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Using Technology to Facilitate Modeling-Based Science Education: Lessons Learned from a Meta-analysis of Empirical Research

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Abstract: *This study focused on the integration of technologies in regular science teaching within the pedagogical framework of modeling-based instruction (MBI), a well-established instructional method in science education, and aimed to identify new trends of technology integration in MBI, explore the particular features (Interactivity, Collaboration, and Scaffolding) and affordances of new technologies, and examine the effect of technology-supported MBI on students learning outcomes. By analyzing empirical MBI studies from 2000 to 2010 through a meta-analysis and qualitatively reviewing studies from 2011-2016, this study shared three major findings: (1) computer-based software was the most commonly used technology in MBI, with Internet and mobile technologies rarely used, thus indicating an alarming gap between technology advancement and its integration in education; (2) the majority of technologies used in MBI were considered highly-interactive, but collaborative and scaffolding features of MBI technologies were rarely discussed in MBI literature; (3) technology-supported MBI had an overall much higher effect size on students' science learning performance. Implications and suggestions for future research were also discussed.*

Keywords: Technology Features, Modeling-Based Instruction, Interactivity, Collaboration, Scaffolding

1. Introduction

Educational technologies have developed substantially in the last two decades, resulting in significant improvements in existing technologies and in the emergence of new tools. According to Aslan and Reigeluth (2011), educational technologies have become increasingly interactive, customizable, multi-functional, and easy-to-use, and "their rooted presence in our educational lives has continually increased over time" (p.1). However, despite the rapid development and growing access of educational technologies, research continues to suggest that technologies have been used infrequently and inconsistently in educational settings for learning with little conclusive effect (Brown & Green, 2008; Selwyn, 201; Christensen, Johnson, & Horn, 2008). Teachers often use computers as a minor supplement to their traditional teaching practices (Aslan & Reigeluth, 2011), and the use of emerging technologies is often limited to support traditional standardized and centralized educational model (Cuban, 2001). In other words, while technologies are widely used in education, the powerful attributes (e.g., interactivity, multi-functionality) they offer are commonly "underused," thus their uses are failing to meet the needs and expectations of both teachers and learners.

As a result, researchers have called for more studies to investigate the unique features and affordances of emerging technologies and their pedagogical implications, with the purpose of increasing the effectiveness of technology use in education. According to Kozma (1991), educational technologies have the capability to transform instructional events because the unique attributes of technologies can enable or constrain pedagogy, and pedagogy can employ and instantiate technology affordances. Spector (2001) also emphasizes such integral relationship between technology and pedagogy, asserting that "educational program management must be integrally linked with technology and theory in order for significant progress in learning and instruction to occur on a global scale" (p. 27). Such a stance is echoed by Ross, Morrison and Lowther (2010), who argue that research on cutting-edge technology applications should be built on well-established theories and principles in learning and instruction.

In line with such calls to research, this study examines the technologies used in K-12 science education classrooms within the pedagogical framework of Modeling-Based Instruction. Modeling-Based instruction (MBI), as defined by Shen and colleagues (2010), is an innovative way to teach science that represents and explains scientific processes and phenomena through the activities of using, creating, sharing, and evaluating models. It has been studied and implemented in the last three decades and has demonstrated effectiveness in improving students' conceptual understanding, critical thinking, and inquiry skills in science (Hart, 2008; Hestenes, 1987; Khan, 2007; Lehrer & Schauble, 2006; Passmore & Stewart, 2002; Schwarz et al. 2009; Sell, Herbert, Stuessy, & Schielack, 2006; White, 1993; Windschitl, Thompson, & Braaten, 2008).. Researchers have proposed MBI frameworks from different theoretical perspectives. In terms of the ontology of models, some scholars emphasized that it is the mental model that students need to develop (Hestenes, 1987; Ifenthaler, Pirnay-Dummer, & Spector, 2008; Vosniadou, 2002), whereas many other scholars focused on studying external representations (Ardac & Akaygun, 2004; 2006; Mayer et al., 2005). In this study, the researchers focus on the external models.

Technologies have brought tremendous opportunities for science education as a result of their capabilities to simulate and model scientific phenomena, thus have been widely used since 2000 for MBI of different science subjects such as chemistry (Chang, et. al, 2010; Pallant & Tinker, 2004), physics (Manlove, Lazonder, & de Jong, 2009; Stocklmayer, 2010), biology (Ergazaki et. al, 2007; Wilensky & Reisman, 2006) and environmental science (Wu, 2010). For example, *Molecular Workbench* is a modeling engine created by the Concord Consortium mainly to simulate the interactions among particles and other microscopic phenomena (Pallant & Tinker, 2004; Xie & Tinker, 2006). *NetLogo* is an agent-based modeling tool that simulates complex and decentralized systems (Goldstone & Wilensky, 2008; Tisue &

Wilensky, 2004). These TMBI environments empower students to model a wide range of science phenomena, especially those often too small to see, too abstract to represent, too complex to comprehend, or too dangerous to explore in real life. These environments also build new forms of collaboration so that students can collaboratively build models within or across classes (Gobert & Pallant, 2004).

Despite the wide availability of MBI tools, technologies are still considered as "underutilized and poorly integrated" in K-12 science education classrooms (Songer, 2007, p. 471), and how technologies support the pedagogy of MBI are rarely examined in existing literature. In addition, the fast-developing computer technologies provide more interactive and powerful modeling environments that offer great potential for MBI to help students gain new understandings of science concepts and inquiry skills if only the teaching techniques and knowledge are not outrun by the technology (Quintana, Zhang, & Krajcik, 2005). Given the diversity of available technologies, pressing is to compare and contrast different approaches in technology-enhanced MBI curricula in order to inform future design of such an environment that fits different class needs.

Therefore, this study aims to review and synthesize effective strategies for incorporating various technologies in regular science teaching by analyzing empirical MBI studies from 2000 to 2010 through a meta-analysis and qualitatively reviewing literature from 2011-2016. A meta-analysis in statistics consolidates the results of related empirical studies that address similar research questions. Usually effect sizes of similar measures are identified and regressed on hypothesized factors (c.f., Hedges & Olkin, 1985; Lipsey & Wilson, 2001).Through synthetically analyzing the MBI literature, this study expects to identify new trends of technology integration in MBI, explore the unique features and affordances of MBI technologies, and determine the overall effect of technology-supported MBI on students' learning outcomes. Specifically, the study intends to answer the following two research questions:

1. What are the most commonly used technologies for MBI in the context of K-12 science education?
2. What is the impact of technology-supported MBI on students' learning outcome?

2. Literature Review

Technology-supported MBI. Modeling-Based instruction (MBI) is an innovative way for science teaching and learning that encourages students to use, create, share, and evaluate models to represent and explain scientific processes and phenomena (Shen, et al., 2010). Students in MBI classrooms are actively engaged in the learning process by creating and revising their own models (Schwarz et al., 2009), and are often exposed to multiple forms and representations of science models (Mayer, 2005). MBI is also believed to facilitate a collaborative learning environment where students work in pairs or small groups to discuss and critique each other's works (Fazio et al., 2008; Penner, 2001; Wu, 2010). The effectiveness of MBI has been supported by many empirical studies, with research findings suggesting it improve students' comprehension of science content (Hart, 2008; Khan, 2007; Passmore & Stewart, 2002; Sell, Herbert, Stuessy, & Schielack, 2006), as well as inquiry skills and critical thinking skills (Stratford, Krajcik, & Soloway, 1998; White, 1993).

The advancement of technologies such as 3D simulator and programming software has provided great opportunities for applying MBI in science education, as the unique affordances of technology (e.g., ease of interaction, immediate feedback, automated scaffolding) enable students to build more complex models with better visualization and greater ease (Dimitracopoulou & Komins, 2005; Linn, Clark, & Slotta, 2003; Penner, 2001). As a result, there is a growing research body in K-12 science education that investigates the technology-supported modeling tools and their applications in various science subjects. Examples of such MBI tools include *Model-it, Molecular Workbench, NetLogo (introduced earlier), PhET, and Wise* (Goldstone & Wilensky, 2008; Linn et al., 2006; Perkins et al., 2006; Xie & Tinker, 2006). PhET Interactive Simulations is an open-source Website developed at the University of Colorado that contains a variety of high quality computer models and simulations in STEM disciplines to help students visualize and test scientific models and processes (Perkins et al. 2006; Wieman, Adams, & Perkins, 2008). *WISE* from the University of California, Berkeley is a Web-based inquiry environment that supports embedded assessments, student notes, peer collaboration and interactive computer models (Linn, 2006; Linn, Clark, & Slotta, 2003).While most of such studies include a brief description of the technology tools, the analysis and discussion of their key features and unique contributions to the modeling process are often absent.

Key features of MBI technologies. Interactivity is identified as a key feature for MBI technologies by Penner (2001), who classify technology tools for MBI into three categories based on their level of interactivity: (1) *simulations* that allow limited manipulation of certain parameters in an existing model such as PhET simulations as described earlier, (2) *icon-based modeling programs* that enable students to develop and modify user-specified models such as STELLA, a system modeling tool used in education and research (http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx), and (3) programmable media that provide students with maximum flexibility to explore their ideas of natural phenomena as they construct their own models such as NetLogo as described earlier. Based on the review of technology tools from each category, Penner (2001) demonstrates how interactive features in modeling tools are used to facilitate the modeling process in K-12 science education. However, most tools reviewed by Penner (2001) are products of the 1990s and the focus of analysis is limited to their interactivity only. Therefore, there is a need for similar research that reviews the MBI technologies in the past decade (2000-2010) with a bigger scope to examine other key features such as collaboration and scaffolding.

Collaboration is an important component of MBI, where students are actively engaged in social interactions with peers or experts to develop, negotiate, and revise their models about science concepts (Komis, Ergazaki & Zogza, 2007; Penner, 2001). Such collaboration in MBI can also be facilitated by emerging technologies. According to Authors (2011), collaborative features of MBI technologies include (a) allowing students to simultaneously work on the same task, (b) making thinking process visible for peers and instructors, (c) emphasizing discourse norms to facilitate discussion, (d) providing immediate feedback to construct coherent conversation, and (e) creating a low-stress environment for collaboration.

Another key feature of MBI technology is embedded scaffolding. The term *scaffolding* was first coined by Jerome Bruner "to describe the process in which a child or novice could be assisted to achieve a task that they may not be able to achieve if unassisted" (Lajoie, 2005, p.542). According to Fretz et al (2002), students in a MBI learning environment "always face a number of difficulties with models for science learning including limited experience in creating and using models and a lack of advanced mathematical skills" (p.568). Students need cognitive and procedural supports in order to carry out scientific inquiry in learning environments that have interactive, dynamic computer models (Linn, 2006; Quintana et al., 2004). As a result, many researchers have addressed the need for adding scaffolding features in technology tools to assist learners in challenging scientific tasks (Jackson, Krajcik, & Soloway, 1999; Linn, 1998; Quintana, 2001; White & Frederiksen, 1998). Scaffolding features can assist learners in procedural and logistic processes in MBI such as learning how to use the tool functions to build a model. According to Jonassen and Reeves (1996), scaffolding features can also be used to facilitate cognitive (e.g., understanding a scientific phenomenon) and meta-cognitive processes (e.g., reflecting on what modeling is about).

3. Methods

Data Collection

Data collection and analysis in this study have been conducted in three major phases: literature selection, coding, and analysis (see Figure 1). The researchers used the following criteria to include studies that: (a) has a focus of Modeling-based Instruction, (b) is conducted in the context of K-12 science education, (c) has been published in English in 1980 or later, and (d) is of high quality. High quality refers to addressing meaningful research questions, adopting rigorous research methodology, collecting data targeting research questions, and contributing significantly to the science education community. The researchers decided to search the literature published on or after 1980 because the development and application of MBI in K-12 science classrooms was not identified prior to 1980, but started to emerge in the early 1980. A total of 111 empirical studies of MBI in K-12 science education have been selected from 1980 to 2010 after four rounds of literature search and selection. However, because the majority of the studies before 2000 do not use technology or have any information on technology, only studies published on or after 2000 have been used. Therefore, a total number of 67 studies are included in the meta-analysis (see Appendix A). In the first round of literature search a combinations of key words including *model-based, modeling, science, instruction, teaching,* and *learning* has been used to search the database of Education Resources Information Center (ERIC) and the ProQuest

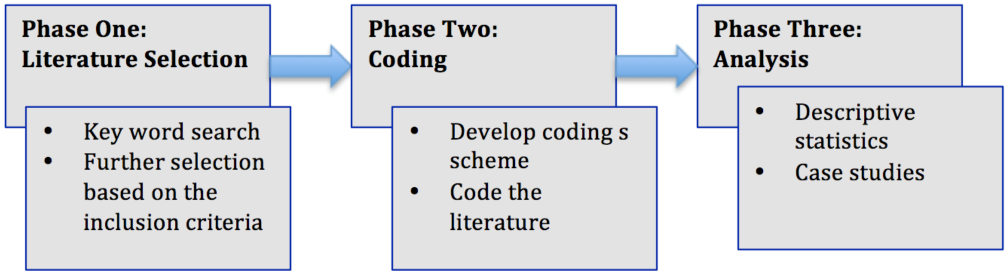

Figure 1. The Data Collection and Analysis Process

dissertation database. Then the researchers searched a total of 14 major journals in the field of science education (see Appendix B) with the same key word combinations in the second round, and compared the search results from the two rounds to ensure all relevant studies were included in our search. The first two rounds of literature search have resulted in 249 entries and those entries have been further reduced in the third round after removing all the inapplicable studies that are not about modeling-base science education in K-12 settings. In the final round of selection, all conceptual papers and synthesis studies have been also excluded because they usually present research findings from several existing research studies, and thus, can result in repetitive data.

Coding

A coding scheme has been developed in Phase Two to code the selected studies, with the purpose to collect information regarding different aspects of MBI technologies such as their type and format, level of interaction, and features for collaboration and scaffolding. The researchers first developed an initial coding scheme based upon existing literature that identify the key features of technology tools in MBI (Fretz et al., 2002; Kosmis, et al., 2007; Penner, 2001). To increase the inter-rater reliability, studies published in year 2010 have been selected to establish coding reliability between different coders. The research team has been divided into two sub-teams, and each team coded the whole set of articles. The two sub-teams then compare the coding results, discuss the inconsistent codes until reaching an agreement, and revise the coding rubrics if necessary. This has resulted in a better understanding of the coding rubrics. The researchers repeated the process for the set of studies published in year 2000 to further strengthen the coding reliability and refine coding rubrics. Part of the codes from the coding scheme and their meanings are summarized in Table 1.

Table 1. The Codes Used in the Study and Explanations

Category	Code	Explanation
Use of technology in MBI	N: No technology P: PC-based software I: Internet-based program M: Mobile technology V:Video/film/animation	N: Technology is not involved in designing MBI environment. P: Personal computer-based software, internet not required. I: Internet is required in MBI. M: Mobile technology is involved in MBI. V: Video/film/animation is used for MBI.
Interactivity of the modeling tool	0: no interaction 1: Low level 2: High level	0: Students are not allowed to manipulate. 1: Students are allowed to manipulate only a few variables. 2: Students are allowed to manipulate several variables, change rules and create models that are responsive.

Table 1. The Codes Used in the Study and Explanations

Category	Code	Explanation
Embedded collaboration tool	0: no 1: yes	0: Collaboration features are not included in MBI technology. 1: Collaboration features are included in MBI technology.
Embedded scaffolding	0: no 1: yes	0: Scaffolding features are not included in MBI technology. 1: Scaffolding features are included in MBI technology.
Scaffolding Focus	P: Procedural C: Cognitive/content M: Metacognitive	P: assistance on procedural/logistic processes. C: assistance on cognitive processes. M: assistance on metacognitive processes.
Collaboration-group size	P: Pairs/Small group L: Large group/whole class B: Beyond the class C: Combined	P: collaboration in pairs or small group (3-4 students). L: collaboration in large group/whole class. B: collaboration beyond the class level. C: combination of a variety of collaboration.
Collaboration-people	P: Peers E: Expert O: Others	P: collaboration with peers. E: collaboration with expert. O: collaboration with others; specify what they are.
Collaboration-mode	O: online F: Face to face H: Hybrid online and f2f	O: collaboration online. F: collaboration in face to face mode. H: collaboration in combination of online and face to face.

Both quantitative and qualitative data are collected and analyzed in Phase Three. Descriptive statistics of codes such as means, frequency and percentage are calculated to examine the general trends of technology-supported MBI. Qualitative data such as ethnographic narratives, interview transcripts, and reflective comments from several exemplary studies (Lee, 2010; Manlove, Lazonder & de Jong, 2009) are also analyzed in this study to demonstrate, verify, and explicate the identified trends. To examine the effectiveness of technology-supported MBI, the average effect size of technology-supported MBI has been calculated using *Cohen's d* in Phase Three, based on the meta-analysis results of all applicable quantitative studies.

Effect Size Calculations

Effect size is a measure of standardized mean difference between two groups. In this study, effect size is computed to estimate the extent of the difference between learning with MBI and learning without MBI. Depending on the information available, the researchers use different strategies to compute the effect size (Lipsey & Wilson, 2001):

- When both mean and standard deviation for both control group and experimental group (or pretest and posttest) are available, effect size is computed using Cohen's d. Cohen's $d = (M_1 - M_2)/S_{pooled}$, where $S_{pooled} = \sqrt{(S_1^2 + S_2^2)/2}$ with equal sample sizes; $S_{pooled} = \sqrt{((N_1 - 1)S_1^2 + (N_2 - 1)S_2^2)/(N_1 + N_2)}$ with unequal sample sizes.
- When the mean and standard deviation are not available, and only the t-test value is reported, and the effect size is calculated as $d = 2t\sqrt{df}$
- When only F value and sample sizes are reported, and when there are only two groups, then effect size is computed by using the following formula: $d = \sqrt{F(1/N_1 + 1/N_2)}$
- The effect sizes are unbiased by sample size through the following procedure:

$J = 1 - (3/(4(N + N - 2) - 1))$ and $T = G \times J$, where G is the initial effect size computed from primary studies, and T is the unbiased effect size.

4. Findings and Discussions

Based on the results from the data analysis, this section describes and discusses three major findings regarding the technology-supported MBI in K-12 science education from 2000 to 2010: (1) computer-based software is the most commonly used technology in MBI, while Internet and mobile technologies are much less used; (2) the majority of technologies used in MBI are considered highly-interactive, but collaborative and scaffolding features of MBI technologies are rarely discussed in MBI literature; (3) technology-supported MBI seem to have an overall positive effect on students' science learning performance.

Finding one: ***As reported in empirical studies published between 2000 to 2016 they reveal that Traditional Computer-Based Software is the Most Commonly Used Technology in MBI, yet Newer Technology is Little Used.***

Synthesis analysis results for literature between 2000-2010. Between 2000 and 2010, there have been a total of 67 empirical studies conducted to investigate the interventions of MBI in K-12 science education. Among them, 47 MBI interventions are supported by technology means such as computer software or multimedia. As shown in Figure 2, computer-based software accounts for 55% of all MBI interventions in research, which is almost four times as many as other types of technologies combined. The computer-based software provides students with an interface where they can visualize and test the dynamic relationship of an existing model by manipulating the values of one or more model components. Students can also create their own models to test hypotheses for a scientific phenomenon or solutions for a scientific problem. Examples of such computer-based modeling software include Air Pollution Modeling Environment (APoME) (Wu, 2010), Computerized Molecular Modeling (CMM) (Kaberman & Dori, 2009), Powersim® (Sins et.al, 2009), Microworlds Logo and

Stagecast Creator (Louca & Zacharia, 2008), ModelsCreator (Komis, Ergazaki & Zogza, 2007), and StarLogo (Klopfer,Yoon & Um, 2005).

While Internet technologies and mobile technologies such as Web 2.0 and smartphones have seen a significant development in the past decade, their role in MBI still seem to be quite limited, accounting for only 6% of the MBI studies in the meta-analysis. Only three studies report the use of Internet for MBI. In those three studies, Internet is used to create a multi-user virtual environment such as *The River City* to support learning through collaborative knowledge construction (Ketelhut, 2010), to provide students with online access to modeling project materials (Eskrootchi & Oskrochi, 2010), or to offer interactive multimedia packages (Tsui & Treagust, 2007). The only MBI intervention supported by mobile technologies is reported by Metcalf and Tinker (2004), which investigates the effect of using probe ware and handheld computers to teach middle school physical science. Also important to note is that not all MBI in K-12 science classrooms involve the use of technology, as 30% of MBI interventions are still developed by conventional means like physical models, mental models, or diagrams.

Qualitative analysis results for literature between 2011-2016. Given the increasingly popular use of mobile technology and Internet in schools today, rather puzzling is that only a very small number of studies use mobile technology and the Internet in the synthesis study. To examine the latest trends in the use of emerging technology in MBI, the researchers have searched and reviewed relevant literature published after 2010 (to 2016) and identify a somewhat improved, yet still quite similar, picture.

The use of mobile technology for modeling-based instruction has been discussed by some researchers (Dunleavy et al., 2009) however, only very few empirical studies have reported the actual use of mobile devices. For example, Chang, Hsu, and Wu (2014) provide tablet computers to students to engage in simulated radiation values to help them understand scientific concepts such as radiation, nuclear pollution, and the impact on ecology. Their results indicate that MBI based learning is as effective as traditional learning in content knowledge gain, and more effective in affective aspects of learning. In

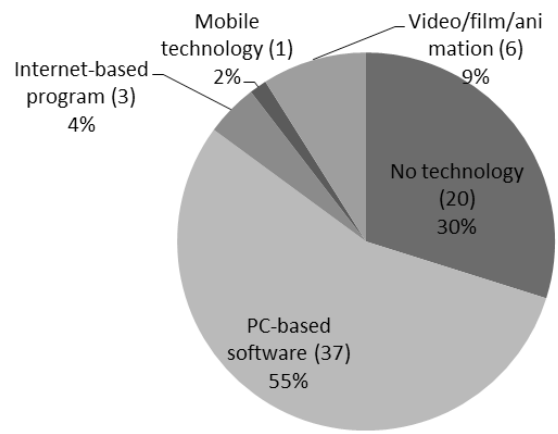

Figure 2. Types of Technologies Used in MBI

another study, researchers have used sound level meters connected to data capture systems, which facilitate the measurement of the intensity level of sound emitted by a sound source and transmitted through different materials (Hernandez, Couso, & Pinto, 2015).

Two empirical studies that use Web-based modeling tools have been found. Barak and Hussein-Farraj (2013) report students in Israel learning from a Web-based biochemistry learning unit that contain molecular modeling activities and animations to encourage active learning and enhance conceptual understanding. They argue that the integration of Web-based models and animations as part of the students' learning environment enhance students' ability to transfer across the levels of chemistry understanding (microscopic, macroscopic, symbol, and process), and improve their understanding of proteins' spatial structure and function. Sun and Looi (2013) describe a research process in the design and development of a science learning environment called WiMVT (Web-based inquirer with modeling and visualization technology) in Singapore. This system is designed to help secondary school students build a sophisticated understanding of scientific conceptions and the science inquiry process, as well as develop critical learning skills through model-based collaborative inquiry approach.

Researchers also report using resources from the Internet for modeling instead of directly interact with models on the Internet. For example, researchers at Grand Valley State University and Miami University worked on a Target Inquiry project, a program designed for secondary science teachers' professional development. The program Website provides particulate-level examples of physical and chemical changes for teachers to use in their teaching (Yezierski & Herrington, 2011).

Using stand-alone computer programs for modeling-based instruction in classrooms is still most frequently reported in empirical studies published in 2011-2016. For example, Basawapatna (2016) report that the use of a new visual programming tool entitled *the Simulation Creation Toolkit*, is a high level pattern-based phenomenological approach to bringing rapid simulation creation into the classroom environment. Xiang's dissertation study (Xiang, 2011) examine how programming an agent-based simulation influences a group of 8th grade students' model-based inquiry (MBI) by examining students' agent-based programmable modeling (ABPM) processes and the learning outcomes. In this study, students program a simulation of adaptation based on the natural selection model in NetLogo, an ABPM tool, in a computer lab. The findings suggest that students made progress on understanding adaptation phenomena and natural selection at the end of ABPM-supported MBI learning, but the progress is limited (Xiang, 2011). In another study, researchers describe how a stand-alone model-based tool, "BioLogica"™, is used to facilitate genetics learning in secondary 3-level biology in Singapore (Kim, et. al, 2015).

Finding two: *Technology is most frequently used to support interactivity, but not much for collaboration and scaffolding.*

This study analyzes three features of the MBI technologies that support the modeling process: level of interaction, embedded collaboration, and embedded scaffolding. As shown in Figure 3, most technology-supported MBI interventions (70%) are considered as highly interactive based on the coding, which allow students to easily change the value or the relationship of components in an existing science model, or even create new models to test hypotheses regarding a scientific phenomenon. Examples of highly interactive technology tools include *Chemation* for teaching middle school chemistry (Chang, et. al, 2010), *ModelCreator* for high school biology (Ergazaki et. al, 2007), and *NetLogo* for high school biology (Wilensky & Reisman, 2006). Fourteen MBI technologies (30%) are considered as having low level or no interactive features at all. Those technologies are mostly multimedia-based instructional teachers are able to help students enhance their comprehension of biology concepts such as respiration and circulation with simple hand-drawn models. Patrick, Carter, and Wiebe (2001) also report that students' understanding of DNA Replication could be improved by using both 2D and 3D simulation slides if the right visual design principles are applied.

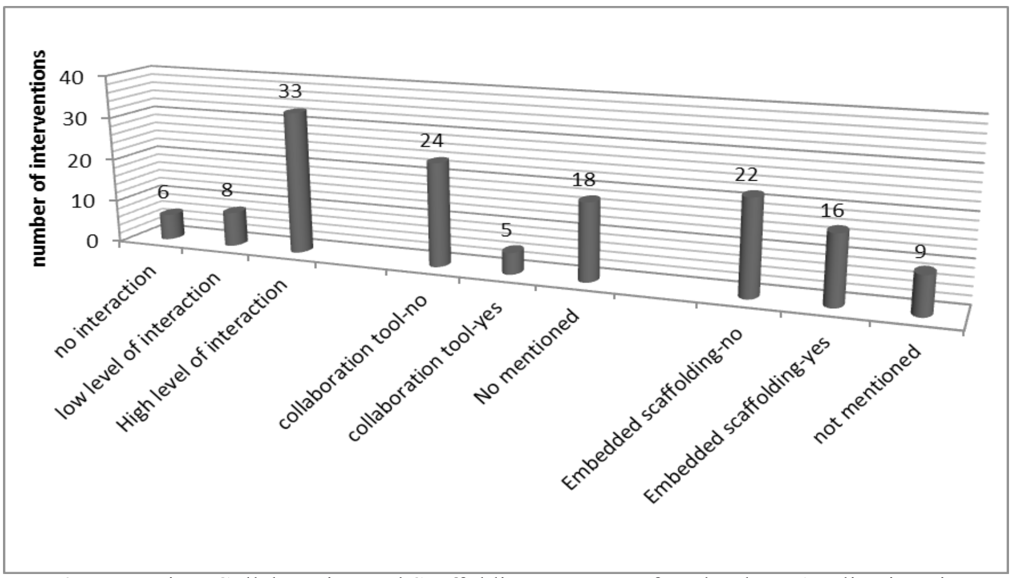

Figure 3. Interactive, Collaborative and Scaffolding Features of Technology Applications in MBI from 2000-2010

materials (Clemen & Nunez-Oviedo, 2003; Patrick et.al, 2001), and devices with limited computing capacity such as handheld probeware (Metcalf & Tinker, 2004).

MBI technologies that have few or no interactive features do not necessarily result in ineffective instruction. The analysis find that by skillfully integrating the low-level interactive MBI technologies such as video or film in modeling processes, teachers could still increase students' science learning outcomes. For example, Clement and Oviedo (2003) report that by using the strategy of analogy,

Although collaboration is an important component of MBI, the analysis reveal that the majority of MBI technologies are designed without any function to support collaboration. Only five studies report technology interventions with embedded collaborative tools, which account for merely 11% of all technology-supported MBI studies. Figure 4 shows collaboration in MBI studies along three aspects: size, partner, and mode. As shown in this figure, the most common form of collaboration is students' collaborating in pairs or small groups (3-4 people), with peers, and in conventional face-to-face classrooms.

In very few cases has collaboration been conducted in large group, with experts, or online. Collaboration with peers in small groups face-to-face is recommended by many researchers. For example, Lou and colleagues (1996) point out that small groups of 3-4 students are especially effective in collaborative learning; Ormrod (2008) also argue that peer-to-peer collaboration is the easiest and the most convenient mode for teachers to manage and students more likely to critique and challenge each other's ideas in peer groups. The high occurrence of small-group size and peer-to-peer mode in collaboration might explain why collaborative tools are often absent in MBI technologies; students can easily work together in pairs or small groups using one computer during MBI, therefore collaborative tools for asynchronous communication or file sharing might be usually unnecessary.

Online collaboration seem to still be a novel idea for most teachers as there are only four studies discussing its role in MBI. Those studies examine the use of Web-based programs such as *KanCRN* (Eskrootchi & Oskrochi, 2010), *River City* (Ketelhut, Nelson, Clarke, & DeDe, 2010), *Collaborative Virtual Workplace 4.0* (Pata, Lehtinen, & Sarapuu, 2006) and *WebLabs* (Simpson, Hoyles, & Noss, 2006), and demonstrate how online communication, data sharing, and peer critique could be realized by asynchronous communication tools, data-gathering/publishing tools, and virtual communities.

According to Wu and colleagues (2010), scaffolding is a process of providing decreasing amounts of support to help students "bridge the gap between their current abilities and the intended goal of instruction" (Rosenshine & Meister, 1992, p. 26) that allows students "to participate at ever-increasing levels of competence" (Palincsar & Brown, 1984, p. 122). Scaffolding that embed instructional guidance in ongoing investigation has been identified as an important aspect

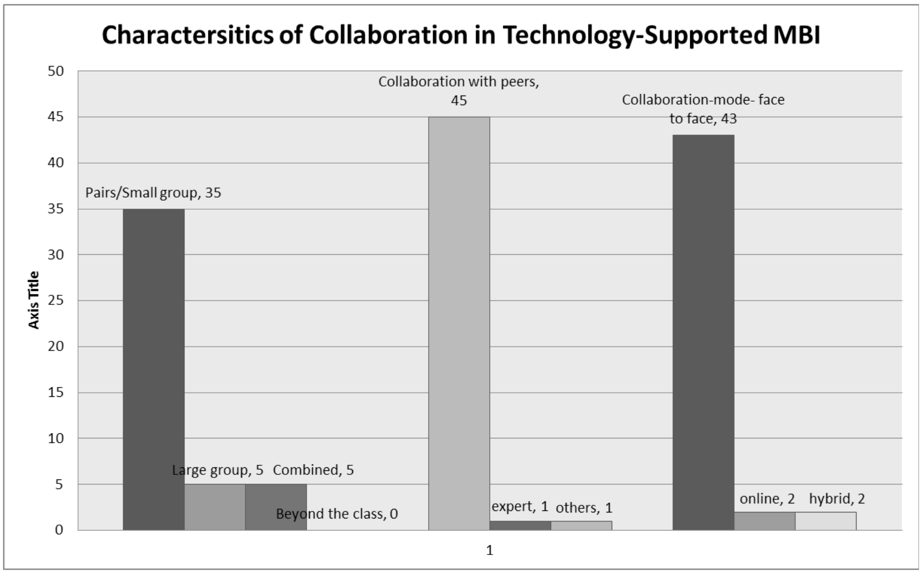

Figure 4. Characteristics of Collaboration in Technology-Supported MBI

in science learning (Quellmalz et al, 2012). For example, process scaffolding can prompt students to pay attention to important components of inquiry or science arguments (Duschl et. al, 2007). However, the majority of studies on technology-supported MBI (31 out of 47) fail to describe the scaffolding features offered by technologies, and have not provided any discussion on how those features assist students in their learning processes. Only 16 studies briefly mention how certain features in a technology program such as prompt questions, visual cues, feedback, and advanced organizers assist students in learning activities such as operating the program, comprehending a scientific phenomenon, and reflecting on the modeling processes. The procedural and the cognitive scaffolding are the most common features, coded 8 and 9 times respectively. However, MBI technologies with meta-cognitive scaffolding features are not mentioned in any studies included in this analysis.

Finding three: *Technology-supported MBI studies had higher effect sizes.*

To determine the effectiveness of technology-supported MBI in K-12 science education, the researchers examine the statistical results of all quantitative research on MBI technologies conducted between 2000 and 2010 and used *Cohen's d* to calculate the effect size(s) of each study. Studies that have more than one independent variable (MBI intervention) or more than one dependent variable (learning domain or content area) are counted as a separate experiment study. Although there is a big body of research on MBI (125 articles), only a small percentage of these studies are empirical studies with quantitative results (28 articles, 22.4%). Within the quantitative studies, it is not uncommon that authors do not report necessary statistics for calculating effect sizes, leaving with only 17 empirical articles with 81 individual studies qualified to be included in this meta-analysis. Therefore, the researchers of this study urge that the research community have and enforce more explicit guidelines in terms of reporting necessary statistics.

As shown in Figure 5, technology-supported MBI has an overall positive effect on science learning performance of K-12 students. Learning performance is indicated

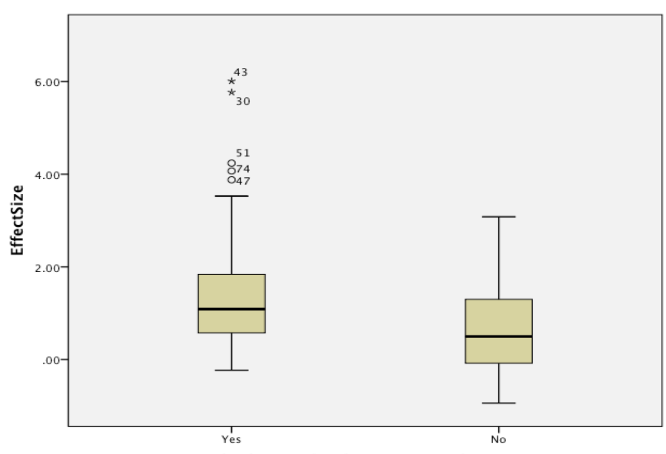

Figure 5. The distribution of the effect sizes of studies with and without technology

by the outcome measures reported in the studies, including science content knowledge, modeling, affective outcomes, and other outcomes such as collaboration or familiarity with particular tools. Studies with technology-supported MBI have an average effect size of 1.45, and studies without technology-supported MBI have an average effect size of 0.76. An independent samples t-test is conducted to compare means of the two groups, and the difference is marginally significant (t_{69}=1.81, p=.07). Therefore, the researchers conclude that using technology-supported MBI is related to increased student's science learning outcome in general and technology-supported MBI is an effective pedagogy for K-12 science education.

Technology-Embedded Scaffolding (TES)

The researchers also look at how embedded scaffolding affect the over effect of technology-enhanced MBI. Among the 81 individual studies that have sufficient statistical information to calculate an effect size, 13 include embedded scaffolding, 26 have not included embedded scaffolding, and the rest have not mentioned such information. As shown in Table 2 below, embedded-scaffolding is a significant factor on effect sizes. The mean effect size of studies without embedded scaffolding is .41, while the mean effect size of studies with embedded scaffolding is 1.53, and the difference is significant with $Q_{(Between\ Group)} = 115.68$ ($P < .0001$)

Table 2. Mean Effect Size Results by Group

Group	Mean ES	SE	-95%CI	+95%CI	Z	P	K
Without TES	.41	.02	.36	.45	17.97	<.0001	26
With TES	1.53	.10	1.33	1.73	15.05	<.0001	13

5. Conclusions

This study analyzes the technologies used in MBI within the context of K-12 science education by examining relevant empirical quantitative studies published between 2000 and 2010. The study also reviewed some qualitative studies published between 2011 and 2016, with the purpose of identifying new trends in technology integration, exploring unique features of technologies and their potential for MBI, and determining the effectiveness of technology-supported MBI on students' learning outcome. Findings from this study have some very interesting implications to the design and further research of modeling-based instruction.

First, the synthesis analyses reveal that computer-based software are still the most commonly used technology for MBI in K-12 science education, which have been used six times as many as video technologies or the second most popular technology. One surprise would be the fact that Internet-based programs account for only 4% of all MBI interventions, despite the dramatic growth in both the access to Internet and the variety of Internet technologies in the past decade. This synthesis study began with empirical studies published from 2000. As early as in 2000, 97% of elementary public schools and 100% secondary public schools have Internet access at the instructional level (Wells & Lewis, 2006), and the percentage of classrooms connected to the Internet have increased from 77% in 2000 (Wells & Lewis, 2006) to 97% in 2009 (Gray, Thomas, & Lewis, 2010). In the meantime, the variety the functionality of Internet programs and applications have also increased exponentially. However, the rapid advancement in the Internet technology is not reflected in the studies conducted during this time period, indicating a gap in integrating Internet technology in modeling-based instruction design. A qualitative review of most recent studies from 2011-2016 show a similar, although somewhat improved picture: computer programs are still the most commonly used technology-supported modeling-based instruction, with very few studies reporting the use of mobile technology or the Internet to support MBI.

One possible explanation for this gap might be that there is a delay in conducting and publishing MBI studies in the field. Although this gap is consistent with other evidence that available technology is not being used for instructional purposes, the degree of this gap is alarming. It might be possible to see more modeling-based instruction or any other type of instruction to incorporate more Internet technology and resources into its design and implementation.

Another possible explanation might be the "underuse" of technology resources in classroom teaching. Today dynamic Web-based applications such as Java and Flash make many animations readily available on the Internet and many educational animations can be found on the Internet (Barak & Hussein-Farraj, 2013). Yet this is not clear as to whether or not, and to what degree, these resources are being used in classroom teaching. Worthwhile is to call for greater attention to this matter, and thus, a heavier emphasis on the meaningful integration of technology in instructional design. Also important is to call for more effort in preparing teachers for integrating technology into teaching in the science learning settings.

Second, the meta-analysis results show that MBI studies with embedded scaffolding have a significantly higher average effect size than those without embedded scaffolding, signifying the importance of using scaffolding in MBI learning environments. However, studies in this meta-analysis mostly do not use technology to provide scaffolding to students in learning. Researchers have pointed out that students need explicit scaffolds to help them productively engage in scientific modeling practices (McElhaney & Linn, 2011; Schwarz & White, 2005). Research indicates that students may have difficulties to attend properly to the complex information of a scientific model (Lowe, 2004). They may not have shared experience, competency, or knowledge as the producer of the scientific model to successfully perceive information represented in the model (Kress & van Leeuwen, 1996). Therefore, designing scaffolds in MBI environments that provide hints or help focus students' attention on key aspects of a model is important. Technology has the potential to provide appropriate scaffolding in a modeling-based instruction, but this potential has not been fully realized yet. Examining how technology can be used to design a supportive learning environment for students and further study how technology-facilitated scaffolding can be incorporated in such environments is important. In addition, further study is needed to explain the added value of using scaffolding in a technology-based environment. For example, does the technology-based scaffolding reduce the cognitive load on the teacher in the face-to-face environment? Does the technology-based scaffolding accentuate differentiation in order to optimize individual student performance?

Third, by comparing the effect size of all applicable quantitative studies from 2000 to 2010, the researchers find that modeling-based instruction that has technology components incorporated into the design and implementation process has a much higher average effect size than that ones that do not (1.45 vs. 0.76), indicating that the use of technology in general can better facilitate modeling-based instruction in K-12 science education. To further explore what ways technology might have contributed to the larger effect on MBI on student learning, the researchers look at the effect of specific features used in the technology. With what is available in the data, the researchers find that modeling-based instructions that has technology-embedded scaffolding has a significantly larger effect on student learning outcomes (Effect Size 1.53 vs. 0.41). These results suggest that it is reasonable to call for more integration of modern technology tools into the design and the implementation of modeling-based instruction, and also reasonable to call for further research to examine how technology tools can best support modeling-based learning.

In order to integrate technology into modeling-based instruction in meaningful ways, further research is in great need to explore why and how technology can help students better learn in modeling-based process. However, this study suggest that the critical features of MBI technologies are very infrequently discussed in existing literature, particularly the collaborative feature and the scaffolding feature. The lack of discussion of, and more importantly, the inclusion of important design features of MBI technology in science educational practices, calls for a closer examination of the design and the implementation of technology-supported MBI to identify effective strategies to better reap the potential benefits of modern technology tools in support of student learning.

One limitation of this study is that the synthesis analysis do not include empirical studies published after 2011 due to the early time the synthesis has been conducted and the amount of time and resources it requires to complete another cycle of analysis. In order to address this issue, the researchers conducted a qualitative review of empirical studies published between 2011 and 2016. They examined the technology use patterns in the latest literature and identified similar trends in using different types of technologies to support modeling-based instruction. Given the time gap in available technology and its integration in classroom practice, the researchers believe that the insights and instructional implications derived from this time period still are useful and applicable to the field.

This synthesis research also sheds light on some challenges in integrating technology into modeling-based instruction. First, it takes a lot of resources to design technology-supported models or modeling environment for instruction, and often requires the collaboration among researchers, designers, and classroom teachers that may take several stages and years to complete (BioLogica™, n.d; Sun & Sooi, 2013). Second, even after the modeling program or environment has already been built, it is challenging to continue developing, maintaining, and providing support for classroom integration. In general, the online modeling projects and programs have been designed, maintained, and researched with external funding. When the funding ends, the program may no longer be available to be used in classroom teaching. For example, BioLogica™, a hypermodel for teaching high school genetics, is supported by a grant from the National Science Foundation. Today, its homepage shows "BioLogica™ is no longer maintained or supported. Third, integrating technology into classroom teaching and learning is another challenge. The time gap between the available technology resources and what is being reported in literature indicates the lack of efficient and effective integration of technology-supported modeling resources in instruction. Future research is needed to examine the affordances and challenges of technology-supported modeling-based instruction, and more research needs to focus on how to help teachers identify and integrate subject-related technology tools and resources into classroom practices.

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Appendix A: Empirical Studies of MBI in K-12 science Education from 2000 to 2010

Year	Authors	Title	Source
2010	Wu	Modelling a Complex System: Using Novice-Expert Analysis for Developing an Effective Technology-Enhanced Learning Environment	International Journal of Science Education
2010	Stocklmayer	Teaching Direct Current Theory Using a Field Model	International Journal of Science Education
2010	Rundgren & Tibell	Critical Features of Visualizations of Transport through the Cell Membrane--an Empirical Study of Upper Secondary and Tertiary Students' Meaning-Making of a Still Image and an Animati	International Journal of Science and Mathematics Education
2010	Mendonca & Justi	Contributions of the Model of Modelling Diagram to the Learning of Ionic Bonding: Analysis of a Case Study	Research in Science Education
2010	Mulder, Lazonder & de Jong	Finding Out How They Find It Out: An empirical analysis of inquiry learners' need for support	International Journal of Science Education
2010	Lee	The Interactions between Problem Solving and Conceptual Change: System Dynamic Modelling as a Platform for Learning	Computers & Education
2010	Ketelhut & Nelson	Designing for Real-World Scientific Inquiry in Virtual Environments	Educational Research
2010	Johnson & Papageorgiou	Rethinking the Introduction of Particle Theory: A Substance-Based Framework	Journal of Research in Science Teaching
2010	Eskrootchi & Oskrochi	A Study of the Efficacy of Project-Based Learning Integrated with Computer-Based Simulation--STELLA	Educational Technology & Society
2010	Cheng & Brown	Conceptual Resources in Self-developed Explanatory Models: The importance of integrating conscious and intuitive knowledge	International Journal of Science Education
2010	Chang, Quintana & Krajcik	The Impact of designing and evaluating molecular animations on how well middle school students understand the particularte nature of matter	Science Education

Appendix A: Empirical Studies of MBI in K-12 science Education from 2000 to 2010

Year	Authors	Title	Source
2009	Kaberman & Dori	Question Posing, Inquiry, and Modeling Skills of Chemistry Students in the Case-Based Computerized Laboratory Environment	International Journal of Science and Mathematics Education
2009	Kucukozer, Korkusuz, Kucukozer &Yurumezoglu	The Effect of 3D Computer Modeling and Observation-Based Instruction on the Conceptual Change regarding Basic Concepts of Astronomy in Elementary School Students	Astronomy Education Review
2009	Maia & Justi	Learning of Chemical Equilibrium through Modelling-Based Teaching	International Journal of Science Education
2009	Manlove, Lazonder & de Jong	Collaborative versus Individual Use of Regulative Software Scaffolds during Scientific Inquiry Learning	Interactive Learning Environments, v17 n2 p105-117 Jun 2009
2009	Prins, Bulte, Van Driel & Pilot	Students' Involvement in Authentic Modelling Practices as Contexts in Chemistry Education	Research in Science Education
2009	Schwarz, Reiser, Davis, Kenyon, Acher, Fortus, Shwartz, Hug & Krajcik	Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners	Journal of Research in Science Teaching
2009	Levy & Wilensky	Students' Learning with the Connected Chemistry (CC1) Curriculum: Navigating the Complexities of the Particulate World	Journal of Science Education and Technology
2009	Sins, Savelsbergh, van Joolingen & van Hout-Wolters	The Relation between Students' Epistemological Understanding of Computer Models and Their Cognitive Processing on a Modelling Task	International Journal of Science Education
2009	Urban-Woldron	Interactive Simulations for the Effective Learning of Physics	Journal of Computers in Mathematics and Science Teaching
2008	Verhoeff, Waarlo & Boersma	Systems Modelling and the Development of Coherent Understanding of Cell Biology	International Journal of Science Education

Appendix A: Empirical Studies of MBI in K-12 science Education from 2000 to 2010

Year	Authors	Title	Source
2008	Angell, Kind, Henriksen & Guttersrud	An Empirical-Mathematical Modelling Approach to Upper Secondary Physics	Physics Education
2008	Buty & Mortimer	Dialogic/Authoritative Discourse and Modelling in a High School Teaching Sequence on Optics	International Journal of Science Education
2008	Meier, Reinhard, Carter & Brooks	Simulations with Elaborated Worked Example Modeling: Beneficial Effects on Schema Acquisition	Journal of Science Education and Technology
2008	Hsu, Wu & Hwang	Fostering High School Students' Conceptual Understandings about Seasons: The Design of a Technology-Enhanced Learning Environment	Research in Science Education
2008	Nitza Barnea & Shauli	The Effect of a Computerized Simulation on Middle School Students' Understanding of the Kinetic Molecular Theory	Journal of Science Education and Technology
2008	Louca & Zacharia	The Use of Computer-Based Programming Environments as Computer Modelling Tools in Early Science Education: The Cases of Textual and Graphical Program Languages	International Journal of Science Education
2008	Nuhoglu & Nuhoglu	Modeling Spring Mass System with System Dynamics Approach in Middle School Education	The Turkish Online Journal of Educational Technology – TOJET
2008	Padalkar & Ramadas	Modeling the Round Earth through Diagrams	Astronomy Education Review
2008	Sensevy, Tiberghien, Santini, Laube & Griggs	An Epistemological Approach to Modeling: Cases Studies and Implications for Science Teaching	Science Education
2008	Hsu	Learning about Seasons in a Technologically Enhanced Environment: The Impact of Teacher-Guided and Student-Centered Instructional Approaches on the Process of Students' Conceptual Change	Science Education

Appendix A: Empirical Studies of MBI in K-12 science Education from 2000 to 2010

Year	Authors	Title	Source
2008	Fazio, Guastella, Sperandeo-Mineo & Tarantino,	Modelling Mechanical Wave Propagation: Guidelines and Experimentation of a Teaching-Learning Sequence	International Journal of Science Education
2008	Windschitl, Thompson & Braaten	Beyond the Scientific Method: Model-Based Inquiry as a New paradigm of Preference for School Science Investigations	Science Education
2007	Tsui & Treagust	Understanding genetics: Analysis of secondary students' conceptual status	Journal of Research in Science Teaching
2007	Ergazaki, Zogza & Komis	Analysing Students' Shared Activity while Modeling a Biological Process in a Computer-Supported Educational Environment	Journal of Computer Assisted Learning
2007	Acher, Arca & Sanmarti	Modeling as a Teaching Learning Process for Understanding Materials: A Case Study in Primary Education	Science Education
2007	Komis, Ergazaki & Zogza	Comparing Computer-Supported Dynamic Modeling and "Paper & Pencil" Concept Mapping Technique in Students' Collaborative Activity	Computers & Education
2007	Schwarz & Gwekwerere	Using a Guided Inquiry and Modeling Instructional Framework (EIMA) to Support Preservice K-8 Science Teaching	Science Education
2007	Finson & Beaver	Time on Your Hands: Modeling Time	Science Scope
2007	Papaevripidou, Constantinou & Zacharia	Modeling complex marine ecosystems: an investigation of two teaching approaches with fifth graders	Journal of Computer Assisted Learning
2006	Li, Law & Lui	Cognitive Perturbation through Dynamic Modelling: A Pedagogical Approach to Conceptual Change in Science	Journal of Computer Assisted Learning
2006	Liu	Effects of Combined Hands-on Laboratory and Computer Modeling on Student Learning of Gas Laws: A Quasi-Experimental Study	Journal of Science Education and Technology

Appendix A: Empirical Studies of MBI in K-12 science Education from 2000 to 2010

Year	Authors	Title	Source
2006	Simpson, Hoyles, & Noss	Exploring the Mathematics of Motion through Construction and Collaboration	Journal of Computer Assisted Learning
2006	Wilensky, Uri; Reisman & Kenneth	Thinking Like a Wolf, a Sheep, or a Firefly: Learning Biology through Constructing and Testing Computational Theories--An Embodied Modeling Approach	Cognition and Instruction
2006	Hennessy, Deaney & Ruthven	Situated Expertise in Integrating Use of Multimedia Simulation into Secondary Science Teaching	International Journal of Science Education
2006	Pata & Sarapuu	A Comparison of Reasoning Processes in a Collaborative Modelling Environment: Learning about Genetics Problems Using Virtual Chat	International Journal of Science Education
2005	Ergazaki, Komis & Zogza	High-School Students' Reasoning while Constructing Plant Growth Models in a Computer-Supported Educational Environment. Research Report	International Journal of Science Education
2005	Klopfer, Yoon & Um	Teaching Complex Dynamic Systems to Young Students with StarLogo	Journal of Computers in Mathematics and Science Teaching
2005	Schwarz & White	Metamodeling Knowledge: Developing Students' Understanding of Scientific Modeling	Cognition and Instruction
2005	Sins, Savelsbergh & van Joolingen,	The Difficult Process of Scientific Modelling: An Analysis Of Novices' Reasoning During Computer-Based Modelling	International Journal of Science Education
2004	Pallant & Tinker	Reasoning with Atomic-Scale Molecular Dynamic Models	Journal of Science Education and Technology
2004	Metcalf & Tinker	Probeware and Handhelds in Elementary and Middle School Science	Journal of Science Education and Technology

Appendix A: Empirical Studies of MBI in K-12 science Education from 2000 to 2010

Year	Authors	Title	Source
2004	Buckley, Gobert, Kindfield, Horwitz & Tinker	Model-Based Teaching and Learning with BioLogica™: What Do They Learn? How Do They Learn? How Do We Know?	Journal of Science Education and Technology
2004	Parnafes & Disessa	Relations between Types of Reasoning and Computational Representations	International Journal of Computers for Mathematical Learning,
2003	Treagust, Chittleborough & Mamiala	The Role of Submicroscopic and Symbolic Representations in Chemical Explanations	International Journal of Science Education
2003	Saari, Heikki	A Research-Based Teaching Sequence for Teaching the Concept of Modelling to Seventh-Grade Students	International Journal of Science Education
2003	Clement & Oviedo	Abduction and analogy in scientific model construction	Paper presented at the National Association for Research in Science Teaching Conference, Philadelphia.
2002	Fretz, Wu, Zhang, Davis, Krajcik & Soloway	An Investigation of Software Scaffolds Supporting Modeling Practices.	Research in Science Education
2002	Passmore, C. & Stewart, J.	A modeling approach to teaching evolutionary biology in high school	Journal of research in science teaching
2002	Schwarz	Using Model-Centered Science Instruction To Foster Students' Epistemologies in Learning with Models.	Paper presented at the Annual Meeting of AERA (New Orleans, LA, April 1-5, 2002).
2002	Johnson & Stewart	Revising and assessing explanatory models in a high school genetics class: A comparison of unsuccessful and successful performance	Science Education
2001	Hogan & Thomas	Cognitive Comparisons of Students' Systems Modeling in Ecology.	Journal of Science Education and Technology

Appendix A: Empirical Studies of MBI in K-12 science Education from 2000 to 2010

Year	Authors	Title	Source
2001	Patrick, Carter & Wiebe	Visual Representations of DNA Replication: Middle Grades Students' Perceptions and Interpretations	Journal of Science Education and Technology
2000	Grotzer	How Conceptual Leaps in Understanding the Nature of Causality Can Limit Learning: An Example from Electrical Circuits.	NSF report in ERIC
2000	Cartier	Assessment of Explanatory Models in Genetics: Insights into Students' Conceptions of Scientific Models. Research Report.	Report in ERIC
2000	Cartier	Using a Modeling Approach To Explore Scientific Epistemology with High School Biology Students. Research Report.	Report in ERIC
2000	Buckley	Interactive multimedia and model-based learning in biology	International Journal of Science Education

Appendix B: The list of journals selected for the second round of literature search

1.International Journal of Science Education

http://www.tandf.co.uk/journals/tf/09500693.html

2.International Journal of Math and Science Education

http://www.springer.com/education+%26+language/mathematics+education/journal/10763

3.Journal of the Learning Sciences

http://www.tandf.co.uk/journals/authors/hlnsauth.asp

4.Journal of Science Education and Technology

http://www.springerlink.com/content/102587/

5.Science Education

http://www3.interscience.wiley.com/journal/32122/home?CRETRY=1&SRETRY=0

Appendix B: The list of journals selected for the second round of literature search

6.Journal of Research in Science Teaching

http://www3.interscience.wiley.com/journal/31817/home

7.Research in Science Education

http://www.springerlink.com/content/108230/

8.Science & Education

http://www.springerlink.com/content/102992/

9.Studies in Science Education

http://www.tandf.co.uk/journals/titles/03057267.asp

10.The Journal of Science Teacher Education

http://www.springerlink.com/content/102947/

11.Cultural studies of Science Education

http://link.springer.com/journal/11422

12.Journal of Chemical Education http://pubs.acs.org/journal/jceda8

13.CBE Life Sciences Education http://www.lifescied.org/

14.Research in Science & Technology Education http://www.tandfonline.com/toc/crst20/current#.VmEaoedVvC4