Designing, Developing and Evaluating Integrated STEM Activities for Junior Science

Gráinne Walshe[1], Jennifer Johnston[1,2], George McClelland[3]

[1]National Centre for Excellence in Mathematics and Science Teaching and Learning, University of Limerick

[2]St Patrick's College, Thurles

[3]Department of Physics and Energy, University of Limerick

Science and mathematics are closely related in the physical world, yet as school subjects they can be very separate, even where they share overlapping content. Science and mathematics integration has been recommended as a way to increase student conceptual understanding of, interest in, and motivation to learn both subject (Czerniak 2007). Moreover, STEM education (involving the purposeful integration of science, technology, engineering and mathematics) is receiving increasing emphasis in Ireland and elsewhere (Breiner et al. 2012). In this research the STEM focus is the design, development and evaluation of a model that permits teachers to assist students to transfer mathematical knowledge and skills into Junior Science. This resulted in a Critical Integrated Skills and Activities (CISA) Model for developing context-appropriate integrated materials. The model consists of a Syllabus Map of the overlapping content on the Junior Cycle science and mathematics curricula, a Teaching and Learning Sequence for overlapping science and mathematics content and skills, a CISA lesson template for developing integrated lessons, and three exemplar CISA lesson packs. The Syllabus Map and Sequence were evaluated in an earlier stage of the research and one outcome was the need to provide flexibility in the Model so that teachers could adapt it to their local situation and to their students' learning needs. Instead of prescribing the science and mathematics topics that should be integrated, teachers can use the Map, Sequence, lesson template and exemplar lessons to identify critical skills that they may adapt to activities suitable for their science teaching. This paper reports on the design of the CISA exemplar lessons, and of the subsequent evaluation of both the lessons and of the overarching CISA Model, by subject matter experts and by teachers.

INTRODUCTION

STEM (science, technology, engineering and mathematics) education has become an important focus of education policy and research in recent years. STEM education initiatives are generally understood to be concerned with increasing the supply of graduates for STEM careers and educating a citizenry to be more knowledgeable about these disciplines. In a fast-changing increasingly globalized economy, the ability to integrate STEM concepts is a prerequisite for solving the complex and multi-disciplinary problems society faces (Johnson 2013, Roehrig *et al.* 2012). However the conceptualization of STEM education as it would be implemented in teaching and learning is less clear (Roehrig *et al.* 2012). Breiner et al provide a useful conception of STEM education as the 'purposeful integration of the various disciplines as used in solving real-world problems', but there is little shared understanding about the nature of STEM education as an multidisciplinary endeavour (Breiner *et al.* 2012, Roehrig *et al.* 2012).

One of the biggest challenges for primary and second-level education is that few guidelines or models exist for teachers regarding how to teach using STEM integration approaches in their classroom (Roehrig *et al.* 2012). Integration of science and mathematics, for example, has long been recommended as a way to make meaningful connections between these two subjects for students, but models for how to integrate them have been found to vary considerably (Pang and Good 2000, Czerniak 2007). The literature on integrating science and mathematics suggests that how and what is integrated will look different depending on the teacher, the school context, the curriculum and the educational context (Roehrig *et al.* 2012, Stinson *et al.* 2009, Rennie *et al.* 2012). The STEM focus in this research has been into the design, development and evaluation of a model that would permits teachers to assist students to transfer mathematical knowledge and skills into lower-secondary level Science in Ireland. This has focused on finding ways to connect overlapping concepts in the two subjects, but also to take a student-centered approach to teaching and learning in integrated lessons, using inquiry-based learning (Johnson 2013, Judson 2013).

DESIGN AND DEVELOPMENT OF THE CISA MODEL

The CISA (Critical Integrated Skills and Activities) Model for assisting teachers to develop integrated lessons consists of three elements:

1. A Syllabus Map showing how the content of the Junior Mathematics syllabus maps onto the Junior Science syllabus, and an Integrated Science and Mathematics Teaching and Learning Sequence for Junior Cycle
2. A CISA lesson template
3. Three exemplar CISA sets of lessons for Junior Science

In an earlier stage of this research the Syllabus Map and the Integrated Sequence were formatively evaluated by subject matter experts, principals and teachers. The Sequence included the identification, and a brief outline, of six CISA mini-schemes. These were envisaged as short sets of lessons based on the most significant overlapping areas between science and mathematics, as found from the Syllabus Map, but also coordinated with the likely stage of learning of students in both subjects through the Sequence. A common theme in the feedback was that science departments, and, to a lesser extent, mathematics departments, vary considerably in how they sequence topics. Hence it is not possible to define a ‘one-size-fits-all’ set of topics for the CISA lessons that will be identical for every Junior Science classroom. The CISA lesson template was designed and developed, therefore, so that instead of prescribing the science and mathematics topics to be integrated in the CISA, teachers and curriculum designers could use the template, in combination with the Map and Sequence, to identify and design their own lessons. The intention is that the overarching CISA Model for developing integrated lessons offers both robust guidelines, and at the same time is flexible enough to accommodate the varying sequence of topics science teachers follow.

Post-primary teachers do not often get the opportunity to experience integration, nor do they have ready access to integrated instructional materials (Czerniak 2007, Stinson *et al.* 2009). The three sets of exemplar CISA lessons are offered as examples of how the CISA lesson template could be utilised to develop integrated mathematics into science topics that are relevant to the current teaching of science teachers. An integrated 'Big Idea', such as the overlap between data analysis in science and relating two variables in mathematics, as per the second CISA lesson pack, is taken as the core concept (Ainley *et al.* 2011). The lessons are then based on specific science topics (for example, relating the amount of solute that will dissolve to the temperature of the solution), but with suggestions for alternative science topics that could be used to explore the same integrated 'Big Idea'. They are a complete set of lessons in their own right, but they are also intended to offer teachers ideas, suggestions and an approach to designing their own integrated lessons.

CISA Lesson Template

The components of the CISA integrated lessons are based on a CISA lesson template (see Figure 1). The backbone of the lessons is the integrated 'Big Idea', but they also incorporate other elements that previous integration research has identified as important. These are: inclusion of syllabus objectives from both subjects, identification of connections and misconnections between the science and mathematics, along with an awareness of the language differences between them (Offer and Vasquez-Mireles 2009, Stinson *et al.* 2009). STEM literacy captures the sense of purposeful integration of the disciplines, while not having to equally include all four in every lesson. In a science lesson, the main perspective would be scientific literacy, incorporating mathematics and the other disciplines as appropriate (Breiner *et al.* 2012). In terms of teaching and learning these integrated lessons are intended to have a student-centred approach (Judson 2013).

Figure 1: The CISA Lesson Template. This shows the components included in the CISA lessons.

The exemplar CISA mini-schemes are designed to support a spiral curriculum of learning of integrated science and mathematics concepts over the course of Junior Cycle. In CISA 1, intended for new first years, students learn about the inquiry process in science and its relation to the data-handling cycle in mathematics. The same inquiry process is used in CISA 2 (later first years) and CISA 3 (end of first year/second year). CISA 1 deals with univariate analysis (counts of single variables in science), while CISA 2 introduces bivariate analysis (paired variables). CISA 3 takes this a step further by focusing on scientific inquiries that result in linear relationships between paired variables. Given how variable the prior knowledge of different groups of students is going to be, both in terms of science and mathematics, the exemplar CISA lessons are intended to permit teachers to adapt the lessons for their own purposes, while still exploring a particular integrated 'Big Idea' with their students.

METHODOLOGY

The methodology for this study is Educational Design Research, which is characterised by iterative design and formative evaluation of interventions in complex real-world settings. Working with practitioners to inform, design, pilot and refine the elements of the CISA Model is an essential part of this methodology (van den Akker 1999). Two prototypes or versions of the exemplar lessons materials were evaluated first by subject matter experts and then by end-users. The method of evaluation chosen at each prototyping stage is related to three generic criteria proposed for high quality interventions: validity, practicality and effectiveness (Nieveen 2009, Plomp 2009, Mafumiko 2006)**.** A 'proof of concept' approach is being used to evaluate the CISA Model. This offers a partial solution to an educational problem, where a full-scale field trial is not yet feasible (Dym *et al.* 2009). Proof of concept is sought through appraisal by experts, practitioners and other stakeholders. It will be possible therefore to make conclusions regarding its 'expected effectiveness' (Plomp 2009), as a process for assisting teachers to design their own integrated STEM lessons. Data is collected via written commentaries, questionnaires, individual interviews and panel discussions, as described below.

The Expert Evaluation Process

A process known as convergent participation was used for the expert review of the integrated lesson materials. It consists of three stages. Initially the evaluators review the learning materials individually. They then send their feedback to a moderator, who amalgamates and summaries their commentary. The experts meet together for a follow-up panel discussion, with the purpose of achieving some convergence of opinion among the reviewers around the changes and revisions that should be made to the material (Nesbit *et al.* 2002). The main concern of this expert review is to obtain formative feedback to help improve the validity and practicality of the lesson packs (Plomp 2009, Nieveen 2009). Science and mathematics experts were asked for their opinion on what changes, if any, they would make to the content of these lessons to a) make them more logical, consistent and accurate with respect to integrating mathematics into science lessons, and b) make them more feasible to use in the day-to-day setting of an Irish Junior Cycle classroom. Experts were also asked to consider the bigger picture where teachers or others would use the CISA Model to design integrated lessons. The main question is: 'Is this Model valid and practical for teachers to use to create their own integrated lessons?'

FINDINGS

Four subject matter experts reviewed the materials. The experts consisted of two third-level educators specializing in post-primary mathematics education, a third-level educator who specializes in primary science education, and a second-level science teacher who develops continuing professional development for other science teachers. Three of the four experts had been involved in the evaluation of the Syllabus Map and Integrated Sequence also. Initial individual written commentary on the materials was reviewed and summarized (Tessmer 1993). Most of the smaller changes were taken on board, while more significant suggestions were put on the agenda for the panel discussion. The review of the materials was generally positive with regard to the validity and accuracy of the science and mathematics being integrated within the lessons. A significant suggested change was to re-structure the lessons materials to account for the differences in teacher knowledge and concerns. By its very nature integrated material draws on skills and knowledge from different subjects. Depending on both the teacher’s area of expertise and their students’ prior knowledge, teachers may need more or less background information, for example, on how data types and different types of data representations are taught in mathematics class. It also became clear that in designing integrated STEM activities, science teachers can draw on student knowledge from primary science and mathematics, as well as from secondary mathematics, but that many of them may not be aware of this. Hence this information should be included in the revised lessons materials, in a more extensive further information section. With these provisos, the consensus was that the CISA Model could assist teachers to develop their own integrated mathematics into science lessons.

The End-user Evaluation

Once changes based on the expert evaluation had been made, end-users, in this case Junior Science teachers, were asked to evaluate the revised CISA exemplar lessons. 16 teachers are involved. The basic procedure is that teachers read the materials, focusing on one of the CISA lesson packs, and subsequently fill out a questionnaire to give their feedback. Eight of the teachers have additionally opted to try-out some of the lessons in their class room, and this process is on-going. Interviews are also being held with the teachers in order that they can elaborate on their written questionnaire and/or on their experience of implementing the lessons. The focus as before is on issues of validity and practicality of use of the Model in a classroom setting, but also on teacher’s views of the expected effectiveness of the lessons in supporting student transfer of mathematical knowledge into science.

Findings from the End-user Evaluation

Initial feedback from the participating teachers suggests the integrated activities are appropriate (practical to implement and in line with the syllabus), and useful for assisting teachers to assist their students to transfer their mathematical knowledge into science. Teachers agreed that they would encourage students to make decisions about the mathematics they require in their science class, are student-centred and will assist them to see the relevance of STEM outside of the science classroom. They liked the lesson activities and materials, and felt they would assist students to make the connections between the science and mathematics. Comments included that the lessons were ‘*well-structured’*, and ‘*relevant, i.e., students can see where statistics is applied in everyday life*’. Another teacher said the lessons were ‘very good for getting students involved in their own learning. They are constantly discussing, creating their own hypothesis, asking questions, analyzing data and reaching their own conclusions'. Suggestions for change were to do with making the introductory sections and the lesson plans less cluttered with detail; which would improve the readability of the materials. Again the differences in teacher knowledge resulted in science teachers who do not teach mathematics saying that they needed even more '*further information'*, e.g., two newly qualified science teachers made comments about their lack of knowledge of the statistical concepts and of the new Project Maths Syllabus. One teacher commented that she 'might find it hard to relate some of the information to Maths, especially using the same terminology that they use in Maths'. A similar comment had in fact been made by one of the science experts in the earlier part of the evaluation. One of the teachers made specific reference to the fact that she had not previously come across stem-and-leaf plots as a way to represent data. On the other hand, a science teacher who also teaches mathematics felt that the lesson packs could be slimmed down considerably. This teacher did not need as much further information on the relationship to the syllabus and so on. Time for integration is always an issue. The importance of placing these STEM activities within the context of the integrated Teaching and Learning Sequence was highlighted by a comment that 'it would be useful to integrate them into the syllabus with a timeframe'….It would be interesting to see if they would fit into the scheme for the year and still get the same amount of work done'. This teacher had not seen the integrated Sequence, and her concern underlines the need for one, so teachers can feel confident that integrating STEM will not detract from their subject-based teaching.

Overall, those teachers who have provided feedback found the exemplar lessons offer them a good model for developing their own integrated STEM lessons.

DISCUSSION

The evaluation by the participating experts and teachers offers initial proof of concept that the CISA Model, in particular the CISA exemplar lessons, is a feasible process for science teachers to follow so that they can develop their own integrated STEM activities. It was always desirable to have such a model for developing integrated activities available for teachers, as the literature suggests, but this evaluation has also indicated that it may be even more important now than before in the Irish context. Some of the feedback suggests that there is a widening gap in interdisciplinary knowledge emerging in the population of Irish secondary science and mathematics teachers. In the past many science teachers would have developed their mathematical knowledge because they were teaching mathematics, even though they did not have a mathematics qualification. This change in regulations has obvious advantages for the teaching of mathematics as a subject, but, it does mean that the numbers of science teachers with a working knowledge of the mathematics curriculum may decrease. Some studies have pointed to gaps in teacher content knowledge as a barrier to integration; however, it is more accurate to say that while science teachers are skilled end-users of mathematics, they may not have the specific subject-based disciplinary knowledge of mathematics necessary to make the connections for their students (Stinson *et al.* 2009, Roehrig *et al.* 2012). Students need teachers who have interdisciplinary as well as disciplinary knowledge. As Nikitina says, the 'role of the teacher as a translator across different systems of disciplinary representation is crucial' (Nikitina 2006). The CISA Model offers such teachers an otherwise unavailable opportunity to acquire this mathematical pedagogical and content knowledge.

Enhancing STEM education will depend on teachers having a facility to move outside the strict confines of their discipline from time to time, and the CISA Model is one way to encourage this.

References

Ainley, J., Jarvis, T. and McKeon, F. (2011) 'Designing pedagogical opportunities for statistical thinking within inquiry-based science', in Pytlak, M., Rowland, T. and Swoboda, E., eds., *Proceedings of the Seventh Conference of the European Society for Research in Mathematics Education*, Rzeszow, Poland, 9th-13th Feb, University of Rzeszow on behalf of the European Society for Research in Mathematics, 705 - 714.

Breiner, J. M., Harkness, S. S., Johnson, C. C. and Koehler, C. M. (2012) 'What Is STEM? A Discussion About Conceptions of STEM in Education and Partnerships', *School Science and Mathematics*, 112(1), 3-11.

Czerniak, C. M. (2007) 'Interdisciplinary science teaching' in Abell, S. K. and Lederman, N. G., eds., *Handbook of research on science education*, New York and London: Routledge, 537-560.

Dym, C. L., Little, P., Orwin, E. J. and Spjut, R. E. (2009) *Engineering Design: A Project-based Introduction,* 3rd ed., Hoboken, NJ: John Wiley & Sons.

Johnson, C. C. (2013) 'Conceptualizing Integrated STEM Education', *School Science and Mathematics,* 113(8), 367-368.

Judson, E. (2013) 'Development of an Instrument to Assess and Deliberate on the Integration of Mathematics into Student-Centered Science Learning', *School Science and Mathematics,* 113(2), 56-68.

Mafumiko, F. S. M. (2006) *Micro-scale Experimentation as a Catalyst for Improving the Chemistry Curriculum in Tanzania*, unpublished thesis (Ph.D), University of Twente.

Nesbit, J., Belfer, K. and Vargo, J. (2002) 'A convergent participation model for evaluation of learning objects', *Canadian Journal of Learning and Technology/La revue canadienne de l'apprentissage et de la technologie,* 28(3).

Nieveen, N. (2009) 'Formative evaluation in educational research', in Plomp, T. and Nieveen, N., eds., *An Introduction to Educational Design Research*, Proceedings of the seminar conducted at East China Normal University, Shanghai, 23-26 Nov 2007, Enschede: SLO - Netherlands Institute for Curriculum Development, 89-102.

Nikitina, S. (2006) 'Three strategies for interdisciplinary teaching: contextualizing, conceptualizing, and problem-centring', *Journal of Curriculum Studies,* 38(3), 251-271.

Offer, J. and Vasquez-Mireles, S. (2009) 'Mix It Up: Teachers' Beliefs on Mixing Mathematics and Science', *School Science and Mathematics,* 109(3), 146-152.

Pang, J. and Good, R. (2000) 'A review of the integration of science and mathematics: Implications for further research', *School Science and Mathematics,* 100(2), 73-82.

Plomp, T. (2009) 'Educational design research: An introduction', in Plomp, T. and Nieveen, N., eds., *An Introduction to Educational Design Research,* Proceedings of the seminar conducted at East China Normal University, Shanghai, 23-26 Nov 2007, Enschede: SLO - Netherlands Institute for Curriculum Development, 9-35.

Rennie, L., Venville, G. and Wallace, J. e. (2012) *Integrating Science, Technology, Engineering, and Mathematics: Issues, Reflections, and Ways Forward, Teaching and Learning in Science,* New York and London: Routledge.

Roehrig, G. H., Moore, T. J., Wang, H.-H. and Park, M. S. (2012) 'Is Adding the E Enough? Investigating the Impact of K-12 Engineering Standards on the Implementation of STEM Integration', *School Science and Mathematics,* 112(1), 31-44.

Stinson, K., Harkness, S. S., Meyer, H. and Stallworth, J. (2009) 'Mathematics and science integration: Models and characterizations', *School Science and Mathematics,* 109(3), 153-161.

Tessmer, M. (1993) *Planning and Conducting Formative Evaluations,* London and Philadelphia: Kogan Page.

van den Akker, J. (1999) 'Principles and methods of development research' in van den Akker, J., Branch, R., Gustafson, K., Nieveen, N. and Plomp, T., eds., *Design approaches and tools in education and training*, Dordrecht: Kluwer Academic Publishers., 1-14.