation, as they need to understand the whole experimental set-up very well to do this, nevertheless, teachers need to enhance the critiquing mindset of students, by emphasizing that models are primarily a representation of ideas about phenomena and can be rejected, replaced, or modified to fit new (empirical) data (Clement, 2000) obtained from experimentation. H and L have not much to contribute in this respect, presumably since they do not teach physics and this problem of 'errors' within experimentation is not so pronounced within biology and chemistry.

Hence, together with investigation, critiquing and model-based reasoning skills should be promoted more through using models in a process-based approach, and findings related to the portrayal of this

skill in cycle 1 (based on C's articulation of experimentation) should be shared with teacher respondents in cycle 2. In advocating this approach of models in a process-based approach, we need to recognize the merits of the contrasting approach too - using models as 'products' of science. The approach of using models as 'products' of science often abides by the age-appropriateness principle, as H pointed out that "standard/latest models or 'products' of science in society (used by industry or research) were not learnt in school due to the 'sufficiency' principle – thus school curriculum has 'curated' the relevant 'product' models that students should learn in school science. Therefore, H reiterated that students are not required to learn the most current model but only needed to comprehend concepts to a 'sufficient' level. Hence, in advocating the process-based approach of using models, it is imperative to consider issues of age-appropriateness too. This will be discussed subsequently through age-appropriateness issues within the NOS, which incidentally is one of the reasons why the process-based approach should be used.

Due to age-appropriateness issues, it is not possible to use the latest models in science in society. However, it is possible to incorporate more investigation and model revision – bringing forth the critiquing mindset, both of which include the use of models in a process-based approach - as a 'tool' of science to facilitate larger aims of science education rather than mere content mastery. Consequently, efforts should be made to encourage the use of models in a process-based approach. Moreover, Prins et al. (2011) argued that students should become "acquainted with advanced model features, like reliability and validity, and with different modelling approaches and procedures" (p. 3). Hence, though age-appropriateness issues are important, they should be balanced with the use of models in a process-based approach.

4.2 Second finding – NOS and the epistemic aspect of science

Referring to NOS and the epistemic aspect of seeing how science unfolds, H summed up that "we are not there yet". It is important to note that H uses models to show students (what has already

been discovered/represented) to facilitate understanding, and not for the aim of allowing students to discover further – to embark on a discovery process. This is a prevalent practice in this context.

Different understandings among teachers on the purpose of using models exist (the why), including for facilitating the Nature of Science (NOS). Even in the use of models as 'products of science', C demonstrates a different understanding of models from the other teacher interviewees, in being more aware of NOS and how these models can be used to develop process-based skills in science. This could likely be attributed to C's privileged yet uncommon experience of working in various posts at the curriculum planning unit and at different schools, with his last post in school as Vice-Principal (V.P). However, in the other teacher respondents, they did not display understanding of using models for model revision and for facilitating students' NOS. This leads to our finding on the need to use models more for developing the NOS.

H and L both use models mainly to facilitate conceptual understanding. Though C viewed models as integral to the understanding of the NOS, and fundamentally a way of thinking about science, he conceded that this is subject to the view of teachers. According to C, understanding the NOS involves getting students to go through a process of doing science, such as model-making, and is not simply replicating what the scientist would do. He recognized age-appropriateness for NOS too, as he articulated that "neither is it about students coming up with a special project at the university level." In sum, models are often used for developing conceptual understanding rather than the NOS, from the examples cited by the teacher interviewees. However, C's view of using models to facilitate NOS in an age-appropriate way should be further propagated among the teacher respondents in cycle 2.

4.3 Final conundrum (Implications for teachers - demands for curriculum time)

As I discussed the aims of science education, I examined the importance of 'product' knowledge in science and concluded that it is important to achieve a balance between knowledge of the nature of science (NOS) and science content knowledge – this is analogous to achieving a balance between 'process' vs. 'product' knowledge respectively. There are indeed potential implications for the curriculum. When interviewee H was asked for his opinion on removing some content knowledge to ensure that there is sufficient time for the development of such process skills, he has this to say:

H conceded that this aim is not important enough to him, for two reasons: Firstly, the NOS should not be hardcoded into the curriculum. To H, getting a good understanding of content is of a higher importance, so that "at higher levels, students are able to criticise and analyse more".

In response to this, I challenged his perspective, that if critiquing and analysing knowledge does not start at lower levels (using models in a process-based approach), thinking becomes habitual and it will be hard to infuse this critiquing mindset at the higher levels. In his reply, he stated that realistically speaking, not everyone grows up to be a scientist. The job of a teacher is just to inculcate scientific literacy, for students to appreciate the relevance of science and how it makes life better. He replied:

> Leave the complicated details and competing theories to those who want to specialise in it. Bear in mind that not every student ends up there, so to preserve the beauty of the subject, let us not 'pigeonhole' them in difficult theories when they are too young. For instance, Lower Secondary Science (LSS) breaking up into the 3 sciences is a bad trend for acquiring in-depth disciplinary knowledge. Better to enthuse them to retain their interest at the lower levels, so we won't end up having no scientists.

So herein lies the conundrum for competing demands on time – which way should we go? A deeper underlying philosophical belief undergirds his opinion, that interest can be translated into in-depth concept learning, only at higher levels. On this note, it seems that at different levels, the amount of NOS should vary in the curriculum. This will be further discussed in 6.3 as part of the questionnaire findings under “Students at different levels of learning (age-appropriateness) could be a factor in the use of models”.

5.0 Intervention – Teacher questionnaires (cycle 2)

Having reported on the findings from the interviews with teachers, this section discusses the intervention designed to address the issues raised by the interviews. The intervention takes the form of a questionnaire, and has the following two focus areas:

Focus areas of the questionnaires

Questionnaires were devised that help teachers to:

i) Reflect on the use of models in their own teaching practice

ii)Consider their contexts and evaluate the appropriateness of the use of models in those situations, and to state explicitly, what changes (if any) they will make to their current use of models, and why.

The questionnaire as the cycle 2 intervention builds on the action research carried out in cycle 1 - what teachers currently thought about models based on RQ1. The questionnaire acts as a form of professional development intervention, with the focus areas designed to help teachers perceive how they can better promote the effective use of models (RQ2). The implications of this research are that with knowledge of this perception (as a first step), teachers will be better informed of how to develop their use of models in their practice – including promoting the use of NOS in their own classrooms.

5.1 Action strategies developed from cycle 1 to inform intervention in cycle 2

Two forms of action decided upon from cycle 1 (reflected in **Table 2**) were the result of two action strategies developed to inform the cycle 2 intervention questionnaire, as follows:

1) To highlight models as key 'tools' of learning science rather than as 'products' of science to be learnt. This includes making models explicit, and using models to bring out the process of doing science.

2) To focus on using models to develop students' NOS.
   This involves model revision. Justi & Gilbert's (2002) figure of "A 'Model of Modelling' Framework" (p. 371) is referenced when teachers are directed to think about model revision in the questionnaires (Appendix C). This provides teachers with some conception of what modelling meant here.

A dialogic relationship can exist between these two action strategies, e.g. perceptions of making models explicit to aid the development of NOS. Consequently, the intervention designed in the form of a questionnaire will incorporate these action strategies as action points (**Table 2**), to help teachers reflect on their current practice, specifically to address RQ2: how they perceive they can better promote the effective use of models – including developing students' NOS.

The next sections justify why these two action strategies were particularly chosen given the evidence from the interviews combined with my own professional experience of the context of science teaching, to inform the intervention in cycle 2.

Significance of Action strategy 1

From my professional practice and experience, there exists a phenomenon of high school teachers blaming secondary school teachers for 'teaching students wrongly' due to simpler models being presented to students at the lower levels. In my professional judgement, some students may not be aware that the prior knowledge they have acquired are *models* and are thus tentative and subject to change when new scientific evidence arises; consequently, teachers and students likewise cannot build upon their knowledge – when exposed to more sophisticated models. Hence, it is very critical to develop teachers' practice in making models explicit to students in their science teaching.

Literature agrees with this through understanding the nature of models explicitly, according to the NRC (2012) on the articulation of the NOS, where model epistemic knowledge is knowledge of the constructs and values that are intrinsic to science. Students need to understand what is meant, for example, by an observation, a hypothesis, an inference, a model, a theory, or a claim and be able to distinguish among them" (NRC, 2012, p. 79). Teacher L also agreed that making models explicit to students is a key part of science teaching and learning. For L, she gave the example that Bohr's model of the atom in secondary school is still relevant, and this should be made explicit to students, even as they learn the quantum mechanical model build-up at higher levels. For the example at lower levels, the electron is modelled as a ping pong ball, whilst the electron as a particle or a wave is introduced at high school - A level. Furthermore, L also had a more complex view about the nature of models and was aware there may be contradictions between simpler and more sophisticated models and that some models are more difficult to visualize, e.g. the Heisenberg uncertainty principle. She recounted, "your mind has to embrace this, instead of having a mindset that pinpoints to this, or that". L shared that this view was not prevalent among teachers teaching higher levels as they not have grasped relevant Pedagogical Content Knowledge (PCK) on the nature of models,

hence highlighting again the importance of our action strategy 1 in making the nature of models explicit in science teaching.

In relation to the point about making models explicit, I also thought about whether teachers are aware of which science content within the curricula are models in nature, which constitute models, laws and theories. This resulted in the question of whether teachers have explicit knowledge of models, in distinguishing them from theories and laws within the syllabuses. It seems that teachers have some understanding of this, though not a concrete knowledge-base of such to make this explicit to students. This relates to the point about the confidence of teachers in the use of models under 5.2 too. According to C, a theory requires models to explicate it. KTM (Kinetic Theory of Matter) requires the model that matter is made up of particles – the kinetic theory builds on this model. So, the natural question that arises would be: do teachers make a distinction between models and theories? In textbooks, L doesn't see much of this. She cited that some vital theory of scientific knowledge was removed without scrutiny. C was uncertain if teachers are aware of models in the curriculum, but thinks that whether a teacher uses models is dependent on his beliefs of models. According to him, it is a matter of reaching a certain level of understanding, and whether they bring it up hinges on the importance they attach to models. This will be further discussed in 5.2, under teachers' professional development needs.

On this note, H raised an interesting point that there are hindrances to making the ideas in models vs. theories vs. hypotheses explicit. He articulated that time and fear of confusing students are the main hindrances. The latter was indeed enlightening to me. He explained that teachers strive to teach students one way (draw dots or crosses) to prevent added confusion - when 'real knowledge' is introduced. H reinforced his earlier point about curricular content not being the best approximation to the truth, but rather, the easiest to understand. For instance, in the 'lock-and-key' hypothesis for the enzyme, he cited that recent studies showed that it is the induced-fit model that

is true rather than the 'lock-and-key' model - which is what is present in the curriculum. To conclude, he added that considering this, when teachers teach, they may forget to highlight that this is just a hypothesis and not make the distinction between hypotheses and theories explicit. However, H raised a further question: if students were told the whole truth, will they be more confused or more interested? In sum, H is afraid of introducing more 'truth' than is required and bears in mind age-appropriateness principle, for fear of confusing students.

Nonetheless, I beg to differ on this view, though I recognise his concerns. I find that he is confusing making knowledge of models explicit to achieve the larger purpose of highlighting the different certainties in scientific knowledge – which could enhance students' NOS understanding in seeing the tentativeness of scientific knowledge, with merely teaching students age-appropriate models. This is a complex issue, and justifies that teachers need more professional development in the aspect of making knowledge of models explicit as highlighted under strategy 1. Otherwise they view these as confusing students with what they should know within curricula rather than see the larger purpose of achieving NOS through this.

Moreover, H also had an alternative view about the role of models and of making models more explicit. For teacher H, it was not so important for students to have knowledge of models, his emphasis was on students having a better understanding of content. In my professional experience, I have two reasons to disagree with this narrow view. Firstly, teacher H may not have the 'bigger picture' of what teachers at the higher levels are saying due to his limited exposure to them – being situated in a working environment within only the secondary school – whereas for me I am at the curriculum planning unit and have a larger perspective on the views of the teachers. Secondly, the school he is situated in has placed high stakes on assessment and hence, his view may be skewed by this perspective to discount the importance of models.

In sum, teachers need to make models and their nature explicit so that when students proceed higher up the education ladder, they will not think that there exists a contradiction and be unable to build upon their past acquired knowledge. H's view justifies that there is a need to work on strategy 1 to promote the alternative viewpoint of L.

Significance of Action strategy 2

Data from the interviews suggested that some teachers had the view that models could be used to develop their students' understandings of the NOS. However, this depended on the teachers' concern about the NOS, which varied greatly among teachers. C emphasized that using models greatly depended on the context and the teachers for the lesson.

For example, C stated that 'If the teacher is concerned about NOS, then he will bring in the model…". On the contrary, H suggested that models at the lower levels should inculcate scientific literacy and enthuse students, and according to him, "complicated details and competing theories [such as those involved in NOS]" should only be taught at the higher levels. The differing emphases of models at different levels of science education can therefore result in differing views of using models to develop students' NOS, and so this should be borne in mind while developing teachers' practice in cycle 2, and 6.3 will reveal how teachers during PD perceive this.

In summary, L and C have acknowledged the usefulness of models in developing students' NOS but articulated the inconsistent use of models in class. L had reiterated that the use of models to develop students' NOS understandings largely depended on the teacher. Hence, how models (especially how models can be revised and developed) can be used to develop NOS should be discussed further with teachers, including helping them to perceive how they might develop their practice in this area to result in confident and consistent use of models in this aspect. Clement

(2000) also stated that model revisions generate new questions that generate a cycle of criticism and improvement essential for enhancing understanding of the NOS. As the gap in these two areas have been discussed and identified, they will be used to inform the subsequent intervention in cycle 2 and addressed through the devised teacher questionnaire.

5.2 Professional development (PD) intervention - What needs do teachers have in the use of models?

As cycle 2 is an intervention that facilitates the professional development of teachers in the use of models, hence, it is vital to consider their needs in this respect. Also, teachers' beliefs in modelling should be explored to develop a teacher education course or professional development that supports their thinking and teaching about the nature of science (Sorensen et al., 2012). This section also presents some of the ideas teachers themselves had about what professional development needs they had in this area and how the professional development could be carried out. All the teacher interviewees had varied views on the bridging required for teachers to use models effectively.

Firstly, C cited that teachers must themselves find relevance in bringing in inquiry and NOS using models, then they will adopt the use of models in a process-based approach to facilitate students' NOS, before they will expand on their current use of models. Currently, from my professional experience, this relevance to bring in inquiry and the NOS may not be strong, and he seems to be addressing this.

Secondly, there is an assessment-driven mindset which is an obstacle to teachers developing their potential in using models fully. L articulated that due to this mindset, teachers do not read beyond the examination syllabuses they are teaching, and H added that it did not help matters when this

importance is also not emphasized in the education system. He gave a suggestion that syllabi can change to suit this, as he substantiated that "ultimately, we are still gearing our students for assessment".

Thirdly, the confidence level of teachers on the use of models is lacking, and according to C, this needs to be boosted. C substantiated that teachers are not scientists, so only through interactions with the faculty will they better understand how science works with scientists. This resonates with what L spoke about earlier, that one should keep abreast of new knowledge in the subject field that one is teaching – reading beyond the examination syllabuses. This helps in keeping oneself updated on the disciplinary knowledge, and builds one's confidence levels in teaching the subject. It also bridges the gap between school science and the latest uncovered scientific knowledge. Growing in professional competency of one's disciplinary knowledge also equips a teacher with the prerequisite knowledge to make the different certainties in scientific knowledge explicit, e.g. hypotheses vs. theories vs. laws – where within parts of the curricula (in school science) these are not made explicit.

In a similar vein, L modelled continual learning by acknowledging that there are new theories, e.g. MO (Molecular Orbital theory) – on top of VSEPR, at the cutting edge of science. She reiterated that it is important that teachers are well-read and keep themselves up-to-date on their subject knowledge, otherwise, this will affect their confidence levels in using models to teach science. She pointed out that there is a limitation on understanding when models are based on 'simpler atoms', using the VSEPR theory. Through her example, she demonstrated how certain models can bridge the latest scientific knowledge with school science knowledge within curricula, and the importance of reading up to improve one's awareness in this sense. I found that her example of role-modelling, in learning the latest Molecular Orbital (MO) theory from tertiary institutions, is the best way to teach by setting an example. Her example of professional development will also be shared with the teacher respondents in cycle 2. Also, this is congruent with L's articulated philosophy of "giving

students the best that he/she can absorb", which is only possible through keeping abreast of the latest knowledge in science – enabled through one's continual quest in professional development (PD).

At this juncture, it would be useful to consider how teachers learn too to ensure that the questionnaire as an intervention tool is effective. After identifying teachers' professional development needs above, it is helpful to look at how the different teachers learn, before looking at how the professional development (in cycle 2) could be carried out. Both teachers, L and H engaged in some form of PD on their own – structured or unstructured. Analogous to L's structured learning to acquire the latest scientific knowledge, H also cited an example of PD, where he learnt through unstructured learning in watching chemistry videos on the nature of models – this was after he graduated from school as his own school teachers were not explicit in making this clear to him. This does show a gap in school teachers' knowledge-base in this respect, and gives credence to the PD questionnaire that we are to embark on in cycle 2, as PD was cited as useful in helping L and H to increase their knowledge and confidence levels, irrespective of which mode they took, whether through structured or unstructured learning.

In terms of how effective professional development in this area can be achieved, all of them agreed that more can be done to enhance teachers' use of models. This professional development of teachers in the use of models can take place through different ways. Firstly, according to L, teachers need to learn more about the latest science models, and this can take place through interactions with tertiary faculty or reading. Secondly, support needs to be provided to teachers. H cited that teachers need a database of models to support them in the use of models. With this database of models, H articulated that the difficulty of using models (perceived as an add-on by many teachers) and requiring more time to teach will be mitigated. Also, in terms of support, H and C concurred that starting with specific topics first to bring in more models and modelling is a useful first step – as

the practical aspect of teaching does not offer them much time, so it is vital that the parts of the syllabus where models are coherent with are made explicit to teachers.

In sum, through professional development to boost teachers' confidence levels and their competence in using models in class, the relevance of using models will be apparent to teachers and students alike. Consequently, the questionnaire takes the form of a **PD intervention** in cycle 2, and is informed by the **2 action strategies** from cycle 1 findings to result in a questionnaire with **two key focus areas**.

6.0 Discussion of Teachers' responses – sharing teacher knowledge

This section presents the findings from the PD questionnaire (cycle 2) to show how teachers reflected on the two action points derived from the interview findings (cycle 1):

(i) Making models explicit; and using models to illustrate the process of doing science

(ii) Model revision (referencing Justi & Gilbert's (2002) "a model of modelling" framework)

Nonetheless, teachers' responses were more complex and often went beyond reflection on these two individual points, but rather, portrayed their consideration of how these points applied to their contexts to result in more complex responses. This indicated that teachers reflected and thought deeply about whether they agreed or disagreed with the interview findings (from cycle 1), to construct responses in cycle 2 (shown below) on how they perceive they may develop their practice in promoting the effective use of models within their own contexts.

Findings of teachers from their questionnaire responses:

6.1 Teachers tend to use models in a process-based approach within the informal curriculum - this includes model revision

The formal curriculum refers to the subjects that are examined in a summative way, whereas the informal curriculum refers to subjects which are not examined in a summative way. For the informal STEM ALP curriculum, it was found that teachers perceived they used a process-based model approach more, whilst within the formal curriculum, models were often illustrated as 'products'. In support of this view, from the questionnaire findings, it was found that teachers from the STEM group tended to do model-making in their lessons – being an applied learning programme which

emphasizes on a hands-on curriculum, whereas the chemistry teachers teaching the formal curriculum considered models within the curriculum as 'products' – when they were asked to deliberate on the use of models. These findings also have implications for teaching about how models can be revised over time in that the STEM informal curriculum currently offers more opportunities for this. Arguably, for the formal science curriculum, there may be room for teaching students how models change and are revised if NOS was brought more into the formal curriculum as well. However, findings from the questionnaire indicate that teachers do not perform modelling as much in formal curriculum based on syllabus and time constraint. For instance, one chemistry teacher delivering the chemistry curriculum substantiated that in view of the syllabus content, teachers could not explore models and modelling as much as they wanted.

The following sections, 6.2 and 6.3 address how teachers perceive they can better promote the use of models (RQ2), through deliberation on student attainment and age-appropriateness issues, and hence this intervention addresses RQ2 effectively. Evidence is cited below as the questionnaire acts both as an intervention and a data collection tool.

6.2 Attainment of students is not a factor in the use of modelling approaches

Some teacher respondents in cycle 2 reported that in learning science through using models in formal curriculum, lower attainment students need more concrete models. The teacher perceived that lower attaining student found it challenging to learn with a 'multi-modal' approach i.e. models presented in various modes, whilst higher attainment students can learn with a 'multi-modal' approach. However, this was challenged by other responses within the group, who stated that a 'multi-modal' approach should be implemented for all students (regardless of ability) to show that there is no 'one way' of solving problems – students should be familiar with multiple representations. There is strong support from literature citing that in using models in science classes, a variety of modalities (e.g. diagrams, text, scale models) allowing students to process information

over multiple cognitive systems (e.g. Visual-spatial, verbal and imagery), should be considered (Gustafson et al. 2010). One teacher respondent agreed that "real world problems are complex and multiple representations should be shown, even for higher ability students". She disagreed, as indicated above, with the view that lower ability students necessarily need more concrete models.

6.3 Students at different levels of learning (age-appropriateness) could be a factor in the use of models

Do students at the lower levels especially need to learn models in a process-based approach - because they have not acquired sufficient content knowledge to appreciate the concept of models in learning them as 'products' of science? This was brought up by a teacher respondent who substantiated that "students have not acquired sufficient depth of content knowledge at the lower levels…hence they need to learn concepts of models and modelling first...". The teacher respondent agreed with H's view that science at the lower levels is to inculcate scientific literacy and enthuse students more than to acquire in-depth conceptual knowledge.

If science inquiry is seen as a 'model', a teacher respondent perceived that she can better promote the use of models, through linking science inquiry (often inherent in the modelling process) to NOS at lower levels of learning to bring across the idea of models and modelling (corroborating the dialogic relationship between action strategies 1 & 2 in 3.4). This supports the idea of age-appropriateness as a factor in the use of models.

To conclude, a fundamental assumption of teachers surfaced through the questionnaire was that they recognised that models and modelling are helpful in portraying how current models in science are derived (through the process of model revision – referencing Appendix C), so teachers perceived that to promote the effective use of models, they could try to bring this idea across to students, explicitly where possible. Most of the teacher respondents, having reflected on the teacher

interviewees' responses in cycle 1, gave responses which were highly contextualized (as shown through 6.1, 6.2 and 6.3), hence fulfilling the focus areas of reflecting and giving thought as to whether they agreed or disagreed with the interview findings, as well as building on these responses to address RQ2 as shown in preceding sections – how they perceive they may develop their practice in the effective use of models within their own contexts. This is aligned to the goals of the questionnaire, which aim to start professionally developing teachers in this area.

7.0 Conclusion and Implications of the research (Summary):

In conclusion, these two research RQs that we started with have been addressed through this study.

RQ1) Why and how are models used in science classrooms?

RQ2) How do teachers perceive they can better promote the effective use of models?

In RQ1, it was revealed that teachers use models in different ways (the how) – mainly as 'products' of science to be learnt or to facilitate the understanding of the process of doing science. Currently, teachers' practice is skewed towards using models as 'products' of science – probably due to the curriculum in this context being content-heavy. However, Clement (2000) stated that model-based reasoning is paramount as a goal in science education; consequently, through a process-based approach, students should understand that models are primarily a representation of ideas about phenomena and can be rejected, replaced, or modified to fit new (empirical) data. Also, according to Harrison and Treagust (2000), teachers should model the scientific modelling process to their students, and encourage the use of multiple models in science lessons, by progressively introducing more sophisticated models, and systematically presenting "in-class models using the focus, action and reflection (FAR) guide - to socially negotiate all model meanings" (p. 2) – as demonstrated in the developed intervention questionnaire (Appendix B).

In RQ1, different purposes were also found out from teachers addressing 'the why' of using models in science. Teachers mainly used models to enhance conceptual understanding of their students, and do not use models to facilitate the Nature of Science (NOS) as much. There are various reasons cited for this. Firstly, teachers may lack the pedagogical content knowledge (PCK) of using models to bring out the nature of models to make them explicit. This often results in a lack of confidence to use models as articulated by teacher interviewees. Secondly, there is a lack of relevance to bring in

models as well, compounded by a content-heavy syllabus and a lack of alignment of assessment with knowledge of the nature of models which could be used to facilitate understanding of the NOS.

Consequently, to address RQ2 in enabling teachers to perceive how they can better promote the effective use of models, a knowledge-base of effective use of models through research findings should be made available to teachers - including developing them professionally, which was achieved in this study through a PD intervention questionnaire that addressed RQ2. Furthermore, the importance of understanding the Nature of Science (NOS) should be highlighted to teachers too, and this will help teachers see the relevance in bringing in knowledge of the nature of models through making models explicit in facilitating understanding of the NOS.

Regarding assessment not entirely aligned to the NOS, therein lies the challenge of showing teachers the relevance of the NOS, especially when its purpose is not for assessment, and assessment drives teacher behaviour in this context. To resolve the other tension of the lack of time to facilitate understanding of the NOS, NOS should also be developed in an age-appropriate manner and brought in where relevant – this was echoed by the teachers within cycle 1 and 2. Taking into consideration teacher respondents' comments of relating NOS to the nature of models at the lower levels, this could be explored more in supporting teachers in this context. At the higher levels, perhaps NOS could be brought out in a process-based approach; C stated that "Depending on the topic...you will mention [a model] is a model again, because you want students to realise that this model is the best explanation you have, but not knowledge that doesn't change…so this idea should be revisited again, and is a process that students will pick up...". At the lower levels, teacher respondents in cycle 2 suggested that NOS could be brought out through the teaching of the nature of models explicitly. Also, H suggested that tapping on a knowledge-base of making models explicit will help teachers, as they do not have to spend more time deliberating on the Pedagogical Content Knowledge (PCK) of this when their main constraint is time. NRC (2012) agreed that teachers need to understand the

nature of models explicitly, for example, “what is meant by an observation, a hypothesis, an inference, a model, a theory, or a claim and be able to distinguish among them” (p. 79); this can be achieved through a knowledge-base. Also, in the use of models, a ‘multi-modal’ approach should be used, and this requires a multi-faceted approach to viewing a model – “its nature, the types of entities it represents, the use to which it can be put, and its stability over time” (Justi & Gilbert, 2002). Teacher respondents in cycle 2 agreed that this should be the approach to use models, as they refuted that lower attainment students should only be shown concrete models, and advocated a ‘multi-modal’ approach to all students.

The knowledge-base of models should acknowledge too that there is no one-size-fits-all solution to using models – which depends on the context and levels of students – analogous to NOS being developed in an age-appropriate manner. This was portrayed by the variety of models that teacher interviewees cited on their use of models in the classrooms – dependent on their purpose and contexts. In using models in a purposeful and contextual manner, Harrison & Treagust (2000) reminded teachers that the use of models is dependent on need, but overall, models must fulfil a purpose: “They can be concrete, abstract or theoretical depending on the needs of their author and audience, but above all models must enhance investigation, understanding and communication and this makes them key tools in thinking and working scientifically” (p. 1012). This should be emphasized in the use of models.

To conclude, through exploring RQ1 on the ‘why’ and ‘how’ models are used as baseline findings, teachers perceive in RQ2 that they can promote more effective use of models through various ways. Firstly, they could increase their use of models in a process-based approach as currently, models are frequently used as ‘products’ of science. Secondly, using models in a process-based approach will also contribute to enhancing the understanding of the NOS, which teachers agreed should be the purpose of the use of models that should be encouraged – currently lacking in teachers’ practice as

they largely use models to facilitate conceptual understanding. Also, teachers perceived that introducing a knowledge-base of making models explicit will help them to promote the effective use of models despite the current time constraints.

8.0 Future Work for investigation (emergent from this research):

Implications of this research involves re-looking at how models and modelling can be made more explicit in the teaching and learning of science, and through bringing in model-making and model revision into the formal curriculum, students will be able to appreciate the process of doing science and the NOS more. However, some further questions to consider involving the use of models and modelling will be:

8.1 Is what I am advocating (use of models and modelling) more suited for the informal applied STEM curriculum than the formal (examined) science curriculum?

8.2 How do we scaffold the use of models for different levels of students?

8.3 Does the idea of age-appropriateness in NOS still stand? Should it be capitalized on and encouraged more at the lower levels through modelling?

9.0 Plan to share findings (including discussion of problems and collaboration with colleagues)

I will share my findings with my colleagues from the Professional development wing of the teaching fraternity, and with my colleagues at the curriculum planning and development division to possibly inform the future direction of the curricula, in terms of expanding the use of models as a pedagogical approach and exploring a better balance between content and epistemic knowledge in the curricula. In discussion with my colleagues, there exists a possibility of structuring curriculum around models and modelling, especially in bringing out key themes of science and in the pedagogical aspect of designing learning activities around models and model revision.

Currently, some problems which exist includes the curriculum being heavily content-centred and this creates difficulties in encouraging teachers to widely adopt the use of models and modelling within their classroom pedagogies. They also do not see the need for developing the nature of science in classroom practice when assessment is not aligned to this need.

However, there exist further possibilities for collaboration with colleagues, in addition to the collaboration carried out with teacher participants in this study through cycle 1 and cycle 2 - where teachers' practice was also developed through the sharing of research baseline findings from cycle 1. This includes devising lesson plans and learning experiences centred around the use of models and modelling, and as the word 'modelling' suggests, to really model to teachers how models and modelling can be done to not only achieve deep conceptual understanding of science, but to develop a deeper appreciation of the NOS.

Appendix A

A guide to interview questions (informed by literature review):

(Part 1) Perceptions of Models:
What are models to you?

How would you classify models?

What are some considerations you have for using models?

How do scientific models differ from other types of models?

(Part 2) Use of models:
Have you used models in science teaching before? Illustrate with a concrete example, how models have been used in your science teaching

Think of a lesson you used models. How did that model work? To your benefit or not, and why?

Give some examples of different models you have used with your students. Do students influence your choice of models? Why or why not?

How did you set up your models? Were they ready-made (off the shelves) or self-made? Why?

To the best of your knowledge, what do your students think models are?

(Part 3) Evaluations of lessons using models
What were your evaluations of those lessons?

Did you carry out pre-tests/post-tests to gauge the effectiveness of models? Why or why not?

What are the typical ways you would use a model? Are there other instances where you use models apart from these?

Are there other aspects of science teaching that models could play a part in? Why or why not?

Do you perceive any prior- or post- teaching to be done when using models? Why or why not?

Are there any possibility of misconceptions with the use of models? How would you tackle that?

Choose from the following that would best describe when you would use models:

For scientific Explanations
Mitigate abstract science concepts
Make visible one's thinking
Improvise knowledge
For prediction of phenomena
To show causal effects

Is modelling a major part of your school curriculum? Would you consider the use of multiple models?

Appendix B

In Appendix B, two versions of the PD questionnaire were devised - "teachers survey on models – for the formal curriculum (chemistry)" and "teachers survey on models ALP - STEM Applied Learning Programme (ALP) – the informal curriculum", for helping teachers to reflect on their practices on the use of models within the STEM ALP informal curriculum versus the formal curriculum, so that data attained could be further nuanced according to both the informal and formal science curriculum.

Teachers' survey on models – for the formal curriculum (chemistry)

There are no right or wrong answers. Do share with me your views, on models in chemistry. Thank you!

PART ONE – teachers' perceptions of models based on their modelling experiences

How you see the subject:

- Are models and the modelling process inherent in Chemistry to you? Are there perfect models in chemistry?
- How do you see models vs. theories vs. hypotheses?
- What are some of the main curricular models in your teaching subject?
- Do you see higher level concepts as illustrative of more abstract models? – to make model revision clear for building up of knowledge
- Are models in the curriculum representative of the best explanations there are, or are they representing 'fixed' scientific knowledge that are unlikely to change?

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Your learning style:

- How do you know that you have fully grasped a concept?
- What interests you in chemistry? How do you further your knowledge on this aspect?

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How you see science education:

- Should science education be focussed on representations or real knowledge of phenomena (e.g. dot and cross diagram, path of an electron)?
- Is there a good balance in the curriculum on this?
- Do you make distinctions in your teaching between models vs. theories? How do you think these are linked?

- Is learning science more of learning ‘discovered knowledge’, or exploring the process of ‘discovery’? Are there examples in the history of science that can bring out this way of thinking more, in understanding the nature of scientific knowledge?

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PART TWO – some professional development ideas on models and modelling

What do you think the results of these suggested pointers will be, when carrying out model-making/modelling activities with your students?

- Elicit their prior conceptions of the model (feasible/not feasible; would you try, why or why not; any other suggestions?)

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- Get them to use familiar items (concrete) or analogies or manipulatives - depending on their learning styles (feasible/not feasible; would you try, why or why not; any other suggestions?)

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- Get students to present, specifically including differentiating representations from phenomena (feasible/not feasible; would you try, why or why not; any other suggestions?)

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- Critique - get students to do this, especially to think of limitations of their models (feasible/not feasible; would you try, why or why not; any other suggestions?)

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- Model revision - tap on the creativity of teachers + focus on changing students’ prior views (feasible/not feasible; would you try, why or why not; any other suggestions?)

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Suggested Scaffolding (guiding) questions for students:

- Why did you choose this representation – what are its pros and cons?
- How is your model better than your textbook explanation? [Is your model sufficient to explain the concept?]

What are your views on these scaffolding questions? (feasible/not feasible; would you try, why or why not; any other suggestions?)

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Teachers' reflection (pre-activity):

- When do I introduce this model-making activity?
- How do I make explicit the entire process of modelling? Are these questions important to you? Why or why not?

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Teachers' reflection (post-activity):

- How do students differ in their way of using models (e.g. in illustrating different aspects of their model to their peers?)
- How can students' models be extrapolated for teachers' use? Are students' models useful for teachers to use for illustration in their future classes?
- Can using students' models, shed light on their conceptions, and bridge the gap between students' alternative conceptions and the conceptions we want them to arrive at?

Have you thought of the questions above? How feasible are these questions for your context?

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Are there others that come to your mind after doing any model-making/modelling activity, and what are they?

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Teachers' survey on models - STEM Applied Learning Programme (ALP) – the informal curriculum

PART ONE – teachers' perceptions of models based on their modelling experiences in STEM ALP

There are no right or wrong answers. Do share with me your views, on the use of models in STEM ALP. Thank you!

How you see the subject:

- Are models and the modelling process (for modelling, refer to the attachment "modelling") inherent in the Science Applied Learning Programme (ALP) to you? Are there perfect models in ALP?
- How do you see models vs. theories vs. Hypotheses? Are they relevant to STEM ALP?
- What are some of the main models that you use in STEM ALP?
- Is conceptual understanding enhanced with more abstract models in STEM ALP?
- Are models used in STEM ALP representative of the **best** explanations out there – of the investigated phenomenon, or are they representing **'fixed' scientific knowledge** that are unlikely to change?

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Your learning style:

- How do you know that you have fully grasped a science concept in STEM ALP?
- What interests you in STEM ALP? How do you further your knowledge in this aspect?

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STEM ALP as part of science education:

- How do you see STEM ALP, in terms of being focussed more on representations (simpler models for understanding), or investigating real knowledge of phenomena (industry use and current research science findings/models)?
- Is there a good balance in the lower secondary science curriculum on this – between representations and real knowledge of phenomena (as defined in the previous question)?
- Do you make distinctions in your STEM ALP lessons between models vs. Theories vs. laws? How do you think these are linked, and is the distinction important to make?
- Is learning science more of learning 'discovered knowledge', or exploring the process of 'discovery' in STEM ALP?
- Does ALP bring out examples (through the history of science or others) that can bring out this way of thinking more, in the understanding of scientific knowledge?

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PART TWO – some professional development ideas on models and modelling in STEM ALP

Some modifications to the current constructing models/modelling activities. What do you think the results of these suggested pointers will be, when carried out in constructing models/modelling activity in STEM ALP for **your** students – for each question, elaborate on the pointers in ():

- Eliciting their prior conceptions of the model they are about to make (feasible/not feasible; would you try, why or why not; any other suggestions?)

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- Get them to use other modes of representations in the making of models/modelling - familiar items (concrete) /analogies /manipulatives – e.g. Acting out depending on their preferred learning styles – cite examples of differentiation for varied student needs (feasible/not feasible; would you try, why or why not; any other suggestions?)

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- Get students to present, specifically including differentiating the representations from the phenomena they are trying to illustrate (feasible/not feasible; would you try, why or why not; any other suggestions?)

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- Critique - get students to do this, especially to discuss limitations of their models – what their models can do and cannot do (feasible/not feasible; would you try, why or why not; any other suggestions?)

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- Attempt Model revision - tap on the creativity of teachers and focus on changing students' prior views (feasible/not feasible; would you try, why or why not; any other suggestions?)

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Suggested Scaffolding (guiding) questions for students:

- Why did you choose this representation – what are its pros and cons?
- How is your model better than any recorded explanation (e.g. In books/manuals etc)? [Is your model sufficient to explain the e.g. Current concept in microprocessor programming?]

What are your views on these scaffolding questions? (feasible/not feasible; would you try, why or why not; any other suggestions?)

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Teachers' reflection (pre-activity):

- When do I introduce this model-making activity in the ALP curriculum? Any prerequisites before introducing modelling?
- Do I introduce modelling before teaching concepts, or after teaching concepts in STEM ALP? In each case, why? What are the pros and cons of each case?

Are these questions important to you? Why or why not?

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Teachers' reflection (post-activity):

- How do students differ in their ways of using model-making (e.g. illustrating different aspects of their model to their peers?)
- Are students' models useful for teachers to use for illustration in their future classes?
- Can using students' models, shed light on students' conceptions (understandings), and bridge the gap between students' alternative (own prior) conceptions and the conceptions we want them to arrive at?

Have you thought of the questions above? How feasible are these questions for your STEM ALP context?

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- Are there others that come to your mind after doing any models building/modelling activity in STEM ALP, and what are they?

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Appendix C

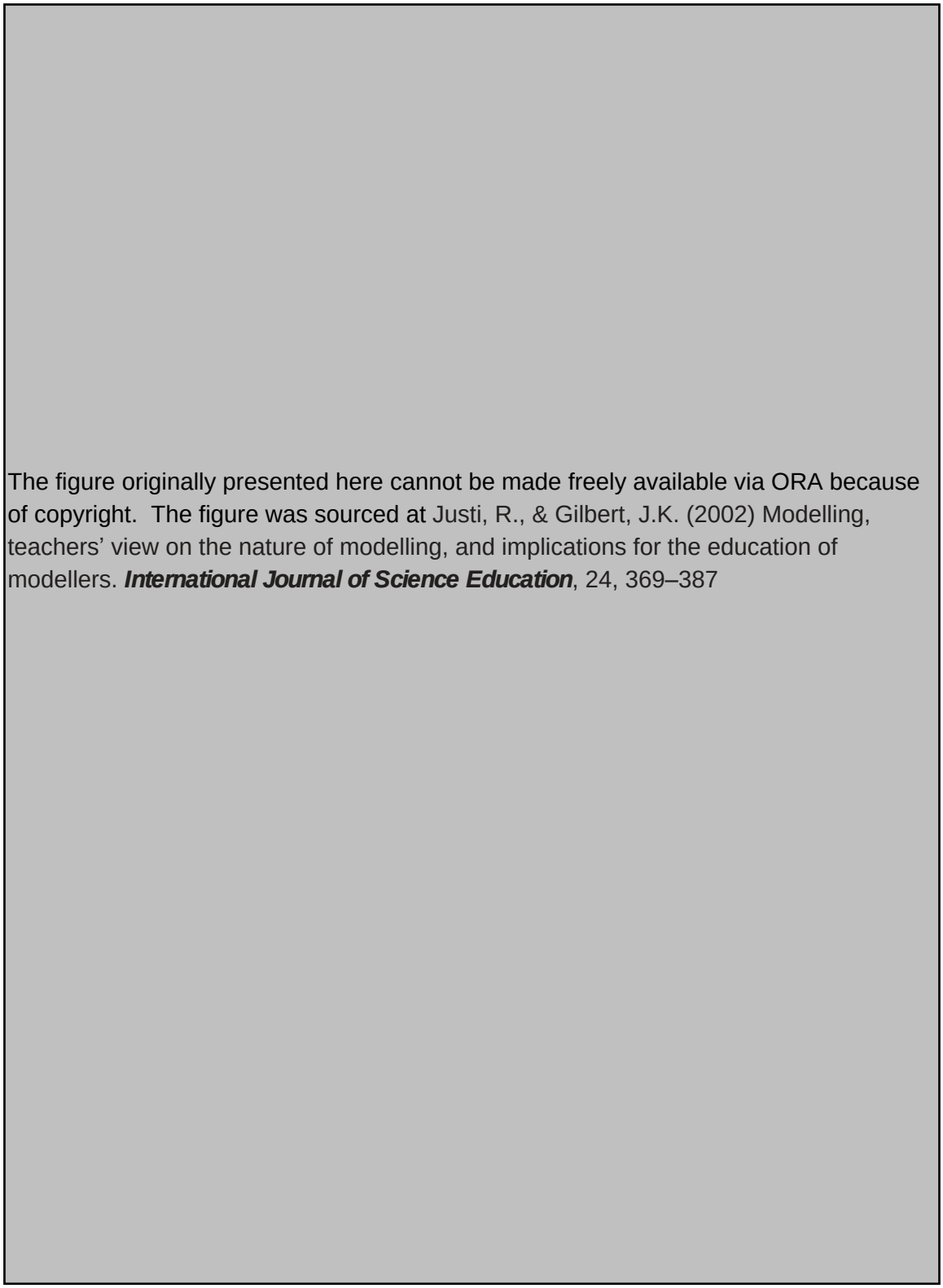


Figure 1. 'Model of Modelling' framework (Justi & Gilbert, 2002, p. 371)

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