Science
Education

An Activity-Based Instructional Framework for Transforming Authentic Modeling Practices into Meaningful Contexts for Learning in Science Education

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Received 12 September 2013; revised 4 May 2016; accepted 4 May 2016
DOI 10.1002/sce.21247

ABSTRACT: One of the challenges of science education is to integrate activities, content, and tools in a meaningful manner. One way to address this challenging goal is the transformation of authentic scientific practices into contexts for learning, in line with sociocultural activity theory. In this respect, authentic scientific practices are interpreted as the totality of human work situated in society. Within such authentic scientific practices, the activities, content, and tools are connected logically and the relevance is clear among its participants. This study presents an activity-based instructional framework that assists educational designers in transforming authentic scientific practices for the population of students in science education. The activity-based instructional framework has been dialectically constructed with the design and classroom enactment of a curriculum unit based on an authentic chemical modeling practice. The curriculum unit was developed through a participatory design process that took teachers' expertise into account. The pedagogical decisions were abstracted in design guidelines. The curriculum unit was implemented multiple times in classroom to evaluate the design guidelines. Research data were collected by means of audio-taped discussions, completed worksheets, and written questionnaires. The findings supported the potential of transforming authentic scientific practices to achieve meaningful science education. © 2016 Wiley Periodicals, Inc. *Sci Ed* **100:**1092–1123, 2016

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INTRODUCTION

The need for meaningful science education, in which coherency exists between scientific activities, content, and tools, is a recurring theme in the research community and beyond (Osborne & Dillon, 2008; Schmidt, Wang, & McKnight, 2005). Achieving meaningful science education faces two challenges (Johnson & Ratcliff, 2004). From a design perspective, one challenge is how to accomplish coherency between scientific activities, content, and tools in learning environments (Gilbert, Bulte, & Pilot, 2011). From a learners' perspective, another challenge is to what extent students perceive such coherency (Lijnse & Klaassen, 2004). This twofold challenge might be addressed by founding science education on authentic scientific practices embedded in society. Therefore, we understand authentic scientific practices as human activities situated in society, a culturally developed, more or less coherent way of dealing with (mental) objects. Within such authentic scientific practices, the activities, content, and tools are connected logically and the relevance is clear and unquestioned among its participants.

The idea to ground science education on authentic scientific practices stems from and relates to activity theory (Engestrom, 1987; Leont'ev, 1978; Van Aalsvoort, 2004). Activity theory builds on principles from sociocultural theories on learning (Van Oers, 1998; Vygotsky, 1978), and is typically grouped with other sociocultural theories of learning, such as inquiry-based learning (Krajcik et al., 1998), problem-based learning (Kolodner et al., 2003), and situated cognition (Brown, Collins, & Duguid, 1989). Activity theory is aimed at understanding the totality of human work and praxis, that is, collective activity systems in society. This implies not only examining what kinds of activities people engage in, but also who is engaged in that activity, what their goals and intentions are, what objects or products result from the activity, the rules and norms that circumscribe that activity, and the larger community in which the activity occurs. Activity theory, in essence, is a descriptive theory that gives an account of how learning is mediated by collective activity. However, transforming authentic practices, that is, collective activity systems in society, into contexts for learning in classroom, that is, classroom activity systems, is no straightforward design task. The sheer number of potentially relevant elements of collective activity systems in society makes it impractical if not outright impossible to account for all of them in classroom activity systems (Witte & Haas, 2005). This has been suggested as one of the reasons that activity theory has not seen more widespread adoption in designing educational interventions (Engestrom, 2008; Roth & Lee, 2007). Key questions in the transformation of authentic practices into classroom activity systems include the following: What should be kept? What should be removed? What should be modified and how?

A limited number of studies do provide heuristics for using activity theory for the design of education. Danish (2014) has described an approach for exploring three core aspects of activity theory as grounding elements for designing classroom activity systems. These core aspects are as follows: (1) identifying the object of the activity, (2) exploring the mediators of the activity, and (3) determining what psychological tools students will likely appropriate from participating in the activity. Jonassen and Rohrer-Murphy (1999) have described a process for using activity theory for describing the components of an activity system. The process consists of a sequence of steps, namely (1) clarify the purpose of the activity system, (2) analyze the activity system, (3) analyze the activity structure, (4) analyze mediators, (5) analyze the contextual bounds, and (6) analyze activity system dynamics. Van Aalsvoort (2004) has formulated design criteria for school versions of chemical or chemistry-related authentic practices. These studies emphasize, on the one hand, procedures to unravel collective activity systems in society, and on the other hand, postulate criteria for classroom activity systems. However, they do not deliver prescriptive guidelines for transforming authentic scientific practices into meaningful contexts for learning in science education.

Existing instructional frameworks for other sociocultural theories of learning, such as the Learning-for-Use model (Edelson, 2001), the Learning goals driven design model (Krajcik, McNeill, & Reiser, 2007), and the Scaffold-design framework (Quintana et al., 2004), contain worthwhile guidelines but none of them suits activity theory completely. What sets activity theory apart from other sociocultural theories of learning is a focus on shared collective activity as the primary unit of knowledge. Activity theory posits that conscious learning emerges from activity, not as a precursor to it (Jonassen & Rohrer-Murphy, 1999). In addition, activity theory emphasizes the relation between human activity and society.

This study sought to develop an instructional framework, aligned with activity theory, that delivers guidance for the transformation of authentic scientific practices into classroom activity systems, such that the coherence between scientific activities, content, and tools is preserved. The instructional framework is abstracted from the design and subsequent classroom implementation of a curriculum unit, using an authentic scientific modeling practice as context for learning. The developmental process consists of several stages in which both the curriculum unit and the corresponding instructional framework are evaluated, revised, and enriched.

ACTIVITY THEORY IN EDUCATION

Activity theory is a powerful sociocultural and sociohistorical lens through which we can analyze most forms of human activity and consciousness within its relevant environmental context. Kuutti (1996, p. 532) described activity theory as a "philosophical framework for studying different forms of human praxis as developmental processes, both individual and social levels interlinked at the same time." Activity theory adopts Marx's dialectic materialist view of activity and consciousness as dynamically interrelated (Leont'ev, 1972), which provides an alternative perspective to the mentalistic and idealist view of human knowledge, which claims that learning must precede activity. There is a reciprocal regulatory feedback between knowledge and activity (Fishbein, Eckart, Lauver, Van Leeuwen, & Langemeyer, 1990). When we act, we gain knowledge, which affects our actions, which changes our knowledge, and so on. This transformation process is critical to the conception of learning in activity theory.

The components of any activity are organized into activity systems (Engestrom, 1987), depicted as a triangle in Figure 1. Any activity system is goal-oriented and involves an object of the activity (mental or physical product) and a subject engaged in the activity (individual or group of actors). The activity is mediated by tools (physical, such as hammers, or mental, such as heuristics), rules, and division of labor in a community. In line with contemporary learning theories, such as constructivism, activity theory claims that learning only takes place as a result of goal-directed activity. Concepts, rules, tools, and theories that are not associated with goal-directed activity have no meaning.

Using activity theory as a basis for learning in formal science education involves the transformation of authentic scientific practices into classroom activity systems. This means that the students are assigned learning tasks that resemble characteristic activities in an authentic scientific practice. When carrying out these tasks, the learner becomes acquainted with the tools, materials, and thoughts belonging to that authentic scientific practice. This includes the language used, via genres such as talks, reports, articles, or designs. Other tools are the scientific procedures to be followed and, for example, laboratory equipment. Equally important are the values and attitudes that are inherent in an authentic scientific

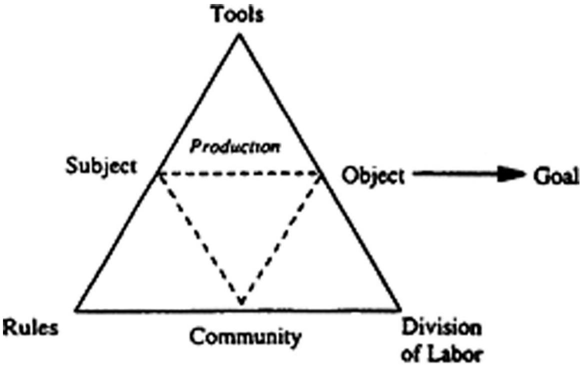

Figure 1. Schematic representation of an activity system.

practice, as well as the quality standards. The teachers' role is to guide learners through the tasks by instructing, encouraging, and, ultimately, letting learners do it by themselves. Inevitably, the greater experience and knowledge of the teacher leads to him/her taking a position of authority, but not one of being an authoritarian in these interactions, taking care to work within the "zone of proximal development" of each student.

Transformation of authentic scientific practices might be a design strategy to achieve coherency in science education, that is, preserve the natural coherency between goal-directed activities, concepts, rules, tools, and theories. To assist in appropriate pedagogical decisions during the transformation process, an instructional framework aligned with activity theory is desirable.

INSTRUCTIONAL FRAMEWORKS

An instructional framework might be regarded as a component of an instructional design theory. An instructional design theory relates specific instructional events to learning processes and learning outcomes, identifies instructional conditions that optimize learning outcomes, and provides a rational description of causal relationships between procedures used to teach and their behavioral consequences in enhanced human performance (Reigeluth, 1999). Existing instructional frameworks building on sociocultural theories of learning consist of basically three components. First of all, the learning trajectory is divided into distinct phases, with explicit modes of learning, such as orienting, planning, or reflecting. Second, each phase consists of design guidelines that articulate the requirements that a set of learning activities must meet to achieve particular learning objectives. Third, each phase holds a number of pedagogical functions (PFs) that link the design guidelines with a spectrum of learning objectives, such as motivation, sense making, or knowledge demand (Mettes, Pilot, & Roossink, 1981; Vermunt & Verloop, 1999).

Initial Instructional Framework for Transforming Authentic Scientific Practices

Previous research has resulted in an initial instructional framework offering heuristics to fuse authentic scientific practices with school environments (Bulte, Westbroek, De Jong, & Pilot, 2006; Kortland, 2001; Westbroek, Klaassen, Bulte, & Pilot, 2010). The initial instructional framework, as depicted in Table 1, is furthermore inspired by the

TABLE 1
Initial Instructional Framework for the Transformation of an Authentic Practice to a Context for Learning in Science Education

Initial Instructional Framework (Bulte et al., 2006)		Guidelines Which Have Inspired the Sequence and Formulation of the PFs
LPs	PFs	Instructional Design Framework for Authentic Learning Environments (Herrington & Oliver, 2000)
I. Orient toward and connect with the practice	PF_a: Evoke motivation to study the practice PF_b: Connect to the prior conceptual knowledge base PF_c: Connect to the prior procedural knowledge base PF_d: Evoke motivation to study exemplary problems or questions	Provide authentic contexts that reflect the manner in which the knowledge will be used in real life
II. Focus on an exemplary problem or question	PF_e: Make explicit and build on the prior conceptual knowledge base PF_f: Make explicit and build on the prior procedural knowledge base PF_g: Evoke an incentive to handle the exemplary problem or question	Provide access to expert performances and the modeling of processes Provide multiple roles and perspectives
III. Solve the exemplary problem or answer the question	PF_h: Proceed through the sequence of actions and learn/apply knowledge until a solution or answer can be presented	Provide authentic activities Provide coaching and scaffolding by the teacher at critical times Support collaborative construction of knowledge
IV. Evoke an incentive to express the findings	PF_i: Induce an incentive to express the learned conceptual and procedural knowledge	Promote articulation to enable tacit knowledge to be made explicit
V. Express and reflect on the findings	PF_j: Make explicit the learned conceptual and procedural knowledge PF_k: Draw up a project plan for handling a similar exemplary problem or question posed in the authentic practice	Promote reflection to enable abstractions to be formed Provide authentic assessment of learning within the tasks

Abbreviations: LP, learning phase; PF, pedagogical function.

Learning-for-Use model (Edelson, 2001), the First Principles of Instruction (Merrill, 2002), and the Instructional Design Framework for Authentic Learning Environments (Herrington & Oliver, 2000).

The initial instructional framework distinguishes five learning phases, listed in the left-hand column of Table 1. The PFs, listed in the second column from the left in Table 1, describe the desired pedagogic outcomes of the learning activities in each learning phase.

The sequence and formulation of the PFs stem from the elements in the Instructional Design Framework for Authentic Learning Environments (Herrington & Oliver, 2000), listed in the right column in Table 1. The initial instructional framework, however, lacks prescriptive design guidelines on how to render complex, multifaceted, authentic scientific practices into contexts for learning in science education. In line with the activity theory, the design guidelines should describe learning activities to be conducted by students, mediated by selected artifacts from the reflected authentic scientific practice.

The initial instructional framework strives to support educational designers in establishing coherency between scientific activities, concepts, and tools from the students' perspective (Bulte et al., 2006). The extent of completion of the PFs is regarded as an indication of students' experienced coherency. In the first learning phase, students are involved in the real-world societal issues embedded in the authentic scientific practice at hand. The starting learning activities should result in students becoming motivated to study the authentic scientific practice itself and the exemplary problems posed in the practice. PF_a to PF_d in the first learning phase reflect that students, in comparison to experts, have different motives and drivers to study a particular problem or question, have a different sense of urgency regarding the (societal) relevance of the issue, and have limited background information and prior knowledge regarding the issue at hand (Prins, Bulte, Van Driel, & Pilot, 2009). The learning activities in the second learning phase should make explicit to students *what* they are going to learn and master as well as *how*, based on their prior knowledge base. The exemplary problem should be transformed so that students feel encouraged to solve it. PF_e to PF_g reflect that, in contrast to experts, students have different goal settings and views on the exemplary problem or question. In the third learning phase, students work on the exemplary problem. The sequence of actions conducted by experts in the authentic scientific practice itself serve as a source of inspiration. The learning trajectory should be outlined so that students see *why* and *what* to do at every point in the process (Klaassen, 1995; Lijnse & Klaassen, 2004). PF_h reflects that, in contrast to experts, it cannot be expected that students have an equal view, if any, on the sequence of actions to conduct to arrive at an answer or solution to the transformed exemplary problem or question on which they are working (Westbroek et al., 2010). Finally, in the fourth and fifth learning phases, students make their learning explicit and reflect on the broader applicability and limitations of their newly acquired knowledge, by examining similar problems that exist in the same or related authentic scientific practice(s). These last two learning phases should allow students to see the relevance of the science content and skills learned that are representative for a collection of authentic scientific practices in the same domain or field (Gott, Duggan, & Johnson, 1999). PF_i to PF_k underline that students should be encouraged to evaluate and reflect on different grounds in comparison to experts. Experts reflect and report on the work performed in light of handling (similar) problems or questions in the (near) future.

SCOPE AND RESEARCH QUESTIONS

This research project is part of a larger program of studies in the Netherlands that aims at making secondary preuniversity chemistry education meaningful to students. This research project specifically focuses on transforming authentic chemical modeling practices into classroom activity systems. The authentic practice "modeling drinking water treatment" is used as a specific case (Prins et al., 2009; Prins, Bulte, Van Driel, & Pilot, 2008).

In recent decades, there has been growing recognition of the necessity of taking the tacit knowledge and expertise of teachers into account so that effective pedagogical decisions regarding the design of curriculum materials can be made (Guskey, 2000; Penuel &

Gallaghet, 2009). Therefore, six chemistry teachers were appointed as codesigners to transform the authentic practice "modeling drinking water treatment" into a context for learning, embodied in a curriculum unit. All six chemistry teachers also enacted the curriculum unit in their own class. The aim of this research project was to evaluate, revise, and enrich the initial instructional framework such that it provides guidance for transforming authentic modeling practices into meaningful science education. Two research questions were addressed. The first research question addressed the coherency between scientific activities, content, and tools in the design of the curriculum unit itself, the second on the perceived coherence from the students' perspective.

A. *Which design guidelines can be abstracted from the transformation of the authentic chemical practice "modeling drinking water treatment" into a context for learning, such that coherency between scientific activities, content, and tools is preserved?*
B. *To what extent do students experience coherency between scientific activities, content, and tools in the curriculum unit?*

METHOD

In this section, we first provide an overview of the authentic practice "modeling drinking water treatment" (Versteegh & Te Biesebeek, 2003) at hand, using the six components of activity systems as proposed by Jonassen and Rohrer-Murphy (1999). Next, we focus on the procedure, participants, data collection, and analysis in this study.

Authentic Chemical Practice "Modeling Drinking Water Treatment"

The Purpose of the Activity System. This authentic practice sought to represent the complete water treatment process using a series of mathematical models that enable the prediction of the quality of drinking water after various treatments, given a certain raw water quality.

The Activity System: Subjects, Community, and Objects. The subjects were (1) experts on water treatment working at the National Institute of Public Health and the Environment in the Netherlands, (2) civil servants from the Ministry of Infrastructure and the Environment and the Ministry of Health, Welfare and Sport, (3) process engineers employed at universities involved in the production of drinking water, and (4) technologists from drinking water companies. Together they formed a community carrying out the activity. The object they worked on was a model for the analysis of the production of drinking water with the following objectives:

- To predict, on a broad scale, the quality of drinking water (including the levels of health risk posed by microorganisms) given a certain raw water quality.
- To determine the probability of the occurrence of pathogenic microorganisms and by-products of disinfection in the product of a treatment plant.
- To advise the drinking water inspectorate by reviewing new or renewed production plants, especially with regard to public health risks.

The activity was managed by the experts working at the National Institute of Public Health and the Environment. The labor was divided within the community, in terms of modeling the removal of specific contaminants by selected treatment methods.

The Activity Structure: Procedures, Actions, and Operations. The modeling procedure consisted of three main steps: (1) for each treatment step the relevant process variables were identified; (2) their influence on the effectiveness of the removal of microorganisms and other contaminants was determined, first on a qualitative level and, second, on a quantitative level, by gathering empirical data through laboratory experiments and/or using real company data; and (3) the gathered data were analyzed using statistical techniques. Figure 2 shows the modeling procedure, actions, and operations.

Mediators: Theories, Writings, Means of Communication, Mental and Physical Tools. Participation in this authentic practice requires, among others, in-depth knowledge of treatment methods, such as activated carbon filtration and coagulation and flocculation, including the underlying theories and principles from the domain of physical chemistry. In addition, one should master the skill of modeling. Each treatment step is represented by a mathematical model ranging in complexity from percent removal, to empirical and mechanistic models. The decision regarding which type of model was developed for a particular treatment step was made on the basis of the available theoretical and empirical data. Numerous instruments are used for collecting empirical data and subsequent analysis, such as turbidity sensors, and advanced software tools for performing regression. To maintain focus on the progress in this large and distributed activity, the subjects involved organized meetings on a regular basis and informed each other using so-called factsheets. A factsheet is a concise, sententious overview about the conducted activities in a certain period of time and the obtained results. This communication tool was frequently used and referred to during the physical meetings. Figure 2 shows the conceptual knowledge used in each step of the modeling procedure.

Contextual Bounds: Subject-Driven or Community-Driven Beliefs, Assumptions, and Methods. The quality of drinking water is an important issue in public healthcare. Different kinds of organic compounds, heavy metals, and microorganisms need to be removed to produce safe drinking water. The government and the drinking water companies expect a growing demand for drinking water due to the increase in the population and the level of prosperity. To meet this extra demand, new sources for the production of drinking water have to be found, or the use of existing sources needs to be intensified. This requires more detailed knowledge of the influence of various process variables on the treatment process.

Activity System Dynamics: How Components Affect Each Other. This component is focused on selecting elements of the authentic practice to use in the context for learning to be designed. The above description of the authentic practice illustrates that the modeling of the complete drinking water treatment was a large and complicated activity, in which many subjects were involved. For use in science education, the focus was on the removal of turbidity by coagulation and flocculation, since this can be investigated empirically within the constraints of a classroom. The end turbidity of the water is influenced by various process variables, such as starting turbidity, dose coagulant, pH, and temperature. The influence can be determined by conducting a series of experiments that manipulate each process variable in a controlled way. The end turbidity as a function of process variables can be described with a multiple regression model. The regression model can be evaluated on characteristics such as purpose, goodness of fit, reliability, and validity. The applied modeling approach can be typified as "data-driven" or "black-box" modeling.

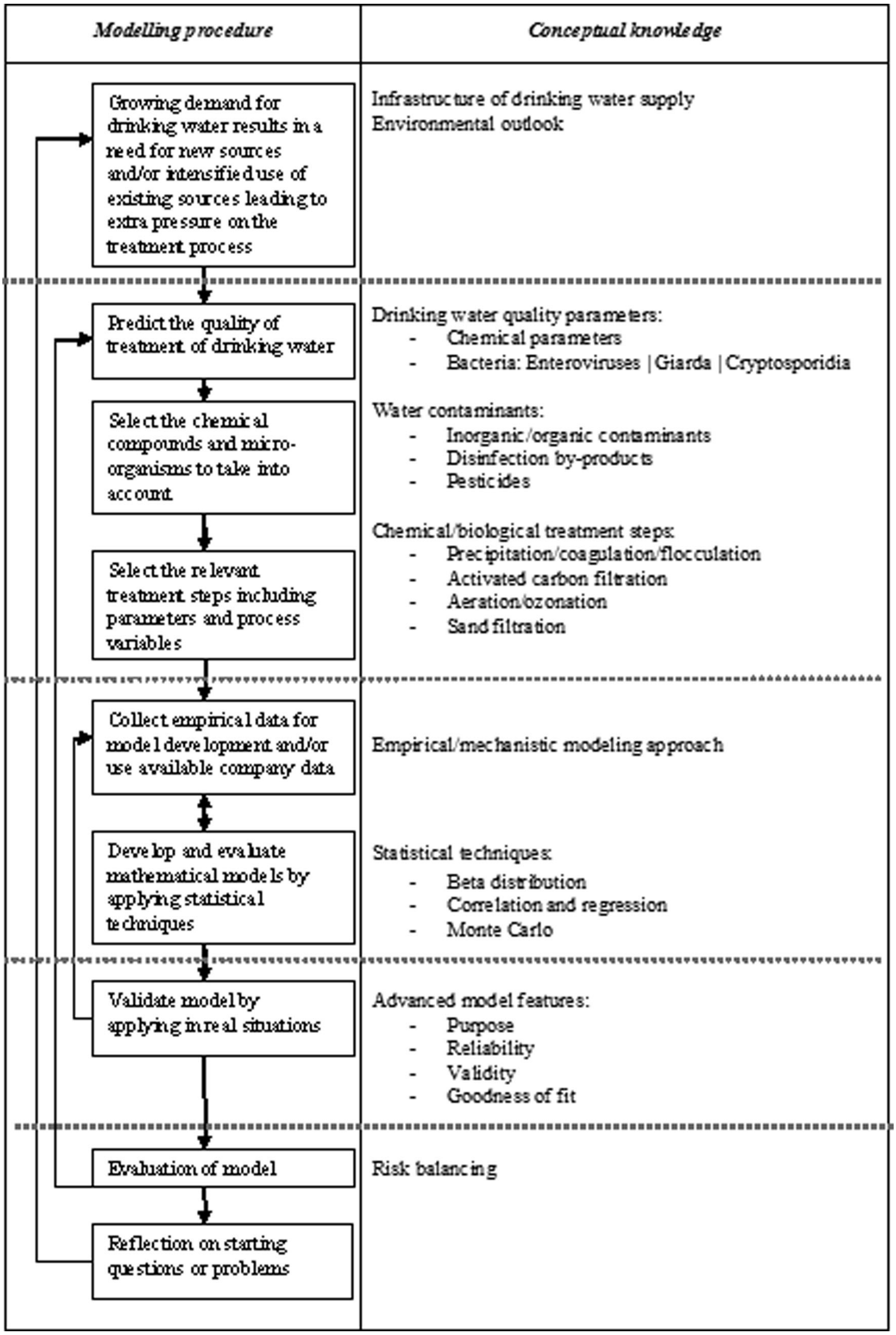

Figure 2. Modelling procedure and conceptual knowledge in the authentic practice "modeling drinking water treatment."

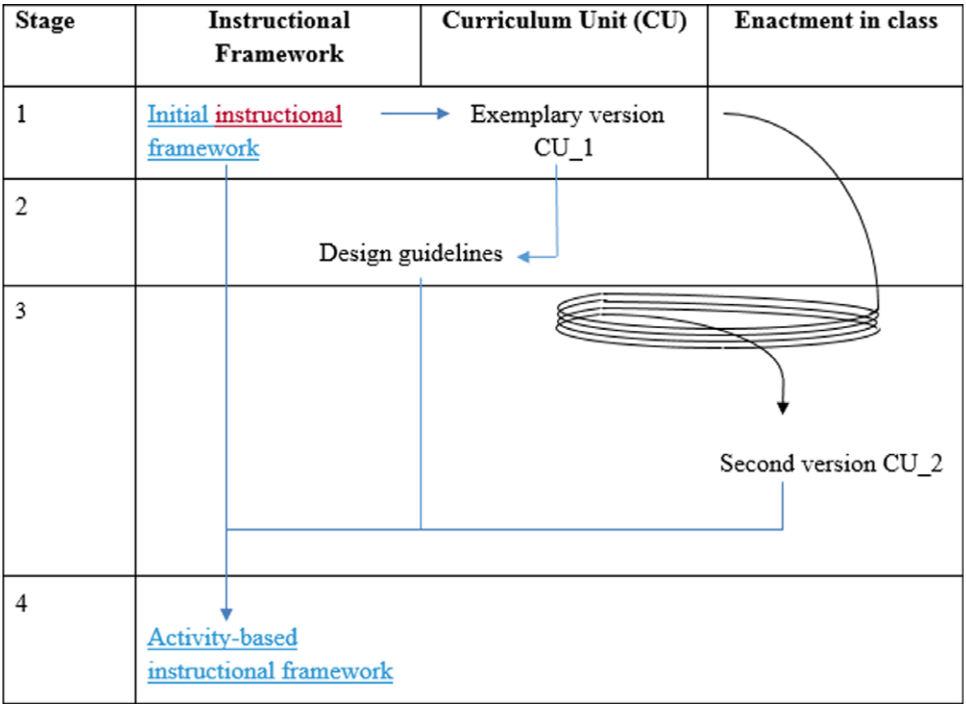

Figure 3. Outline of the research project in four consecutive stages.

Procedure, Participants, Data Collection, and Analysis

This design-based research project encompassed four consecutive stages, depicted in Figure 3. In Stage 1, an exemplary version of the curriculum unit (CU_1) was designed, guided by the initial instructional framework. In Stage 2, the pedagogic decisions were conceptualized as design guidelines. In Stage 3, the exemplary curriculum unit (CU_1) was piloted in four different classes resulting in a second version (CU_2). This second version (CU_2) was enacted in two different classes and studied in-depth to reveal the experienced coherency in learners. Finally, in Stage 4, the results of the implementation of CU_2 were analyzed and used to revise and enrich the initial instructional framework, yielding an activity-based instructional framework.

Participants. This study involved six chemistry teachers in Stage 1 and 36 students in Stage 3, Grades 10/11 (aged 16–17). Each of the teachers had over 10 years of experience in chemistry education from Grade 7 up to Grade 12. They all participated voluntarily and had the intention of teaching the curriculum unit in their own class. The students who were taught the curriculum unit CU_2 came from different schools. The schools can be characterized as rural schools with few students from ethnic minorities.

Stage 1: Transformation of the Authentic Modeling Practice Into a Curriculum Unit. The exemplary version of the curriculum unit CU_1 was developed according to a participatory design (PD) process by the authors with six chemistry teachers. PD entails the collaboration of designers and intended users (Foster, Dimmock, & Bersani, 2008) and is a method that takes into account the latter's tacit knowledge, that is, the implicit or unarticulated knowledge that has been developed and transmitted through experience and apprenticeships (Mankin, Cohen, & Bikson, 1997). The chemistry teachers and the two researchers (the first and second author) met four times in 3-hour sessions over a period of 8 months, in which the authentic practice "modelling drinking water treatment" was analyzed and transformed guided by the initial instructional framework (Table 1). In the first meeting, the focus was on designing Learning Phases I and II (orient toward and connect with the practice; focus on an exemplary problem or question). In the second meeting, Learning Phases IV and V were outlined (evoke an incentive to express the findings; express and reflect on the findings). Learning Phase III (solve the exemplary problem or answer the question) was constructed in the third meeting. After each meeting, the teachers individually summarized their views and ideas about how to transform the authentic modeling practice. Finally, in the fourth and final meeting, the teachers discussed a preliminary version of the entire curriculum unit, which had been constructed by the first author based on the input from the teachers in the preceding three meetings. The group discussion was audio-taped and transcribed verbatim. The outcomes of the discussion led to the construction of the exemplary version of the curriculum unit (CU_1).

Stage 2: Formulation of Design Guidelines. The pedagogic decisions in each learning phase in the preceding stage were abstracted and conceptualized in design guidelines by the first and second author. The analysis was conducted from an interpretative perspective (Smith, 1995). The first author analyzed the group discussion in the fourth meeting to reveal the major arguments underpinning the filling-in and sequence of teaching and learning activities (TLAs) in each learning phase. Next, the first and second author individually (1) related the assigned TLAs to one (or more) PF(s) and (2) abstracted the pedagogic decisions into design guidelines. Lastly, the three authors discussed the formulated design guidelines and their linkage with one (or more) PF(s).

Stage 3: Classroom Enactment of the Curriculum Unit. CU_1 was piloted four times by four of the six participating teachers. The outcomes gave rise to small text modifications, resulting in a second version (CU_2). CU_2 is described in the Appendix in terms of the sequence of TLAs and the expected students' notions. The overall learning aim of CU_2 was to contribute to students' scientific literacy, with emphasis on models and modeling (Clement, 2000; Prins, Bulte, & Pilot, 2011). CU_2 was implemented in two separate small-scale interpretative case studies (Cobb, Stephan, McClain, & Gravemeijer, 2001) by two of the six teachers. The classroom enactments comprised eight 3-hour lessons, excluding time for self-study by the students. During all lessons, the students worked in groups of four. The results obtained in the two classes in the two schools were pooled, resulting in nine teams.

Data Collection. The data collection focused on the TLAs. The conversations of the student teams at work were audio-taped and transcribed verbatim. The students' written answers for each teaching and learning activity were also collected. Furthermore, after each learning phase, each student individually completed a written questionnaire (WQ), shown in Table 2. The purpose of the WQ was to reveal students' experienced coherency on the following aspects:

- their engagement in the authentic practice at hand (Question 1);
- their valuation of the conducted TLAs (Question 2); and
- their overview of future actions to solve the exemplary modeling problem (Question 3).

TABLE 2
The Written Questionnaire for Students to Complete Individually After Each Learning Phase to Gain Insight Into the Fulfillment of the Pedagogical Functions

Question		
1	Please judge the practice of the modeling of water treatment—turbidity removal by coagulation/flocculation on the following aspects:	
	– Motivating	Low—☐-☐-☐—high
	– Interesting	Low—☐-☐-☐—high
2	Please evaluate the teaching and learning activities on the following aspects:	
	– Instructiveness	Low—☐-☐-☐—high
	– Appreciation	Low—☐-☐-☐—high
	– Relevance	Low—☐-☐-☐—high
3	Formulate the actions that should be done (next) to solve the modeling problem—turbidity removal by coagulation and flocculation treatment	

In both classes, field notes were taken by the first author during the entire implementation of the curriculum unit CU_2. The purpose of the field notes was to determine whether the curriculum unit was implemented in class as intended. Table 3 presents an overview of the data sources used to evaluate the extent of the fulfillment of the PF, as a means to gain insight in students' experienced coherency between scientific activities, content, and tools.

Data Analysis. The data analysis consisted of two distinct steps. In the first step, preceding the actual data analysis, the first and second authors developed and reached consensus on a coding scheme. This coding scheme consisted of a set of expected student notions per TLA as indicators of the fulfillment of the PFs. The expected students' notions per TLA are descripted in Appendix.

In the second step, the realized students' notions from each student team were analyzed and judged from an interpretive perspective by the first and second author independently (Smith, 1995). The transcripts of the audio-taped conversations of the student teams at work were used as primary data sources, and the written answers were used as secondary data sources. The realized outcomes were used to judge the completion of the PFs using a 3-point scale, ranging from good (good fulfillment, students show expected notions and/or insights) to none (no fulfillment, expected notions and/or insights among students are largely absent or not accessible). The rater consistency was calculated using the intraclass correlation coefficient using a two-way mixed effects model (Shrout & Fleiss, 1979).

To reveal students' experienced coherency, the first author combined all results from all nine student teams. The PFs were deemed fully accomplished when the related TLAs worked out as expected in at least 80% of all student teams and deemed not accomplished when the related TLAs did not work out as expected in 80% of the student teams. When a score fell somewhere between these two extremes, the PFs were deemed partly accomplished. The individual WQs were analyzed by the first author using the 80% level as the determining criterion (Miles & Huberman, 1994). An aspect was deemed high when valued highly by at least 80% of the students. In contrast, when valued low by at least 80% of

TABLE 3
Overview of Data Sources Used to Gain Insight Into the Completion of the Pedagogical Functions in Each Learning Phase as a Means to Evaluate Students' Experienced Coherency

		Data Sources	
LPs	PFs	Conversations and Written Answers of Students Working on TLA	WQ
I. Orientate toward and connect with the practice	PF_a: Evoke motivation to study the practice	2	1
	PF_b: Connect to the prior conceptual knowledge base	1, 2, 3	-
	PF_c: Connect to the prior procedural knowledge base	3	3
	PF_d: Evoke motivation to study exemplary problems or questions	3	1
II. Zoom in on an exemplary problem or question	PF_e: Make explicit and build on the prior conceptual knowledge base	5	-
	PF_f: Make explicit and build on the prior procedural knowledge base	5	3
	PF_g: Evoke an incentive to handle the exemplary problem or question	4	1
III. Solve the exemplary problem or answer the question	PF_h: Proceed through the sequence of actions and learn/apply knowledge until a solution or answer can be presented	6–15	1, 2, 3
IV. Evoke an incentive to express the findings	PF_i: Induce an incentive to express the learned conceptual and procedural knowledge	16	3
V. Express and reflect on the findings	PF_j: Make explicit the learned conceptual and procedural knowledge	18	-
	PF_k: Draw up a project plan for handling a similar exemplary problem or question posed in the authentic practice	17	-

Abbreviations: LP, learning phase; PF, pedagogical function; TLA, teaching and learning activity; WQ, written questionnaire.

the students, the overall assessment of the aspect was low. Between these extremes, the judgment was considered partly accomplished.

Stage 4: Activity-Based Instructional Framework. The results of the classroom implementation of CU_2 were analyzed by the three authors. The extent of the accomplishment of the PFs was considered and discussed. In case of a full accomplishment of a PF, the related design guideline(s) was (were) also deemed sufficient. In case the PF(s) was (were) partly accomplished, the related design guideline(s) was (were) adjusted. In case the PF(s) was (were) not accomplished, both the PF(s) and related design guideline(s) were revised. Finally, the results were used to evaluate and enrich the initial instructional framework, yielding an activity-based instructional framework.

RESULTS

Research Question A

In response to Research Question A, in this section, we describe the transformation of the authentic chemical practice "modeling drinking water treatment," and the design guidelines abstracted from the transformation process. We describe the filling in of the five learning phases in the curriculum unit, with emphasis on the learning activities students are supposed to conduct.

Learning Phase I: Orient Toward and Connect With the Practice. As a starting point, the issue of the treatment of groundwater and surface water to produce drinking water was introduced to students. Students were given the task to analyze and map the treatment process to activate students' prior knowledge regarding quality norms for drinking water and treatment methods, such as filtration, sedimentation, and aeration. Next, students studied official governmental data concerning the quality of drinking water in the Netherlands, including occasions when parameters exceeded legally set safety guidelines. By taking note of such official data, it was expected that students would develop a broad interest in the treatment of water. Finally, the students analyzed an adapted version of the original project plan Modeling of water treatment (Versteegh, Van Gaalen, Rietveld, Aldenberg, & Cleij, 2001), providing students with an orientation to the authentic practice, its societal embeddedness, and a driver for modeling the influence of process variables on drinking water quality.

The pedagogic decisions were abstracted in three design guidelines connected with the indicated pedagogic functions in the initial instructional framework:

1. Let students outline and schematize the issue at hand to activate students' prior knowledge base (PF_b; PF_c).
2. Let students find out for themselves which major questions or problems exists in the authentic practice concerning the issue above, such that they become interested (PF_a; PF_d).
3. Let students analyze the method used in the authentic practice in response to the reported questions or problems, such that students become informed about the what, why, and how experts work and what kind of solutions they strive for (PF_c).

Learning Phase II: Focus on an Exemplary Problem or Question. To evoke ownership among students, students were appointed as junior employees (of the Institute for Public Health and the Environment) and received the assignment to model the removal of turbidity by coagulation and flocculation (the exemplary modeling problem or question). As a precursor to take on the assignment, students studied and summarized a worked-out analogous modeling problem. The analogous modeling problem should function as an advance organizer (Ausubel, 1968). In the present case, students studied an authentic factsheet reporting the modeling of the removal of trichloromethane by activated carbon filtration. The study of an analogous modeling problem would lead students to (1) draw up a modeling procedure to apply to their modeling assignment and (2) focus on a set of advance modeling features that would enable them to judge the quality of the models they would develop. The designers decided that students should produce a factsheet reporting the findings related to their modeling assignment, that is, the modeling of turbidity removal by coagulation and flocculation, to be assessed by the teacher.

The pedagogic decisions were abstracted in three design guidelines connected with the indicated pedagogic functions in the initial instructional framework:

4. Let students study an assignment, related to an exemplary modeling question or problem posed in the authentic practice, to induce ownership among students (PF_g).
5. Let students analyze a worked-out analogous modeling question or problem posed in the authentic practice, such that students become informed about the actions to conduct and the knowledge and skills to learn to solve their exemplary question or problem (PF_e; PF_f).
6. Let students take notice of and orient toward the product to be delivered, related to an artifact that is used in the authentic practice and fits the exemplary modeling question or problem, such that they become aware of the criteria for assessment (PF_g).

Learning Phase III: Solve the Exemplary Problem or Answer the Question. At the start of learning phase III, students observed a demonstration of coagulation and flocculation in class to further foster students' attention to the influence of process variables and to emphasize the essentials of the modeling problem. After having attended the demonstration, it was expected that students would be able to express the major steps in the modeling procedure, that is, selecting relevant process variables, conducting experimental research, and analyzing correlations describing the relationships between process variables and turbidity. Related to the first step in the modeling procedure, that is, selecting relevant process variables, students studied two adapted articles, one that addressed the working of coagulation and flocculation (A) and another that presented the chemistry underlying the coagulation and flocculation mechanisms (B). Both articles were adapted versions of authentic professional writings. Related to the second step in the modeling procedure, that is, conducting experimental research, students carried out experiments using laboratory prescripts. In the experiments, students investigated the influence of process variables including dosage of coagulant, starting turbidity, temperature, pH, and salt concentration on the end turbidity. In the third step in the modeling procedure, that is, analyzing correlations describing the relationships between the process variables and turbidity, students conducted a regression analysis of their gathered empirical data. A manual that explained and illustrated the method using Microsoft (MS) Excel software as a computer tool was given as guidance. Students were supposed to (1) draw scatter plots of the measured influence of all individual variables on the end turbidity, (2) select the variables that showed (obvious) correlation, (3) fit several regression models, and (4) conduct a multiple regression to construct one mathematical formula that describes the end turbidity as a function of the relevant variables.

The pedagogical decisions were abstracted in five design guidelines, all connected to PF_h in the initial instructional framework:

7. Let students observe the exemplary modeling question or problem, such that they feel the need to obtain more (theoretical) knowledge to familiarize themselves with the issue at hand (PF_h).

8. Let students study real writings used in the authentic practice, such as articles, reports, or manuals, such that they become acquainted with and understand the scientific theories related to the exemplary question or problem (PF_h).
9. Let students conduct a series of actions, analogous to the modeling procedure experts performed in the authentic practice, such that students constantly have sight on why and what to do at every step in the trajectory (PF_h).
10. Let students carry out experiments, analyze the obtained empirical data and construct the model, such that they experience the origin of the model, obtain insight into the advanced model features and underlying assumptions (PF_h).
11. Let student report on the progress to look ahead toward future actions related to the exemplary modeling question or problem (PF_h).

Learning Phase IV: Evoke an Incentive to Express the Findings. The fourth learning phase aimed to evoke an incentive among students to express their findings. Students applied the constructed model to calculate the amount of coagulant needed to produce clear water. It was expected that this activity would provide an incentive to express the advanced model features of purpose, goodness of fit, reliability, and validity.

This pedagogic decision was abstracted in one design guideline connected to PF_i in the initial instructional framework:

12. Let students apply their constructed model in a real-world setting it was designed for, so that students feel the need to express and evaluate to what extent the exemplary question or problem has been solved (PF_i).

Learning Phase V: Express and Reflect on the Findings. In the fifth learning phase, the students were supposed to report and reflect on the findings. The challenge was to keep students focused on the applied modeling procedure and to emphasize that the learned conceptual and procedural knowledge is also applicable to other (related) modeling problems. Students, in their role as junior employees, advised another project team on future research regarding the removal of turbidity by coagulation and flocculation. The final activity was to report all the findings in a factsheet, already introduced in the second learning phase. Students were challenged to make explicit their learning gain regarding models and modeling within the context.

The pedagogic decisions were abstracted in two design guidelines connected to the indicated pedagogic functions in the initial instructional framework:

13. Let students propose a modeling procedure for a similar question or problem posed in the authentic practice, such that students focus on the broader applicability of the learned conceptual and procedural knowledge (PF_k).
14. Let students report on the exemplary modeling question or problem worked on and hand in the product they have studied in learning phase II, so that students share and communicate about the learned conceptual and procedural knowledge (PF_j).

Research Question B

In response to Research Question B, we present the results of the classroom implementation of CU_2. Table 4 presents an overview of the extent of fulfilment of each PF per learning phase, which reflects students' experienced coherence between scientific activities, content, and tools. The interrater consistency was substantially reflected in the intraclass correlation coefficient of 0.75.

TABLE 4
Extent of Fulfilment of the Pedagogical Functions per Learning Phase

LPs	PFs	Extent of Fulfilment of the PFs (Good, Partly, Not)		Major Remarks Related to the Students' Experienced Coherency
		Based on TLAs	Based on WQ	
I. Orientate toward and connect with the practice	PF_a: Evoke motivation to study the practice	Good	Good	The students were not focused on modeling themselves after having studied the authentic project plan "modeling of water treatment" (PF_d)
	PF_b: Connect to the prior conceptual knowledge base	Good	-	
	PF_c: Connect to prior procedural knowledge base	Good	Partly	
	PF_d: Evoke motivation to study exemplary problems or questions	Partly	Good	
II. Zoom in on an exemplary problem or question	PF_e: Make explicit and build on the prior conceptual knowledge base	Good	-	The appointment of students as junior employees did not contributed to students' engagement (PF_g)
	PF_f: Make explicit and build on the prior procedural knowledge base	Good	Good	
	PF_g: Evoke an incentive to handle the exemplary problem or question	Good	Partly	

(*Continued*)

TABLE 4
Continued

LPs	PFs	Extent of Fulfilment of the PFs (Good, Partly, Not)		Major Remarks Related to the Students' Experienced Coherency
		Based on TLAs	Based on WQ	
III. Solve the exemplary problem or answer the question	PF_h: Proceed through the sequence of actions and learn/apply knowledge until a solution or answer can be presented	Good	Question A: good Question B: good Question C: good	The practical demonstration of coagulation and flocculation in class fostered the fulfillment of PF_d to PF_g in Learning Phases I and II and focused students on modeling themselves The majority of the students did not see the reason to investigate the process variables total salt concentration and pH, because they lacked theoretical knowledge related to coagulation mechanisms; all relevant theoretical knowledge needed to cope with the exemplary problem or question should be presented and discussed in class (PF_h)
IV. Evoke an incentive to express the findings	PF_i: Induce an incentive to express the learned conceptual and procedural knowledge	Partly	Partly	The majority of the student teams showed a good understanding of the advanced model feature reliability, while (only) half of the student teams showed an understanding of validity and goodness of fit (PF_i)
V. Express and reflect on the findings	PF_j: Make explicit the learned conceptual and procedural knowledge	Good	-	Students encountered difficulties in creating a generic modeling procedure for similar modeling problems (PF_k)
	PF_k: Draw up a project plan for handling a similar exemplary problem or question posed in the authentic practice	Not	-	

Abbreviations: LP, learning phase; PF, pedagogical function; TLA, teaching and learning activity; WQ, written questionnaire.

Learning Phase I: Orient Toward and Connect With the Practice. Learning phase I aimed at engaging students in the authentic practice at hand and establishing a firm connection with students' prior knowledge base. The data collected from TLA 1 revealed that students were familiar with water treatment in a rudimentary sense and with some drinking water quality norms, such as clarity, taste, and smell. In addition, students showed awareness of the variables affecting the treatment process. The study of the drinking water quality norms and the occasional exceeding thereof evoked curiosity and discussion among the students concerning what is done to prevent outruns (TLA 2). All student teams identified turbidity as one of the "problematic" parameters. When discussing possible measures to take to prevent the exceeding of norms, essentially two options were brought to the fore: *preventing pollution of the raw water* and/or *improving the treatment processes*. The majority (seven out of nine) of the student teams, however, were of the opinion that the treatment process most likely was already "at its best" because "drinking water companies have implemented all their knowledge and experience." In TLA 3, the students took notice of the modeling procedure of experts to improve the treatment process itself as a remedy to prevent outruns. Although this option was noted by students, it raised questions, such as *Do the experts not know everything about the treatment process?* The results showed that, after having studied the authentic project plan Modeling of water treatment, the majority of the students was not fully aware that they themselves were going to perform a modeling activity.

The current sequence of TLAs and the concrete filling-in thereof proved sufficient in supplying students with a broad, albeit rudimentary, idea of the *why*, *what*, and *how* related to water treatment. Table 4 shows the extent of the fulfillment of the PFs in Learning Phase I. The results revealed that, on average, students were motivated and interested in studying the authentic practice. In conclusion, PF_a to PF_c were sufficiently fulfilled. PF_d, however, was partly fulfilled since the majority of the students were not fully focused on modeling themselves.

Learning Phase II: Focus on an Exemplary Problem or Question. Learning Phase II started by addressing students as junior employees of the Institute for Public Health and the Environment and supplying them with an assignment: modeling turbidity removal by coagulation and flocculation (TLA 4). The students appreciated the clear assignment. However, the results from the WQ showed that the appointment of students as junior employees was regarded as artificial in their school environment (Question 2). In TLA 5, the student teams studied a factsheet reporting a worked-out analogous modeling problem to make explicit and build on their conceptual and procedural knowledge. This activity was expected to lead students to three developments:

1. Drawing up a modeling procedure for turbidity removal by coagulation and flocculation.
2. Becoming aware of the advanced model features.
3. Familiarizing oneself with a factsheet as a means of communicating results and findings.

Regarding the first development, the findings revealed that the majority of the student teams (seven out of nine) devised modeling procedures that, on the surface, resembled the approach of the experts in the authentic practice. This was confirmed by the results obtained from the WQ Question 3 (see Table 2). The second development was partly achieved. The majority of the teams (six out of nine) did not record the advanced model features of goodness of fit, reliability, and validity. At this particular point in the teaching process, the features lacked meaning for some students. The third development was realized to a large extent. Students familiarized themselves with a factsheet as a means to report their own findings.

In conclusion, at the end of Phase II, the majority (eight out of nine) of the teams was aware of the “optimization of coagulation and flocculation” to “enhance turbidity removal” by means of “modeling the influence of process variables.” This awareness provided a drive to understand more about turbidity and the operation of the treatment coagulation and flocculation. Table 4 shows the fulfillment of the PFs in Learning Phase II. PF_e and PF_f were sufficiently reached. As for PF_g, the findings revealed that appointment of students as junior employees did not result in enhanced engagement.

Learning Phase III: Solve the Exemplary Problem or Answer the Question. Learning Phase III consisted of 10 activities, that is, a practical demonstration of coagulation and flocculation (TLA 6), the listing of all process variables and hypothesizing their influence (TLA 7, 8), the experimental investigation (TLA 9, 10), the selection of process variables correlated with the end turbidity (TLA 11–13), and finally the regression analysis (TLA 14, 15).

The demonstration of coagulation and flocculation in class (TLA 6) proved successful in focusing students’ attention on the influence of process variables and emphasizing the essentials of the modeling problem. The majority of the students (eight out of nine teams) identified relevant process variables and started to express ideas about how to investigate the effects on these process variables empirically. The proposed modeling procedure by students was described in much more detail compared to TLA 5 in Learning Phase II. In TLAs 7 and 8, all student teams conducted a literature study on coagulation and flocculation and made a list of all process variables possibly affecting the treatment process. Students noted the starting turbidity of the water, the dosage of the coagulant and the temperature, and understood the influence of these three variables on coagulation and flocculation. However, students failed to identify acidity and total salt concentration. To understand the influence of acidity and total salt concentration, one needs in-depth knowledge of the interactions between charged particles. However, the teachers introduced the process variables of acidity and total salt concentration with a limited explanation, although an article on the “mechanisms of coagulation” was available in the teaching materials. The majority of the student teams (seven out of nine) perceived the investigation of the influence of the acidity and total salt concentration on the end turbidity as not meaningful. This finding underlines the importance of (theoretically) underpinning each of the process variables to be investigated. The fragment below shows a typical student’s answer after being asked by the teacher about his/her investigation of the process variable acidity during the laboratory work. Lines 1 and 3 underline that this student did not understand why the acidity might have an influence on the turbidity.

> Line 1 (student_25): But, why do we investigate the acidity of the water?
> Line 2 (teacher_2): Because it affects the final turbidity. It is one of the process variables.
> Line 3 (student_25): But I don’t see why. We just need to find the amount of coagulant needed to clear the water, right?
> Line 4 (teacher_2): Of course, but the acidity also influences the final result, and it is necessary to determine this.
> Line 5 (student_25): Explain to me in what way the acidity affects the final turbidity.

The empirical investigation of the influence of starting turbidity, dosage of coagulant, and temperature proceeded according to expectations. After the empirical data were collected, all student teams made scatter plots with the aim of selecting the process variables that showed a correlation with the end turbidity. During the class discussion on the scatter plots (TLA 13), students argued about observed trends using relevant arguments: the number of measurements, the errors, and the tested range of the process variables.

In the subsequent activities, all student teams performed a regression to find suitable mathematical models describing the observed correlations (TLA 14, 15). First, every process variable showing a correlation was analyzed separately. Second, a multiple regression was applied. These activities were accompanied by short lectures on regression and a manual on regression analysis. Starting from the scatter plots, the majority of the student teams (seven out of nine) intuitively felt the need to find the best fitting line and formula using the "goodness of fit" as the deciding criterion. It became apparent that the large majority (seven out of nine) of the teams understood the general idea behind the multiple regression method, that is, developing one mathematical model that would account for the influence of several process variables.

In conclusion, the results showed that the majority of the students regarded the sequence of actions in Learning Phase III as coherent. The PF PF_h in Learning Phase III was sufficiently fulfilled, as depicted in Table 4.

Learning Phase IV: Evoke an Incentive to Express the Findings. In TLA 16, students applied the multiple regression model to calculate the dosage of coagulant needed to produce clear water given a certain raw water quality. Students evaluated the outcomes based on the aspects of reliability, validity, and goodness of fit. The majority (eight out of nine teams) showed that they were able to express (and reflect on) the reliability of the developed model, as typified by statements in their factsheet, such as the following from student Team 2.

> *There are reasons for future research because the results are not reliable. An effort should be made to increase the accuracy of the measurements. Also, more measurements are needed. It is advisable to conduct extensive research on all process variables.*

Regarding validity, five of nine teams showed awareness of the limited range in which the regression model is valid. Four teams, however, extrapolated the regression model outside the tested range without any hesitation, an indication that they were not fully aware of the meaning of validity. As for the goodness of fit, three teams did not show understanding of the significance of the goodness of fit criterion as related to the number of measurements. In the fragment below the reasoning of student Team 5 related to the validity and goodness of fit of their developed model is depicted. This student team suggested deleting deviant measurements to obtain a better goodness of fit, as typified by the last two sentences in the statement below.

> *Our model only holds for restricted circumstances. That is the validity of the model. Because our model depends on the variables of starting turbidity, dose of ferric chloride and temperature, the range of these variables determines the scope of validity.*
>
> - For the starting turbidity: between 43 and 215 NTU;
> - For the concentration Fe^{3+}: between 0.02 and 1.00 g/L;
> - For the temperature: between 5 and 26°C.
>
> *In addition, we checked the 'goodness of fit' of our model, denoted by R^2. This value varies between 0 and 1. In case of a value > 0.8, the fit is considerable. Our value of R^2 was 0.40, so our model isn't that good. We can improve the goodness of fit by removing all*

> *'suspicious' measurements, that is, leaving out all measurements falling outside the major trend.*

In conclusion, regarding the advanced model features, the findings revealed that the majority of the teams did show an understanding of reliability, while about half of the teams showed an understanding of validity and goodness of fit. PF_i in Learning Phase IV was partly achieved, as depicted in Table 4.

Learning Phase V: Express and Reflect on the Findings. In the final Learning Phase, all student teams reflected on their conducted learning activity and reported their findings in a factsheet. Regarding the planned reflection on the modeling procedure (TLA 17), it appeared that the majority of the teams (six out of nine) encountered difficulties in creating a procedure for similar modeling problems. Students could list some stages, such as "identifying process variables," "laboratory work," and "regression," but they were not able to provide relevant content for these stages. Finally, each student team wrote a factsheet describing their results on modeling the removal of turbidity by coagulation and flocculation, comprising all the activities conducted and the results (TLA 18). Students recalled the example factsheet modeling the removal of trichloromethane by activated carbon filtration introduced in TLA 5 and adopted its basic structure. All factsheets clearly stated the problem regarding the removal of turbidity, described the process of coagulation/flocculation, and noted the process variables identified and their influence. In conclusion, PF_j in Learning Phase V was fully realized, while PF_k was not, as shown in Table 4.

CONCLUSION

Below, we reflect on the design guidelines per Learning Phase, with emphasis on the improvements and alterations based on the implementation of the second version of the curriculum unit. In case a PF was fully accomplished, the related design guideline(s) remained unaltered. In case of partly or even no accomplishment of a PF, the related design guideline(s) was (were) adjusted or new design guidelines were added. Summarizing all implications, we arrived at an activity-based instructional framework, as depicted in Table 5.

The results in Learning Phase I showed that PF_d was not fully fulfilled. We hypothesize that the fulfillment of PF_d can be enhanced by letting students observe the coagulation and flocculation treatment, in the present curriculum unit CU_2 conducted at the beginning of Learning Phase III. The demonstration concretized the problem, thus providing students with a valuable problem orientation. The obtained results argue for incorporation of the demonstration at the end of Learning Phase I, to induce a need for modeling in students themselves. In addition, the obtained results in Learning Phase III underline the importance of portraying and delivering to students all necessary and relevant theoretical knowledge needed to solve the exemplary modeling problem. The possible influence of process variables acidity and total salt concentration on turbidity was not well understood by the majority of the students. Regarding Learning Phases IV and V, it was observed that PF_i and PF_k, aimed at making explicit and evaluating the learned conceptual and procedural knowledge by students, were not fulfilled satisfactory. To induce reflection on the modeling procedure among students, we propose a number of alterations in Learning Phases I, III, IV, and V, both on the level of PFs and on the level of design guidelines.

TABLE 5
Activity-Based Instructional Framework for the Transformation of Authentic Modeling Practices Into Meaningful Contexts for Learning

LPs: Components of Activity Systems	PFs	Design Guidelines
I. Orient toward and connect with the practice: – Contextual bounds – Subjects, community, objects	PF_a: Evoke motivation to study the practice PF_b: Connect to the prior conceptual knowledge base PF_c: Connect to the prior procedural knowledge base PF_d: Evoke motivation to study exemplary problems or questions	i. Let students outline and schematize the issue at hand to activate students' prior knowledge base (PF_b; PF_c) ii. Let students find out for themselves which major questions or problems exists in the authentic practice concerning the issue above, such that they become interested (PF_a; PF_d) iii. Let students analyze the method used in the authentic practice in response to the reported questions or problems, such that students become informed about the what, why, and how experts work and what kind of solutions they strive for (PF_c) iv. Let students observe and conceptualize the exemplary modeling question or problem, such that they feel the need to obtain more (theoretical) knowledge to familiarize themselves with the issue at hand (Pf_b; PF_c; PF_d)
II. Focus on an exemplary problem or question: – Purpose of activity system – Writings and language used	PF_e: Make explicit and build on the prior conceptual knowledge base PF_f: Make explicit and build on the prior procedural knowledge base PF_g: Evoke an incentive to handle the exemplary problem or question	v. Let students study an assignment, related to the exemplary modeling question or problem posed in the authentic practice, to induce ownership among students (PF_g) vi. Let students analyze a worked-out analogous modeling question or problem posed in the authentic practice, such that students become informed about the actions to conduct and the knowledge and skills to learn to solve their exemplary question or problem (PF_e; PF_f) vii. Let students take notice of and orient toward the product to be delivered, related to an artifact that is used in the authentic practice and fits the exemplary modeling question or problem, such that they become aware of the criteria for assessment (PF_g)

(*Continued*)

TABLE 5
Continued

LPs: Components of Activity Systems	PFs	Design Guidelines
III. Solve the exemplary problem or answer the question: – Activity structure, actions, and operation – Theories, mental, and physical tools	PF_h: Proceed through the sequence of actions and learn/apply knowledge until a solution or answer can be presented	viii. Let students think about different modeling approaches for the exemplary question or problem at hand, so that they become informed about the various ways to deal with the issue (PF_h) ix. Let students study real writings used in the authentic practice, such as articles, reports, or manuals, such that they become acquainted with and understand the scientific theories related to the exemplary question or problem (PF_h) x. Let students conduct a series of actions, analogous to the modeling procedure experts performed in the authentic practice, such that students constantly have sight on why and what to do at every step in the trajectory (PF_h) xi. Let students carry out experiments, analyze the obtained empirical data, and construct the model such that they experience the origin of the model, obtain insight in the advanced model features and underlying assumptions (PF_h) xii. Let student report on the progress to look ahead toward future actions related to the exemplary question or problem (PF_h)

(*Continued*)

TABLE 5
Continued

LPs: Components of Activity Systems	PFs	Design Guidelines
IV. Evaluate and reflect on the findings: – System dynamics	PF_i: Evaluate the learned conceptual and procedural knowledge PF_j: Reflect on the procedural knowledge	xiii. Let students apply their constructed model in a real-world setting it was designed for, so that they feel the need to express and evaluate to what extent the exemplary question or problem has been solved (PF_i). xiv. Let students recall the different modeling approaches and let them reflect on the assumptions and estimations made and the possible effect of neglected variables so that they gain insight into the pros and cons of the applied modeling approach (PF_j) xv. Let students propose a modeling procedure for a similar question or problem posed in the authentic practice, such that students focus on the broader applicability of the learned conceptual and procedural knowledge (PF_i; PF_j)
V. Express the findings: – Means of communication	PF_k: Make explicit the learned conceptual and procedural knowledge	xvi. Let students report on the exemplary modeling question or problem worked on and hand in the product they have studied in Learning Phase II, so that students share and communicate about the learned conceptual and procedural knowledge (PF_k)

Abbreviations: LP, learning phase; PF, pedagogical function.

On the level of the design guidelines, we advise that students should be prompted for reflection multiple times during their learning trajectory. Therefore, to induce reflection on the modeling procedure, we hypothesize to (1) let students conceptualize the exemplary modeling question or problem and (2) let students think over and discuss different modeling approaches in response to the exemplary modeling question or problem, for example, a theory-driven, mechanistic approach or a data-driven, empirical approach. We suggest that the conceptualization of the modeling problem occurs in Learning Phase I, and that the different modeling approaches should be portrayed early in Learning Phase III. The conceptualization of the modeling problem and the different modeling approaches should then be recalled in Learning Phase IV, so that students compare the different modeling approaches and note some pros and cons. On the level of the PFs of Learning Phases IV and V, we suggest displacing the reflection before the explicating phase. The focus of Learning Phase IV becomes evaluation and reflection, whereas the major function of Learning Phase V is the explication of the findings.

The authentic modeling practice used as context for learning in this study has been unraveled and typified using the components of activity systems proposed by Jonassen and Rohrer-Murphy (1999), as described in the Method section. In retrospect, we hypothesize that each Learning Phase addresses a selected number of the components of the reflected authentic practice, as depicted in Table 5. In Learning Phase I, the emphasis is on focusing students on the contextual bounds, especially the societal embeddedness of the authentic practice. The relevant participants and their contribution to the collective activity system should become clear to students. In Learning Phase II, students become engaged with the purpose of their assignment, related to an exemplary question or problem posed in the reflected authentic practice. In addition, students start orienting themselves on the specific writings and language used in the reflected authentic practice. In Learning Phase III, the students conduct a sequence of actions, mediated by theories, mental and physical tools resembling those employed in the reflected authentic practice. In the Learning Phases IV and V, finally, students evaluate and reflect on the systems dynamics and express their findings by means of communication used the reflected authentic practice.

DISCUSSION

The aim of this study was to develop an instructional framework that provides educational designers with a set of prescriptive guidelines for transforming authentic modeling practices into contexts for learning, while maintaining the coherency between scientific activities, content, and tools. The heuristics in the activity-based instructional framework, depicted in Table 5, follow from a codesign and classroom implementation of a curriculum unit (CU_2).

The results showed that students experienced coherency between scientific activities, content, and tools in the curriculum unit, given that most of the PFs were fulfilled to a sufficient extent. The classroom implementation gave rise to some revisions, such as letting students observe the exemplary modeling question or problem in Learning Phase I and multiple alterations in Learning Phases I, III, and IV to let students reflect on the applied modeling procedure. The effectiveness of the proposed design guidelines with respect to inducing reflection in students should again be investigated empirically. Schwarz and White (2005) have reported difficulties in allowing students to reflect on the metamodeling knowledge. They suggest that this difficulty might be because students still “exhibited a school science view of accepting information from books, teachers, or empirical evidence, without distinguishing between them” (p. 646). While this suggestion most likely holds for (the majority of) the students in our study, we (also) have indications that students perceive reflection as not meaningful. Students are aware that they will not encounter a similar modeling problem in their school career.

The resulting activity-based instructional framework consists of learning phases, pedagogic functions, and design guidelines. In comparison with other instructional frameworks in the family of sociocultural theories on learning, some similarities and differences become apparent. Regarding the learning phases, our framework distinguishes five separate phases, which are comparable with the learning phases and processes as articulated in the Learning-for-Use model (Edelson, 2001). Both frameworks emphasize sequential steps in the learning trajectory, with similar pedagogic functions to achieve in consecution. The scaffold-design framework (Quintana et al., 2004) does distinguish three phases, namely sense making, process management, and ongoing articulation and reflection. The framework for designing authentic learning environments (Herrington & Oliver, 2000) in vocational education, does not divide the learning trajectory into distinct phases. For the population of students in preuniversity science education, however, we think it is advisable to explicitly guide students in their learning trajectory. Regarding the design guidelines, our framework articulates learning activities that students need to carry out mediated by selected (and adapted) artifacts from the reflected authentic scientific practice. The Learning-for-Use model, on the contrary, places emphasis on the teaching tasks to be designed and implemented. The primary focus of the Scaffold-design framework is on guidelines to be implemented by the teacher to guide the students though their learning process. Our framework as well as the Scaffold-design framework emphasizes the use of tools and artifacts from the scientific (authentic) practice, and attention toward the semantics of the discipline. In their guidelines, however, the Scaffold-design framework has limited attention on the affective component of learning, such as students' motivation, interest, and curiosity.

With regard to the method applied in this research study, it should be noted that the availability of in-depth information on the authentic modeling practice at hand was an important prerequisite. The authentic modeling practice was well-documented and had already been judged as feasible for use in chemistry education (Prins et al., 2008). The conditions for the codesign process were optimal and the participants could immediately focus on the transformation of the authentic modeling practice rather than on the need to first explore the practice and reveal its essential components. The PD procedure that we employed in this study functioned well in terms of making explicit and using the expertise of the teachers involved.

To our knowledge, this is the first (complete) instructional framework explicitly aligned with activity theory, which is based on earlier studies (Bulte et al., 2006; Kortland, 2001; Westbroek et al., 2010). We advocate further empirical research to investigate the prescriptive value and the quality of the provided guidelines in the activity-based instructional framework. The results obtained in this study support the design strategy of transforming authentic scientific practices into contexts for learning to arrive at meaningful science education, both from a design and learners' perspective. It is therefore worthwhile to further elaborate this design strategy to achieve coherency between scientific activities, content, and tools.

The authors wish to thank the Dutch chemistry teachers Rens Bijma (Griftland College, Soest), Wijnand Rietman (Het Streek, Ede), Jan de Vries (Oosterlicht College, Nieuwegein), Jeannine Acampo (St. Bonifatius College, Utrecht), Frans Teeuw (Koningin Wilhelmina College, Culemborg), and Sanne Spijker (ORS Lek & Linge, Culemborg) for their contribution as members of the design team in this research project.

APPENDIX

OVERVIEW OF THE CURRICULUM UNIT CU_2 IN TERMS OF TEACHING AND LEARNING ACTIVITIES AND EXPECTED STUDENTS' NOTIONS

Learning Phase I: Orient Toward and Connect With the Practice

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Sequence of teaching and learning activities (TLAs)

TLA 1: Broad orientation on treatment of water. Students make an outline of the treatment process of ground- and surface water to produce drinking water.

Expected students' notions
Students show familiarity with basic concepts of water treatment, such as techniques as filtration, sedimentation, the sequence of steps, and (some) process variables involved. Students distinguish different treatment techniques for groundwater and surface water.

TLA 2: Exceeding of chemical parameters. Students analyze a list of (occasionally) exceeded chemical parameters for drinking water (source government document).

Expected students' notions
Students recognize (some important) quality parameters related to drinking water, such as acidity, turbidity, and taste. Students especially pay attention to quality parameter turbidity. Students start asking how turbidity is removed.

TLA 3: Orientate on the modeling approach proposed by experts. Students study an adapted and shortened version of an authentic project plan "modeling of water treatment."

Expected students' notions
Students are expected to gain a broad view on why, what, and how experts work on the modeling of water treatment. They become informed about the reason for modeling (*why*: prevent exceeding of quality norms), the purpose (*what*: model the quality of drinking water as a function of the treatment process and quality of certain raw water), and the method (*how*: examine all treatment steps and parameters separately to find relations between ingoing and outgoing concentrations of contaminants, and describe the relation with a mathematical formula). Students are expected to:

Draw up a procedure for modeling turbidity removal by coagulation/flocculation.
Become aware of the advanced features to evaluate the models, such as purpose, validity, and reliability.
Familiarize oneself with a factsheet as means to communicate results and findings.

Learning Phase II: Focus on an Exemplary Problem or Question

Sequence of TLAs

TLA 4: Junior employee with project assignment. Students study a project assignment to solve an exemplary problem: modeling turbidity removal by coagulation/flocculation.

Expected students' notions
Students recognize the different tasks in the project assignment as basic steps in the modeling procedure. Students start discussing on how to work on the project.

TLA 5: Draw up a modeling procedure for removal of turbidity by coagulation/flocculation. Students analyze a factsheet summarizing the approach and outcomes of an analogous modeling problem: modeling trichloromethane removal by activated coal filtration.

Expected students' notions

Students identify and are able to give content to the major stages in the modeling procedure:

- Select relevant process variables;
- Undertake experimental research: conduct experiments under controlled circumstances and measure the outgoing concentration as function of ingoing concentration and the relevant process variables; and
- Use regression to analyze correlations and describe these in mathematical formulas.

Students take notice of and show understanding of the advanced model features purpose, goodness of fit, validity, and reliability. Students become aware of the end product to be delivered and the criteria for assessment.

Learning Phase III: Solve the Exemplary Problem or Answer the Question

Sequence of TLAs

TLA 6: Visualization of the exemplary modeling problem. Students observe a practical demonstration in class of treatment step coagulation/flocculation.

Expected students' notions

Students are able to mention some relevant process variables, such as dose coagulant. Students express the need to learn more about coagulation/flocculation to understand the underlying mechanisms.

TLA 7–8: Select relevant process variables. Students study coagulation/flocculation by means of adapted scientific articles.

Expected students' notions

- Students understand basic concepts and mechanisms of coagulation/flocculation, for example, clay particles and colloids, turbidity (NTU), coagulant, . . .
- Student identify process variables that affect coagulation/flocculation, for example, start turbidity, dose coagulant, acidity, temperature, and total salt concentration.

TLA 9–10: Conduct experiments. Students conduct experiments under controlled circumstances to measure the influence of process variables on the end turbidity.

Expected students' notions

Students are able to judge the quality of the measurements. Students show understanding why each of the identified process variable is investigated under controlled conditions.

TLA 11–15: Correlation and regression analysis. Students draw scatter plots between quantities and typify correlations. Students use MS Excel as computer tool and a manual as study material.

Expected students' notions

- Students learn to draw scatter plots between quantities and type of correlations. Student show understanding to select those parameters that significantly influence the end turbidity.
- Students formalize the correlations by performing a regression analysis (single and multiple regression models) and show understanding of the advanced model feature goodness of fit.

Learning Phase IV: Evoke an Incentive to Express the Findings

Sequence of TLA

TLA 16: Apply developed multiple regression model. Students apply their multiple regression model to calculate the dosage of coagulant needed to produce clear water in a production side given a certain raw water quality.

Expected students' notions

- Students show understanding of and evaluate the outcomes of the regression model on the aspects of goodness of fit, reliability and validity.

Learning Phase V: Express and Reflect on the Findings

Sequence of TLAs

TLA 17: Future research on turbidity removal. Students think over future research on turbidity removal by coagulation/flocculation based on their own experiences and extended knowledge.

Expected students' notions

- Students reflect on the applied modeling procedure and are able to discuss pros and cons. Students show awareness of neglected variables and assumptions made. Students propose future research on turbidity removal by coagulation/flocculation based on their own experiences and extended knowledge.

TLA 18: Factsheet "modeling turbidity removal by coagulation/flocculation." Students write a factsheet summarizing the applied modeling procedure, main findings, conclusions, and advice for future work. This factsheet is assessed by the teacher.

Expected students' notions

- Students show familiarity with a factsheet as means of communicating the findings.
- Students realize that this type of modeling is an exemplary example of process modeling, and thus is worthwhile to make explicit.

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