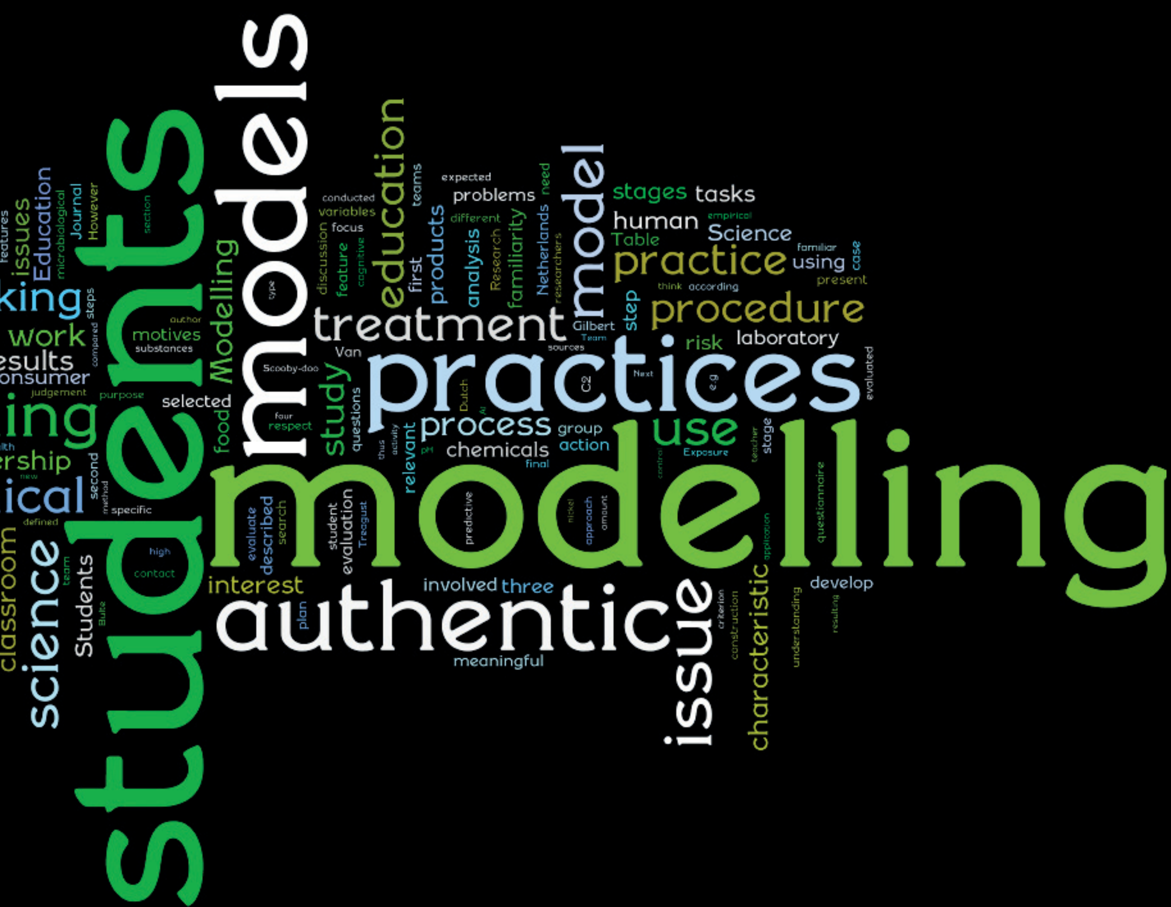
Gjalt Prins

Teaching and Learning of Modelling in Chemistry Education

Authentic Practices as Contexts for Learning



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Gjalt T. Prins

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Teaching and Learning of Modelling in Chemistry Education

Authentic Practices as Contexts for Learning

Onderwijzen en Leren van Modelleren in het Scheikunde Onderwijs
Authentieke Praktijken als Contexten voor Leren

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor
aan de Universiteit Utrecht
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ingevolge het besluit van het college voor promoties
in het openbaar te verdedigen
op woensdag 9 juni 2010 des middags te 4.15 uur

door

Gjalt Tjerk Prins

geboren op 2 oktober 1970 te Leeuwarden

Promotor: Prof.dr. A. Pilot

Co-promotor: Dr.ir. A.M.W. Bulte

‘Essentially, all models are wrong, but some are useful.’ – George E.P. Box[1]

[1] In George E. P. Box and Norman R. Draper (1987). *Empirical Model-Building and Response Surfaces*, Wiley, p. 424.

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The designed curriculum materials are available on:
http://betavak-nlt.nl/les/modules_v/gecertificeerd/Zuiver_drinkwater/

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Introduction and Research Overview

Introduction

Chemistry deals with substances, the way substances interact, aggregate, dissociate and rearrange. Chemists study the behaviour of substances and communicate their findings in theories and models. Models are generally viewed as connections between the theory and the world as experienced. In this respect, models are defined as a set of representations, rules, and reasoning structures that allow one to generate predictions and explanations, and describe behaviour, regarding an idea, object, event, process or system (Gilbert and Boulter, 2000; Schwarz and White, 2005). Due to the wide diversity of ontological status, models can range from scale models, iconic and symbolic models depicting chemical formulae and chemical equations, mathematical models representing conceptual relationships of physical properties and processes (e.g. $PV = nRT$), and computer simulations, to theoretical models, describing well-grounded theoretical entities (e.g. kinetic theory model of gas volume, temperature and pressure). The term modelling denotes the process used in much of modern science that involves (a) embodying key aspects of theory and data into a model, (b) evaluating that model using epistemic values such as reliability and validity and (c) revising the model to accommodate new theoretical ideas or empirical findings (Schwarz and White, 2005). Chemistry education aims to involve students in the domain of chemistry. This study is about students learning modelling in chemistry.

Why this topic?

Learning models and modelling is an important educational goal. Models are essential to the production, dissemination, and acceptance, of scientific knowledge in general (Giere, 1988). Because cultural heritage is one of the main goals of education in general, in chemistry education students should learn about the main lines and results of chemistry as a science discipline, including its models (Gilbert and Boulter, 1998; Vollebregt, 1998). As a result of the recognition that scientific knowledge has an influence on our society, the learning of models and modelling is currently regarded as an integral part of scientific literacy (Clement, 2000). This influence is visible, for example, in new products (e.g. medicines, catalysts), more efficient processes (e.g. food production, energy supply) or (long-term) policies (e.g. climate change, biotechnology). In society, there is a growing tendency to involve civilians in decision making on these issues, because some hold implications for human behaviour, evoke societal debate and/or give rise to ethical considerations. If education aims to prepare students to become responsible civilians, some general understanding about the nature of scientific knowledge, captured in theories and models, is needed, including the wording of that knowledge. The current state of the art of the (scientific) knowledge of chemistry guides and directs the actual activities of scientists to a large extent. In this respect the process of modelling is a key activity. The process of modelling deals with uncertainties, making assumptions and simplifying and marking out the phenomena, processes and/or objects under consideration. It is generally accepted that involving students in secondary education in a process of modelling is an effective way to help them grasp the epistemology of models and modelling, in contrast to 'direct instruction of models and modelling designed by others' (Edelson, 1998; Gobert and Pallant, 2004). In addition, since one of the goals of secondary chemistry (science) education is to prepare students for a future study in science, or technology, and their professional activities later on, it is desirable that students should enrich their epistemological views regarding models and modelling at this early stage.

In general, these are important reasons why students should learn about models and modelling in chemistry education, as in science and other domains.

Why this study?

Results of recent educational research have shown that students have an incomplete and limited understanding of the role and functioning of models and modelling in science. The study of Grosslight, Unger, Jay and Smith (1991) revealed that students generally do not clearly distinguish the ideas and/or purposes underlying models, the content of the models, and the experimental data which support or refute the validity or usefulness of models. Instead, students usually view models as toys or miniatures of real-life objects, and few students understand why models are used in science (Ingham and Gilbert, 1991). In addition, many students do not experience the meaningfulness of learning about the process of modelling.

The problems students have learning about models and modelling suggests the need for a redesign and a redefinition of the learning trajectory. Students need to gain an understanding of how and why models are constructed and what modelling process is used (Erduran and Duschl, 2004). The conventional chemistry curriculum emphasises students' acquisition of conceptual information and declarative knowledge on models (Duschl and Gitomer, 1997; Erduran, 2001). Within this traditional setting, the motivation, strategies and argumentation underlying the development, evaluation and revision of models are neglected, and therefore remain unclear to students. A promising assumption is that if students become involved in a modelling process, their understanding will contribute to the development of their models, and the evaluation and testing of their models contributes to their evolving understanding (Penner, Lehrer, & Schauble, 1998; Roth, 1998).

In response to this assumption, several instructional strategies have been developed. These include incorporating authentic model-based tasks in education (Gobert and Pallant, 2004), engagement in a historical line of model development (Gilbert, 2004; Justi and Gilbert, 1999), and designing a model-centred, computer-supported, semester-long science curriculum to encourage conceptual understanding and to foster the development of model-based reasoning skills (Raghavan and Glaser, 1995).

However, Schwartz and White (2005, p. 168) state:

> Even though model-centered instruction may accurately reflect the purposes and practices of science, and there is strong evidence that it can help students improve content knowledge and inquiry skills, the challenges presented by such an approach are considerable.

These challenges cover teachers' modelling knowledge (Van Driel and Verloop, 1999), curricular and classroom constraints and the content-specific outlining of the teaching-learning process (Lijnse and Klaassen, 2004).

Instructional strategy explored in this thesis

This thesis deals with the design of a teaching-learning process using an authentic chemical modelling practice as a context for learning. An authentic practice is defined as a homogeneous community of people working on real-world problems and/or societal issues characterised by three features: (1) shared content-related motives and purposes (to take on a certain issue), (2) a characteristic procedure (sequence of activities leading to an outcome) and (3) use of relevant scientific knowledge (needed for the issue at hand) (Bulte, Klaassen, Westbroek, Stolk, Prins et al., 2005). The main assumption in this thesis is that if we manage to maintain these features coherently within the constraints of the classroom, students will naturally come to give appropriate meanings to models and modelling. From a theoretical point of view on learning, this approach is underpinned by the activity theory in education, rooted in sociocultural views on learning (Leont'ev, 1978; Van Aalsvoort, 2004; Vygotsky, 1978). From a designer point of view, this strategy is based on the argument that an authentic modelling practice serves as a valuable source of inspiration for developing a meaningful teaching-learning trajectory from students' perspectives (Bulte, Westbroek, De Jong, & Pilot, 2006; Westbroek, 2005). However, promising as this approach might be, it still remains difficult to implement this strategy in the classroom (Edelson, 1998). At present, we lack a specific knowledge base for designing teaching-learning processes using authentic modelling practices as contexts for learning.

Aims and research questions

The motive for this study is to gain an improved understanding of the design of a teaching-learning process, using an authentic modelling practice as context for learning, during which students:

- become meaningfully involved in a modelling process;
- gain understanding of the theoretical and empirical foundation of models;
- learn about epistemic notions, such as goodness of fit, reliability and validity.

At a more generalised level, this thesis aims to contribute to a knowledge base for designing teaching-learning processes in science education, such that students reach an adequate understanding of (the nature of) models and the process of modelling. The knowledge involved will be captured in a design framework, consisting of design principles, learning phases and accompanying instructional functions. Inspired by McKenny, Nieveen and Van den Akker (2006) design principles are defined as theoretically and empirically grounded constructs linking strategy components with intended pedagogic effects, underpinned by arguments. Strategy components prescribe *what*, *when* and *how* to do in the teaching-learning process, in order to achieve the intended pedagogic effects among students, e.g., that students see the point of modelling and achieve improved understanding of epistemic notions. The underpinning arguments originate from literature on educational research, empirical findings from previous applications and/or practical considerations. The learning phases and accompanying instructional functions are inspired by previous research on meaningful teaching-learning processes (Kortland, 2001).

The central research questions addressed in this thesis are:

1. *Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?*
2. *What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?*
3. *What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?*

Research method

The applied method is design research (Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003; Lijnse, 1995). This approach implies the design of a teaching-learning process, accompanied by a set of argued expectations of how the process is expected to take place and why it should operate according to the expectations (Bulte et al., 2006). The initial design of a teaching-learning process is based on theoretical aspects and valuations of the design team. Next, the designed teaching-learning process is enacted in the classroom in several research cycles, focused on testing, reflecting and adjusting the process, in close cooperation with teachers. The testing of the teaching-learning process takes place in a small-scale case study, with a classroom and its teacher as the unit of analysis.

Research overview

This thesis consists of a series of articles dealing with specific (sub) research questions, each presented as a separate chapter. The objective of each article is to contribute to answering one of the central research questions. Below, for each research question the aim and content of each of the chapters is described. An overview of the study is presented in Figure 1.

Research question 1: Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?

Chapter 2 focuses on the selection of suitable authentic chemical modelling practices for use as contexts for learning in secondary education. The suitability of seven practices was reviewed using criteria such as students' interest and ownership, modelling procedure, issue knowledge and feasibility of the laboratory work in the classroom.

Chapter 3 examines to what extent the selected practices initiate students' involvement in modelling processes. For this purpose, learning tasks were designed which were enacted with a focus group of students. During the enactment students' interests and ownership were mapped, their familiarity with the issue and their perceptions of its complexity were investigated, and the modelling procedures they devised in response to the modelling problems, as expressed by students, were analysed.

Research question 2: What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?

Chapter 4 reports a laboratory experiment that was developed and incorporated in the teaching-learning process using the authentic practice of 'Modelling drinking water treatment' as a context for learning.

Chapter 5 describes the initial design of a teaching-learning process using the authentic practice of 'modelling drinking water treatment' as a context for learning. The knowledge involved is captured in a design framework, a synthesis of learning phases, instructional functions and three design principles, labelled 'context', 'content modelling' and 'chain of activities'.

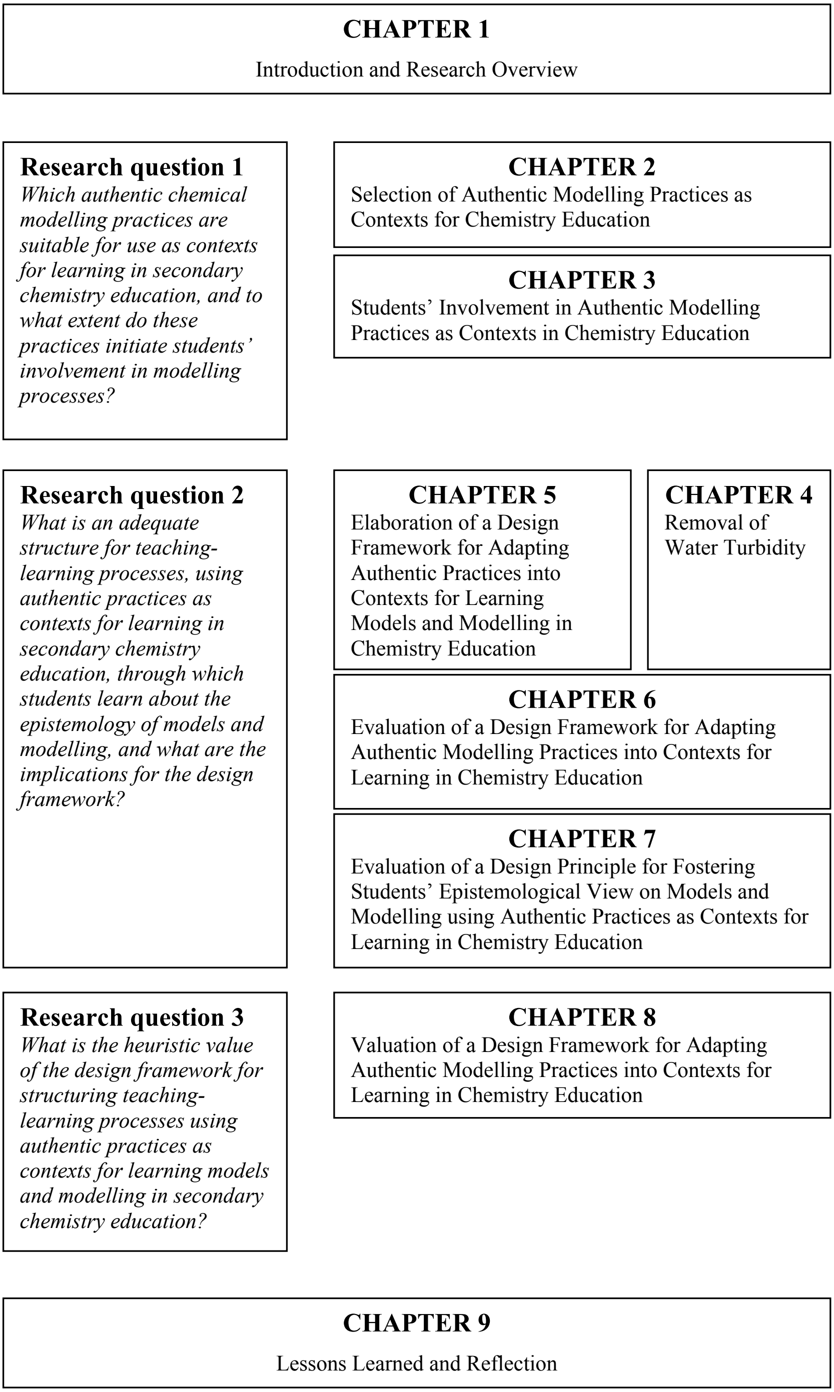

Figure 1. Research overview of the studies in this thesis.

Chapter 6 focuses on the empirical testing and evaluation of the designed teaching-learning process in the classroom. The findings are used to reflect on the design framework in light of the overall functioning of the curriculum unit.

Chapter 7 investigates the specific learning gain regarding the epistemology of models and modelling. The design principle of 'content modelling' is the object of this study.

Research question 3: What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?

Chapter 8 describes the heuristic value of the design framework to adapt another authentic chemical modelling practice into a context for learning. The heuristic value of the design framework was measured upon the completeness, instructiveness and appreciation.

Lessons learned and reflection

In Chapter 9 we summarise all the major findings and conclusions regarding the three central research questions. In this final chapter, we also reflect on the implications, and discuss the contribution of this study to theory-based design with respect to learning models and modelling in chemistry and science education.

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2

Selection of Authentic Modelling Practices as Contexts for Chemistry Education[1]

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1 Prins, G. T., Bulte, A. M. W., Van Driel, J. H., & Pilot, A. (2008). Selection of authentic modelling practices as contexts for chemistry education. *International Journal of Science Education,* 30(*14*), 1867-1890. DOI: 10.180/09500690701581823

CHAPTER 1
Introduction and Research Overview

Research question	Chapters
Research question 1 *Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?*	**CHAPTER 2** Selection of Authentic Modelling Practices as Contexts for Chemistry Education **CHAPTER 3** Students' Involvement in Authentic Modelling Practices as Contexts in Chemistry Education
Research question 2 *What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?*	**CHAPTER 5** Elaboration of a Design Framework for Adapting Authentic Practices into Contexts for Learning Models and Modelling in Chemistry Education **CHAPTER 4** Removal of Water Turbidity **CHAPTER 6** Evaluation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education **CHAPTER 7** Evaluation of a Design Principle for Fostering Students' Epistemological View on Models and Modelling using Authentic Practices as Contexts for Learning in Chemistry Education
Research question 3 *What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?*	**CHAPTER 8** Valuation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education

CHAPTER 9
Lessons Learned and Reflection

Chapter 2 focuses on the selection of authentic chemical modelling practices for use as contexts for learning in secondary education. We concentrated on authentic chemical modelling practices in which the models are used as tools for prediction. The suitability of seven practices was reviewed by document analysis and expert interviews. The review was focused on the following criteria: students' interest and ownership; familiarity with the issue and perceived complexity; modelling procedure applied; issue knowledge involved and feasibility of the laboratory work in the classroom. The procedure resulted in the selection of two practices: (1) modelling human exposure and uptake of chemicals from consumer products, and (2) modelling drinking water treatment.

The following research questions are addressed:

1. *In what authentic chemical practices are models used as a predictive tool?*
2. *To what extent do these authentic chemical practices meet the criteria of students' interest, complexity of the issue, familiarity with the issue and the feasibility of the laboratory work in the classroom?*
3. *What are, for each of the selected authentic chemical practices, the motives and purposes to construct models, the characteristic modelling procedures for developing such models and the related issue knowledge?*
4. *To what extent are these selected authentic chemical practices suitable for use as contexts for learning in secondary chemistry education?*

Abstract

In science education, students should come to understand the nature and significance of models. In case of chemistry education it is argued that the present use of models is often not meaningful from the students' perspective. A strategy to overcome this problem is to use an authentic chemical modelling practice as a context for a curriculum unit. The theoretical framework for this strategy is activity theory rooted in sociocultural theories on learning. An authentic chemical modelling practice is characterized by a set of motives for model development through a well defined modelling procedure using only relevant issue knowledge. The aim of this study was to explore, analyse and select authentic chemical modelling practices for use in chemistry education. The suitability of the practices was reviewed by applying a stepwise procedure focussed on criteria such as students' interest and ownership, modelling procedure, issue knowledge and feasibility of the laboratory work in the classroom. It was concluded that modelling drinking water treatment and human exposure assessment are both suitable to serve as contexts, because both practices exhibit clear motives for model construction and the applied modelling procedures are in line with students' pre-existing procedural modelling knowledge. The issue knowledge involved is consistent with present Dutch science curriculum and it is possible to carry out experimental work in the classroom for model calibration and validation. The method described here to select and evaluate practices for use as contexts in chemistry education can also be used in other science domains.

Introduction

Models are essential to the production, dissemination, and acceptance, of scientific knowledge (Giere, 1988). It therefore seems appropriate that models play equally important roles in science education (Gilbert and Boulter, 1998; Hodson, 1992). Learning to understand the nature and significance of models is regarded as being central to science education. At present, models and modelling are considered integral parts of scientific literacy. However, the study of Grosslight, Unger, Jay and Smith (1991) revealed that students generally do not clearly distinguish the ideas and/or purposes underlying models, the content of the models, and the experimental data which support or refute the validity or usefulness of models. Instead, students usually view models as toys or miniatures of real-life objects, and few students understand why models are used in science (Ingham and Gilbert, 1991). Students generally do not give meaning to the process of modelling. While these problems are apparent in different science education domains, in this paper we concentrate specifically on chemistry education.

The described learning problems related to models and modelling do apply to a variety of models used in chemistry education (Harrison and Treagust, 2000), such as *iconic and symbolic models* to depict chemical formulae and chemical equations, *mathematical models* to represent conceptual relationships of physical properties and processes (e.g. PV = nRT) and *theoretical models* to describe well-grounded theoretical entities (e.g. kinetic theory model of gas volume, temperature and pressure). In this paper we use the term model as some structured representation, including symbolic elements, of the essential characteristics of an idea, object, event process or a system (Gilbert and Boulter, 2000). In addition, we define the act of modelling as the construction, evaluation and revision of a model in response to a particular task (Gobert and Buckley, 2000).

The conventional chemistry curriculum emphasises students' acquisition of conceptual information and declarative knowledge on models (Duschl and Gitomer, 1997; Erduran, 2001). Within this traditional setting, the motivation, strategies and argumentation underlying the development, evaluation and revision of models are neglected, and therefore remain unclear to students (Erduran and Duschl, 2004). Given this situation of utilisation of models it is not surprising that many students have difficulties seeing the meaningfulness of models and modelling.

Students need to gain an understanding of *how* and *why* models are constructed and what modelling process is utilised. We concur with Erduran and Duschl (2004) that the experienced lack of meaningfulness requires a redesign and a redefinition of the trajectory of learning models and modelling. Instead of providing students with models designed by others and uncovering facts to be memorised, the focus should be on the process of modelling and the use of models.

The learning of models and modelling must be legitimised from a student's perspective (Roth, 1996; Sabelli, 1994). In addition, they should become involved in a modelling process in which their understanding contributes to the development of their models and the evaluation and testing of their models contributes to evolving understanding (Penner, Lehrer, & Schauble, 1998; Roth, 1998). This can be achieved if the students' learning is positioned within a well selected context in which a modelling approach is inextricably linked to recognisable real-world problems and societal issues from students' perspective (Bennett and Holman, 2002; Edelson, 1998). By means of such a context students are expected to recognise that chemistry, including its models, matters for society and thus can be relevant for themselves. In fact, engaging students in a context in which they employ authentic model-based tasks has proven to promote the students' understanding of the role and functioning of models in science (Gobert and Pallant, 2004).

Within this perspective we position the challenges for learning models and modelling within the broader international development of context-based science education (Bennett and Holman, 2002; Pilot and Bulte, 2006). However, as promising this strategy might be, it has remained difficult to implement these challenges within the classroom. Part of the problem is that the idea of context-based chemistry education has been used in different meanings (Gilbert, 2006; Van Oers, 1998). The numerous interpretations of the term context evoke some important educational design questions, such as which contexts are suitable for learning models and modelling in chemistry education? What are the essential features of these contexts that need to be implemented in a learning process? How to evaluate the context upon its potential use in chemistry education? To address these design problems contexts need to be identified in which models are employed in a meaningful way. These should be analysed to reveal the essential features and evaluated with respect to learning models and modelling in chemistry. These are the key objectives addressed in this paper.

Authentic chemical practices as contexts

In our interpretation of contexts, we use *authentic chemical practices* for the design of meaningful learning environments(Bulte, Klaassen, Westbroek, Stolk, Prins et al., 2005; Bulte, Westbroek, De Jong, & Pilot, 2006; Westbroek, 2005). In our society many chemistry-related practices are available. For example, practices aimed at quality evaluation of products, e.g. drinking water, food or consumer products for personal health, or practices with an emphasis on research, e.g. developing new catalysts or acquiring fundamental understanding of structure-property relations of proteins. We define an authentic practice as a homogeneous group of people working on real-world problems and societal issues in a 'community' connected by three characteristic features (Bulte et al., 2005):

A. having common *motives* and *purposes*, e.g. evaluation of the quality of a product or development of a new product,
B. working according to a similar type of *characteristic procedure* leading to an outcome, e.g. procedure for quality assessment or design procedure,
C. displaying apparent necessary *knowledge* about the issue they work on, e.g. chemical concepts (or science concepts in broader perspective).

Within such a practice the specific attitudes, characteristic procedures and issue knowledge play a natural role. The relevance of the skills and issue knowledge involved is not questioned, since the participants of such a practice have clear motives to use and extend these accordingly. In an authentic practice people connect the three above features in a meaningful way.

Using an authentic practice as a context for chemistry education involves the implementation of the essential set of motives and purposes, the characteristic procedure and relevant issue knowledge in curriculum units. If we manage to actively involve learners in a practice and perform activities within this practice, they are expected to appreciate the implications of the concepts and give appropriate meanings (Psarros, 1998). Authentic practices can be used as sources of inspiration for designing a sequence of learning activities such that students see the point of what they are doing and have motives to extend their knowledge at every step in the teaching - learning process. This consistency between the learning activities reflects the coherency in the flow of activities in an authentic practice. This view on, and use of, authentic practices in education for the design of meaningful learning processes, stems from, and closely relates to activity theory in education. Activity theory (Engestroem, 1987; Leont'ev, 1978; Van Aalsvoort, 2004) builds on principles of sociocultural theories on learning (Van Oers, 1998; Vygotsky, 1978). Activity theory describes society in terms of connected social practices as manifestations of activity. The unit 'activity' is considered the foundation of knowledge. Rooted in sociocultural theories on learning, activity theory considers the zone of proximal development as a core concept, in which development involves cognitive, affective and volitional aspects. Identifying students' cognitive, affective and volitional aspects in respect of an activity to be studied is a major task to be addressed (Confrey, 1995).

The challenge in adapting an authentic practice for use in education is to maintain authenticity and achieve coherency within the constraints of the classroom environment. The adapted authentic practice for students must reflect a similar set of the three characteristic features for two essentially different populations of learners and experts. Some differences to account for are other interests and dissimilar motivation for involvement into certain issues. Moreover distinct pre-existing procedural knowledge of experts, which students do not possess, regarding the pattern of activities can lead to an outcome (e.g. solution for a problem, product). Consequently, not all authentic practices are equally suitable for use in chemistry education. There is need for explicit selection criteria to analyse and evaluate to what extent authentic practices are within students' zone of proximal development. In this particular study we aim to contribute to the development and use of such criteria by analysing in detail some authentic chemical modelling practices. We specifically focus on authentic chemical modelling practices in which the models are used as tools for prediction. Insight into the predictive potential of models is considered important to be able to judge the quality of models, but is not fully utilized in present chemistry (or science) education (Harrison and Treagust, 2000; Treagust, Chittleborough, & Mamiala, 2002).

Criteria for selection of authentic modelling practices as contexts

We formulate a set of criteria for selection of authentic chemical modelling practices with the aim to develop context-based units for meaningful learning of models and modelling. These criteria are based on the three characteristic features of authentic modelling practices. On each feature we give an overview of cognitive, affective and volitional aspects to account for from the students' point of view based on literature. These aspects in turn give rise to explicit criteria, which are then used to evaluate whether the corresponding feature of selected authentic modelling practices is within the students' zone of proximal development.

Furthermore we have formulated a conditional criterion focussing on laboratory work in the classroom. Models are inseparably linked to empirical data. In most authentic chemical modelling practices empirical data is collected at a certain particular stage for model construction, revision, validation or calibration. To maintain authenticity the laboratory work in the authentic practice should also be feasible within the constraints of a classroom.

Feature A: Motives and purposes

To assess the operational capacity of feature A we discuss two specific aspects of students' involvement into certain issues: interest and ownership.

Osborne and Collins (2001) investigated students' attitudes on school science curriculum, the aspects the students found interesting and valuable, and their views about current content. Their study reported that many students perceive school science to be dominated by content with too much repetition and too little challenge. On the other hand the study showed that most of the students recognise the importance of science and its influence on society. Osborne and Collins concluded that students can become interested and motivated in issues when they perceive an immediate relevance and practical work, provided that these are implemented in challenging teaching materials and with high-quality teaching. Students suggested that there was a need for more contemporary examples in order that school science addresses, at least occasionally, the same issues as science in the media. We thus define criterion A1 (students' interest): students are interested in and motivated for a certain issue.

In addition, several studies have concluded that students' involvement will raise if pupils are able to take control of their learning and develop both knowledge and personal autonomy with the issue at hand (Donnelly, 2001). This aspiration might be realised if students are given opportunities to conduct open-ended investigations in which the students own judgements, case making and interpretations are brought to the fore. In the present case, conditional for students to develop ownership is that they themselves see the point of modelling. So, the authentic motives and purposes for modelling should be recognisable for students. This leads to formulation of a second criterion A2 (students' ownership): students can develop ownership and personal autonomy with a certain issue.

Feature B: Characteristic modelling procedure

The characteristic modelling procedure in the authentic practice, feature B, is of special importance because it should provide for coherence when sequencing modelling activities in the classroom. This flow of modelling activities should be recognisable from the perspective of students to achieve a meaningful learning process. Hence, it is necessary to evaluate to what extent the characteristic modelling procedure fits with the students' common sense notions and pre-existing procedural modelling knowledge. The Modus project, a collaboration between the Advisory Unit for Micro technology in Education and King's College London, focusing on implementing computer-based modelling across the curriculum, outlined a modelling process for general application, as depicted in Figure 1. Webb (1994) tested this modelling process for general application in primary schools among students aged 8-11. The results showed that students successfully employed the modelling stages as outlined, provided that they were familiar and knowledgeable with the subject matter (see also the criteria as formulated for feature C.). These findings are in line with other research studies showing that children learn and use models from an early age onwards (Schauble, Klopfer, & Raghavan, 1991).

Furthermore, it demonstrates that there is no fundamental difference between the thinking of children and adults (experts), except when accounting for domain specific knowledge (Carey, 1985; Kuhn, 1989). In conclusion, we will compare the main stages in the characteristic modelling procedure in an authentic practice with the stages in the proposed modelling procedure for general application. In case of resemblance, we expect that the characteristic modelling procedure is in line with students' pre-existing procedural modelling knowledge.

We therefore formulate criterion B (modelling procedure): The main stages in the characteristic modelling procedure in an authentic practice are in line with the stages in the proposed modelling procedure for general application.

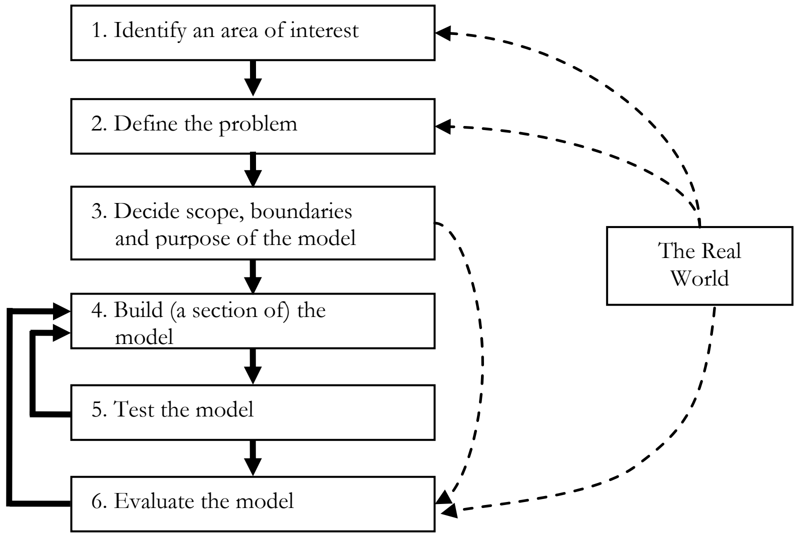

Figure 1. A six-stage modelling process for general application, originating from the Modus project. Bold lines indicate the direction of the process, the dotted lines represent the flow of information (Webb, 1994).

Feature C: Issue knowledge

Experts use specific issue knowledge to act competently in an authentic practice. Students will have to learn the same issue knowledge in the instructional version of the authentic practice, yet consistent with and linked to established science knowledge. Students' cognitive state consists of two areas: they have a certain knowledge base, consisting of domain and general knowledge, and a skills base, which is the repertoire of cognitive activities the students master at that moment (Hmelo-Silver, Nagarajan, & Day, 2002; Schunn and Anderson, 1999).

Although knowledge and skills are mentioned as separate domains, it is broadly recognised that these are used interlinked. Thus, the issue knowledge and skills to be learnt by students should be within students' capacities, and preferably such that they can be productively built on students' initial cognitive state. Although knowledge and skills required in cognitive tasks may vary widely, primarily two factors evolve as being more important: the complexity and familiarity (Taconis, Ferguson-Hessler, & Broekkamp, 2001). The complexity depends on the number of variables involved and number of sub-problems to be solved to reach an outcome. The familiarity depends on the amount of known knowledge and routine skills versus the amount of new information in the situation presented. We therefore define two specific aspects to evaluate the involved issue knowledge in authentic modelling practices:

Complexity (C1): Students must be able to deal with the complexity of the issue

Familiarity (C2): Students must be familiar with the issue.

Conditional criterion D: Laboratory work in the classroom

By means of experiments empirical data is collected for model construction, revision, validation or calibration. However, conducting experiments in classroom is restricted in several ways. Firstly, one should pay attention to the working and safety conditions, both in agreement with legislation. Secondly, the duration of the experiments should not be too long, preferably within a few hours, to ensure finishing the laboratory work in one lesson. Thirdly, the school should have suitable equipment, or if not, the necessary equipment should not be too expensive. The same applies for chemicals to be used. Finally, the preparation time needed from the staff should be reasonable compared to the length of the experiments. Taken together, the above mentioned aspects with respect to laboratory work leads to a conditional criterion for the selection of feasible practices: laboratory work must be feasible in the classroom (D).

In fact, besides the conditional criterion D, the criteria A1 / A2, B and C1 / C2 evaluate whether the features A, B & C of authentic practices are close enough to students interests, modelling abilities and their pre-existing knowledge base. In activity theory the socially accepted attributes of an authentic practice are brought together as far as these are recognised from the perspective of students. Starting from this recognition, students should enter the zone of proximal development. Put another way, the selected authentic modelling practices should provide students with just enough challenges to extend their knowledge of modelling.

Scope and research questions

In this study we focus on the selection, analysis and evaluation of authentic practices for the design of a context-based unit about modelling intended for students aged 16/17 years, grade 11 (third year of the chemistry course), in The Netherlands. The following specific research questions are addressed in this research study:

1. *In what authentic chemical practices are models used as a predictive tool?*
2. *To what extent do these authentic chemical practices meet the criteria of students' interest, complexity of the issue, familiarity with the issue and the feasibility of the laboratory work in the classroom?*
3. *What are, for each of the selected authentic chemical practices, the motives and purposes to construct models, the characteristic modelling procedures for developing such models and the related issue knowledge?*
4. *To what extent are these selected authentic chemical practices suitable for use as contexts for learning in secondary chemistry education?*

Based on the purpose of this study, we started to construct a list of authentic chemical modelling practices from which we short listed a number of promising practices for the design of chemistry units, by applying research questions 1 to 4 subsequently. All criteria are used twice to evaluate the practices, except for criteria students' ownership (A2) and characteristic modelling procedure (B). Criteria A2 and B are used once in the final evaluation step (research question 4), since proper judgement on these criteria is only possible with substantial information on features A and B of the selected authentic practices, which is the case after answering research question 3.

Method

Given the purpose of this study, the data required are essentially qualitative. Authentic practices for educational purposes were searched, selected and analysed in four consecutive steps. Each of the four steps corresponds to answering research question 1 till 4 in turn. Firstly, a list of authentic chemical practices was generated by internet search. Secondly, these practices were evaluated according to the criteria students' interest (A1), complexity of the issue (C1), familiarity with the issue (C2) and feasibility of the laboratory work in classroom (D). Thirdly, the selected practices from the second step were analysed in detail using relevant documents (reports, articles) and by expert-interviews. The aim was to gain more insight into the authentic chemical modelling practices with respect to the three characteristic features. Fourthly, the results of the in-depth analysis of the authentic chemical modelling practices were evaluated according to all criteria. Below each step is described in more detail.

Research question 1: In what authentic chemical practices are models used as a predictive tool?
In this first step, an internet search was conducted to find authentic chemical practices in which models are employed as predictive tools. The search was conducted by one researcher (first author of this article) in January 2004 with search machine Google using a combination of the keywords 'modelling', 'procedure', 'predictive', 'chemistry' and 'practices'. These keywords were derived from our theoretical framework. Our rationale for using this very open search method was to acquire a broad range of authentic chemical modelling practices, including social, technological and research practices. Given concerns about the reliability of some internet resources, the validity of this search method was ensured by selecting only references to well established institutes, e.g. companies or governmental authorities. Solely Dutch websites were included in our search, since Dutch practices were expected to be more recognisable for Dutch students.

Research question 2: To what extent do these authentic chemical practices meet the criteria of students' interest (A1), complexity of the issue (C1), familiarity with the issue (C2) and feasibility of the laboratory work in the classroom (D)?

Each practice found in the previous step was elaborated using information found during the internet search. The information retrieval was carried out by one researcher (first author). Using this information each practice in turn was reviewed according to a subset of the criteria. This review process was conducted independently by two researchers (first and second author). Next, both researchers compared and discussed their judgements on each criterion per practice resulting in a final judgement, which then was reviewed in the full research team (all authors) yielding a decision about which practices to be analysed in detail in the third step.

Research question 3: What are, for each of the selected authentic chemical practices, motives and purposes to construct models (feature A), the characteristic modelling procedures for developing such models (feature B) and the related issue knowledge (feature C)?

In this third step, each of the selected practices were analysed in depth using relevant literature to gain more insight in the characteristic features of each authentic practice. This literature study was performed by one researcher (first author). The outcomes of this analysis were discussed with a second researcher (second author). Next a semi-structured expert-interview was designed and again evaluated with a second researcher. The purpose of the expert-interview was to check whether our interpretation of the motives and purposes for model construction (feature A), characteristic modelling procedures (feature B) and issue knowledge (feature C) involved were correct and complete. The interview outline is listed in Table 1. Next the interview was conducted with one expert per practice. The expert was chosen based on his (or her) in-depth background knowledge on the practice, evidenced by being (co-)author of selected literature. All experts were employed at well-established Dutch institutes in research positions or in charge of a research team. The length of the interview was approximately 90 minutes.

Table 1. Scheme for the semi-structured expert interview

Feature A: Motive to develop models

1. Which (type of) questions or problems led to the development of models?
2. Can you mention some concrete examples of those questions or problems?
3. Why did these questions or problems evoke the need for a model?

Feature B: Characteristic modelling procedure

4. Can you describe the development of the models in a sequence of activities?
   a. What information was used in each stage?
   b. What specific actions were taken in every stage?

Feature C: Issue knowledge

5. What issue knowledge and skills do you consider important for somebody working on these kinds of questions or problems?

The interview was audio-taped and transcribed verbatim. Afterwards the expert was given the opportunity to check the transcript. The interview data were analysed from an interpretative perspective (Smith, 1995). The focus was on the expert's statements concerning the motives and purposes for model construction (feature A) and issue knowledge (feature C), and the expert's response and feedback on the proposed characteristic modelling procedure (feature B). The analysis was conducted by two researches (first and second author) independently, after which the selected statements and feedback were compared and differences in interpretation were discussed. The combined results were again submitted to the expert for final comments, resulting in a complete and thorough description of the practices with respect to features A, B and C.

Research question 4: To what extent do these detailed studied authentic chemical practices meet all criteria for selection as contexts for chemistry units?
Each authentic chemical modelling practice studied in the previous step was evaluated according to all criteria: students' interest (A1), students' ownership (A2), characteristic modelling procedure (B), complexity of the issue (C1), familiarity with the issue (C2) and feasibility of the laboratory work in the classroom (D). This review process was (again) conducted independently by two researchers as described in step 2 (see research question 2). The resulting judgements of both researchers were discussed in the full research team (all authors) for a final decision which modelling practices are usable for designing curriculum units for meaningful learning of models and modelling.

Results

The results will be presented according to the steps described in the method section.

Research question 1: In what authentic chemical practices are models used as a predictive tool?
The internet search yielded a range of issues in the field of science, engineering and technological enterprises. The first run through Dutch websites with Google using keywords 'modelling', 'procedure', 'predictive', 'chemistry' and 'practices' resulted in 120 hits. This search result was refined by eliminating all issues not containing laboratory work by filtering using keywords 'experiments' and 'laboratory work'. This procedure left about 45 links to be visited separately. These links to issues were roughly evaluated on the state of the presented work (starting phase, ongoing project or finish work) and type of laboratory work done. All links to issues in the starting phase were eliminated, for example, those yet to be or recently approved, proposals for development of new modelling techniques.

Also issues in which the laboratory work was very complex or only feasible using advanced equipment were abolished, for example molecular modelling using advanced computer tools. This elimination left 29 issues to take into account. Finally, these 29 issues were clustered depending on the type of topic dealt with, eventually resulting in seven practices to be evaluated. These seven practices are short described in Table 2.

Table 2. Short description of the seven topics of the practices resulting from the internet search

Topics of the practice	Number of references from the internet search	Short description
Climate modelling	7	Modelling circulation of chemical substances in the troposphere to predict climate changes.
Microbiological risk assessment	2	Modelling microbiological (re)contamination in food chains to predict food safety.
Modelling emissions of volatile organic substances	3	Modelling emission of volatile organic substances to predict safety of factory environments.
Modelling drinking water treatment	4	Modelling the water treatment process to predict the quality of drinking water out of surface water.
Model-based predictive control of food production	5	Modelling treatments steps in food production to predict the food quality, - variation and process efficiency.
Human exposure assessment	4	Modelling human exposure and uptake to chemicals emitted by consumer products to predict safety of consumer products.
Modelling a biogas installation	4	Modelling a biogas installation to predict energy supply.

At this point two remarkable aspects could be identified within the list of authentic practices resulting from the internet search. Firstly, all practices found tend to have a multidisciplinary character, in which several science or technology domains are involved, beyond the 'pure' chemical domain. Secondly, the types of models emerging from the found practices are, in fact, mathematical equations, depicting conceptual relationships between chemical concepts. This could be due to our emphasis on the predictive function of the model, since mathematical models are considered the most accurate and predictive of all models (Harrison and Treagust, 2000).

Research question 2: To what extent do these authentic chemical practices meet a subset of the criteria, namely students' interest (A1), complexity of the issue (C1), familiarity with the issue (C2) and feasibility of the laboratory work in the classroom (D)?

Based on the information gathered the seven practices were reviewed according to a subset of the criteria. In four practices, namely climate modelling, model-based predictive control of food production, modelling emissions of volatile organic substances and modelling a biogas installation, little opportunities were seen to implement experiments in classroom, thus resulting in a negative judgement on criterion D in this particular project. In addition, the practices climate modelling and model-based predictive control of food production were judged low on criteria complexity (C1) and familiarity (C2). The issue knowledge involved (feature C) in these two practices was considered not within the zone of proximal development of students. Likewise, the practice modelling emissions of volatile organic substances was judged negatively on motives and purposes for model construction (feature A). This practice dealt with volatile organic substances in factory environments only, which was considered not to be within the students' zone of interests. The results are summarised in Table 3.

With respect to the conditional criterion feasibility of the laboratory work (D), three practices were judged to comply: microbiological risk assessment, modelling drinking water treatment and human exposure assessment. Especially in case of modelling drinking water treatment many opportunities were seen for laboratory work, due the availability of 'ready to use' experiments related to water treatment for use in classroom (Jacobsen, 2004). The three practices microbiological risk assessment, modelling drinking water treatment and human exposure assessment were also expected to score high on students' interest due to dealing with issues students themselves frequently encounter in daily life: food, drinking water and all kinds of consumer products. The judgement on criteria complexity (C1) and familiarity (C2) for these three practices was sufficient with respect to use in chemical education at this stage of analysis.

After this first evaluation step three practices were judged to comply with all the applied criteria. Each practice was studied in detail in the third step to reveal the characteristic features.

Table 3. Combined results of independent judgement by two researchers of the seven practices with respect to criteria: students' interest (A1), complexity of the issue (C1), familiarity with the issue (C2) and feasibility of the laboratory work in classroom (D).

	Students' interest (A1)	*Complexity (C1)*	*Familiarity (C2)*	*Laboratory work (D)*
Climate modelling	+	-	-	-
Microbiological risk assessment	+	+	+	+
Modelling emissions of volatile organic substances	-	+	+	-
Modelling drinking water treatment	+	+	+	+
Model-based predictive control of food production	+	-	-	-
Human exposure assessment	+	+	+	+
Modelling a biogas installation	+	+	+	-

\+ Positive judgement with respect to use in chemistry education at upper secondary level

\- Negative judgement with respect to use in chemistry education at upper secondary level

Research question 3: What are, within the selected authentic chemical practices, the motives and purposes to construct models (feature A), the characteristic modelling procedures for developing such models (feature B) and the related issue knowledge (feature C)?

In this section the combined results of literature study and expert-interviews are presented of the practices microbiological risk assessment (Den Aantrekker, 2002), modelling drinking water treatment (Versteegh, Van Gaalen, Rietveld, Aldenberg, & Cleij, 2001) and human exposure assessment (Van Veen, 2001). We consulted experts from the National Institute of Public Health and the Environment and Wageningen University. The internet search revealed references to these institutes. Both institutes are well known in The Netherlands as being concerned with mentioned topics of the practices. Since the focus during analyses was on motives and purposes, characteristic modelling procedure and issue knowledge, the results are described in that order.

Motives and purposes for model construction

The motives and purposes to construct models in each of the three authentic practices were identified by document analysis and by expert interview. Afterwards the results of both methods were combined, checked and approved by the expert.

Microbiological Risk Assessment

Food has to meet high standards regarding food safety and food quality to prevent food borne illnesses. Obviously, food manufacturers and the government are concerned because of public health reasons. Food manufacturers also have an economic interest besides public health. There is a growing tendency that consumers prefer ready-to-eat meals and more fresh and tasteful food. As a consequence more attention has to be paid to the microbiological safety of food. To control the safety of food, manufacturers are obliged by law to apply a proper hazard procedure. During manufacturing of food, several control systems are applied to control the microbiological quality of food. However, even with the best control measures in place, a food product may still pose a risk to the consumer. In order to quantify this risk, scientists and food manufacturers did join forces to work on a proper quantitative Microbiological Risk Assessment (MRA) to minimize the risk of food borne illnesses. The aim of this practice was to quantify the recontamination risk of food after inactivation steps in the production environment.

Modelling drinking water treatment

The quality of drinking water is an important area within public health care. Different kinds of organic compounds, heavy metals and micro-organisms need to be removed to produce safe drinking water. Therefore several treatments methods are available, such as sand filtration and activated carbon filtration. In the Netherlands, the government and the drinking water production companies expect a growing drinking water demand due to an increase of the population and the level of prosperity. To supply for this extra demand, new sources for production of drinking water have to be found, or the use of existing sources need to be intensified. Since decisions on these matters have effects for a long period of time, it is necessary to have detailed information about future consequences. One would like to have data about the quality of the produced drinking water depending on the quality of the source, e.g. the un-treated water, and type, number and sequence of treatments steps. Such data can be provided with the use of a model predicting the quality of drinking water after treatment. The aim of this practice was to develop such a model consisting of modules representing separate steps in a drinking water treatment process.

Human exposure assessment

Consumer products comprise a large diversity, ranging from shoe polish, to detergents and pesticides. All these products may contain hazardous chemicals. Consumers use all kinds of products for their personal convenience on a daily basis. In the Netherlands, the manufacturers themselves are responsible for the safety of their products for which they use different systems. A commonly used method is expert judgment. However, when a product is encountered with questionable health risks, also a quantitative judgment is needed about the actual human health risks. Many questions are encountered during human risk assessment. How to estimate exposure? Which exposure data are available? Are they representative for the situation in which the product is used? Which factors that control exposure are important? How to characterise risk? Which effects cause the main risks? On which time scale are effects relevant? The aim of this practice was to develop mathematical models, describing exposure and uptake of chemicals from consumer products, to assist in conducting a quantitative human risk assessment.

Characteristic modelling procedures

The characteristic modelling procedure in each of the three authentic practices was primarily distilled from document analysis. During the interview the expert reflected on the proposed procedure, resulting in several modifications and changes. The refined procedures were again submitted to the expert for a final check. Below the approved procedures are presented.

In Figure 2, the characteristic modelling procedures followed by employee(s) in the practices microbiological risk assessment, modelling drinking water treatment and human exposure assessment are presented. The actual modelling procedures all start with the authentic questions or problems, as described in the previous part on motives and purposes, and end with an evaluation with a sequence of activities in between. The flow of activities is compared with the stages in the general modelling procedure for students' (Webb, 1994), as depicted in Figure 2. The comparison reveals that the basic structure of the characteristic modelling procedures resemblances the stages in the general modelling procedure. Therefore, we expect that the characteristic modelling procedures are consistent with and linked with students' pre-existing procedural modelling knowledge. That is, when students are confronted in a proper way with the starting authentic questions or problems, we expect that students do have a basic approach in mind resembling the authentic modelling procedures. It seems appropriate to use the characteristic modelling procedure as a guideline for designing a meaningful sequence of modelling activities from students' perspective.

Issue knowledge

The issue knowledge involved in constructing models in each of the three authentic practices was firstly identified from document analysis. During the expert interview the respondent was asked to point out the main issue knowledge needed to act competently. The combined results regarding issue knowledge, as depicted below, were checked and approved by the expert.

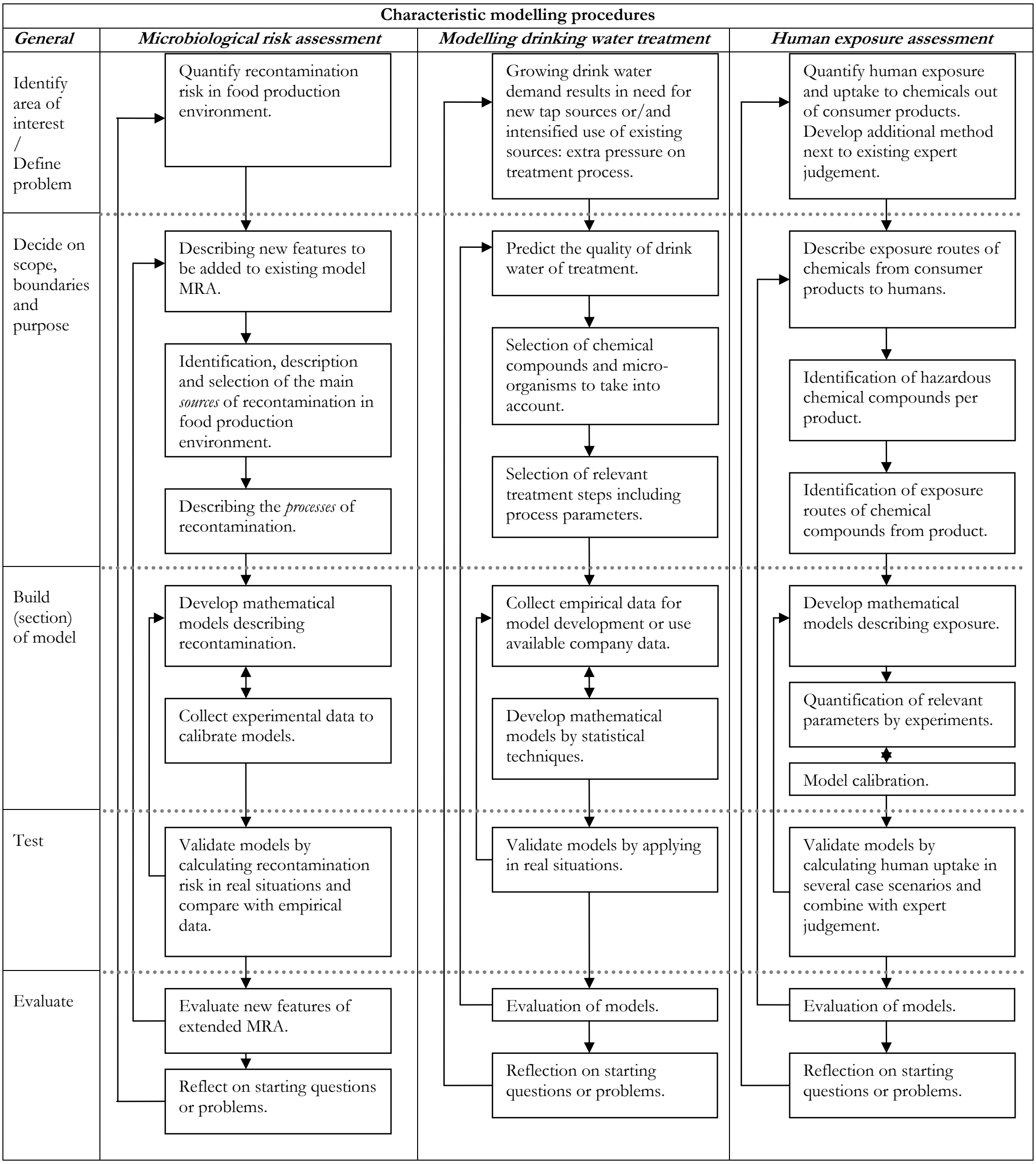

Figure 2. The characteristic modelling procedures in microbiological risk assessment, modelling drinking water treatment and human exposure assessment approved and checked by the experts. Arrows indicate the direction of the processes. The different stages in the procedures are outlined according to the stages in the modelling process for general application depicted on the left (Webb, 1994).

In Table 4 an overview of the involved issue knowledge in the practices microbiological risk assessment, modelling drinking water treatment and human exposure assessment is presented. All elements present Dutch science curricula at grade 11 are depicted in bold. These findings illustrate once again, but in much more detail, the multidisciplinary character of all three authentic practices. Furthermore, this overview of issue knowledge involved in each of the three practices gives some insight into the expected learning output when used as contexts.

It can be concluded that the issue knowledge involved in modelling drinking water treatment and human exposure assessment correlates well with the actual content in chemistry (science) curricula. Many chemical (science) concepts are expected to be familiar to students in upper secondary chemistry education (age 16/17). In addition, both modelling drinking water treatment and human exposure assessment do offer some degree of flexibility with respect to specific issue knowledge needed, since in both cases different treatment steps and contaminants or consumer products, chemical substances and emission routes, can be selected or omitted to focus upon in classroom.

Table 4. An overview of involved issue knowledge in microbiological risk assessment, modelling drinking water treatment and human exposure assessment, approved and checked by the experts. In bold are depicted elements present in Dutch science curricula at grade 11.

Domain of issue knowledge	***Microbiological risk assessment***	***Modelling drinking water treatment***	***Human exposure assessment***
Chemistry / technology	Mass- and heat transfer Flow characteristics of complex, heterogeneous media at different size and timescales	<u>Water contaminants:</u> **Inorganic / organic contaminants** Disinfection products Pesticides **<u>Chemical treatment processes:</u>** **Precipitation** / coagulation / flocculation **Activated carbon filtration** Aeration / ozonation **<u>Drinking water supply:</u>** **Drinking water quality parameters** Infrastructure of drinking water supply Environmental Outlook	**Mixtures / pure substances / solvents** **Concentration (weight fraction)** Evaporation characteristics Mass balances for evaporation **Diffusion** **Chemical identification of substances** **Molecular structure of substances**
Biology	**Physiology and taxonomy of micro-organisms (bacteria, fungi, viruses, etc.)** Metabolic flux analysis to describe behaviour of micro-organisms during stress periods *'Predictive'* microbiology (develop quantitative models to describe behaviour of micro-organisms)	<u>Biological treatment processes:</u> - Flocculation / settling - **Slow (rapid) sand filtration** **<u>Health risks and dangers of bacteria:</u>** - Enterovirusses - Giarda - Cryptosporidia	<u>Dose-effect relations:</u> - **Long term average vs. acute** - Worst case dose - Standard dose **<u>Contact:</u>** - **Exposure (chemical)** - **Uptake (breath in, skin, month)** - Scenario's (duration, frequency)
Mathematics	**Statistical analysis of large data sets** **<u>Differential equations</u>** - partial - numeric - analytical Develop and analyse complex models for metabolic flux analysis Symbolic and numerical solutions Experimental/statistical experiments	**<u>Statistics:</u>** - **Averages** - **Standard deviation** - Regression analysis	**<u>Statistics:</u>** - **Averages** - **Standard deviation** - **Distributions:** ▪ **mean** ▪ **uniform** ▪ **empirical** **Differential equations**
Modelling	The skills to select from experimental observations the essential factors or conditions needed to describe or explain a phenomena and to use them develop a simple model capable to describe the dependence of the factors in the phenomena. Draw up and analyze physical mechanisms aimed to develop simple models 'Data driven modelling'	Empirical / systematic modelling approach <u>Predictive value of models:</u> - uncertainties - reliability Risk balancing	Systematic modelling approach Categorisation of consumer products Dealing with uncertainties Risk assessment

In case of microbiological risk assessment however, a relatively large number of elements that are not present in the Dutch science curricula can be distinguished, thus resulting in a negative judgement on criterion familiarity with the issue (C2). Moreover, microbiological risk assessment, unlike the other two models, puts a rather high demand on mathematical and technological background knowledge.

Research question 4: To what extent do these authentic chemical practices meet all criteria for selection as contexts for chemistry units?
Based on the information gathered in the step 3 the three authentic chemical modelling practices were again reviewed to criteria students' interest (A1) and ownership (A2), the characteristic modelling procedure (B), complexity of the issue (C1), familiarity with the issue (C2) and practical feasibility of the laboratory work in classroom (D). The outcome is summarised in Table 5.

Table 5. Combined results of independent judgement by two researchers of microbiological risk assessment, modelling drinking water treatment and human exposure assessment with respect to criteria: students' interest (A1), students' ownership (A2), modelling procedure (B) complexity of the issue (C1), familiarity with the issue (C2) and feasibility of the laboratory work in classroom (D).

	Students' interest (A1)	*Students' ownership (A2)*	*Modelling procedure (B)*	*Complexity (C1)*	*Familiarity (C2)*	*Laboratory work (D)*
Microbiological risk assessment	+	-	+	+	-	-
Modelling drinking water treatment	+	+	+	+	+	+
Human exposure assessment	+	+	+	+	+	+

\+ Positive judgement with respect to use in chemistry education at upper secondary level

\- Negative judgement with respect to use in chemistry education at upper secondary level

Two authentic practices are considered to be adequate to serve as contexts for designing curriculum units: modelling drinking water treatment and human exposure assessment. In this second evaluation step the practice microbiological risk assessment was judged low on criteria students' ownership (A2), familiarity with the issue (C2) and feasibility of laboratory work in classroom (D). It appeared that the motive to develop models is drawn from a long term need to control food safety. Apparently, one needs to be well informed in the field of food safety to gain some sense of importance of this long-term need. Such a long term motive seems less suitable to foster students' ownership with the problem at hand. Furthermore, in case of microbiological risk assessment, advanced background knowledge in biology, mathematics and technology is needed in order to act competently. Hence, the expected familiarity of students with the issue is judged low. With respect to issue knowledge, difficulties might be expected in managing the total cognitive load of students. Finally, this second evaluation revealed that implementing laboratory work for model calibration and validation in classroom will be difficult. In the first analysis, the familiarity of students with the issue was considered sufficiently and opportunities were seen to implement laboratory work in classroom. However, the literature study and consultation of the expert have lead to other judgements on these criteria.

In case of modelling drinking water treatment and human exposure assessment it is expected that students do experience ownership for the topic at hand due to clear motives and purposes for model construction from student's perspective. The characteristic modelling procedures in both practices are expected to be in line with students' common sense notions and pre-existing procedural modelling knowledge. The depicted modelling procedures are applicable to a choice of treatment steps and contaminants, or consumer products, chemical substances and emission routes, thus facilitating implementation in classroom. Both practices do offer opportunities to implement real experiments for model calibration and validation in the classroom. Results on the issue knowledge involved indicated that it seems possible to build upon the existing knowledge base of students.

In conclusion to this step-wise selection procedure to search, select, analyse and evaluate authentic practices to be used for modelling education, we formulate the answer on research question 4 as follows. Both modelling drinking water treatment and human exposure assessment meet the criteria to a large extent. The results show that both practices are within the students' zone of proximal development and thus are potentially usable as contexts for the design of meaningful units for the learning of models and modelling.

Conclusions and discussion

In the final section of this paper, the results described above are discussed in relation to the purpose of this study. The present study has sought to select authentic chemical modelling practices as contexts for meaningful learning of models and modelling, based on activity theory rooted in sociocultural theories on learning. Authentic practices provide guidelines for designing context-based units. These guidelines are the motives and purposes for model construction, the characteristic modelling procedure employed, and the involved issue knowledge. Not all authentic practices are suitable for use in upper secondary chemistry education. Therefore we formulated a set of criteria for selecting and evaluating authentic practices. This study revealed two authentic chemical modelling practices which can serve as a context for unit design. Both practices meet all formulated criteria to a large extent. The motives for model development appeared to emerge from clear problems or questions, which seem recognisable from the students' perspective. The characteristic modelling procedure corresponds to a large degree with students' expected common sense procedural knowledge, and thus can be used to design a coherent sequence of modelling activities in classroom. One of the challenges in adapting an authentic practice into an instructional version is to account for the differences in issue knowledge between experts and students. Both practices can be elaborated flexibly, for instance by focusing on well chosen treatment steps or chemical substances within consumer products, thus establishing a solid connection with students' pre-existing knowledge base.

However, one should consider that these conclusions are situated within the Dutch perspective. Therefore only Dutch websites were reviewed reporting about essentially Dutch authentic issues. As a consequence, Dutch experts were interviewed. Finally, the involved issue knowledge in the authentic practices was compared to the actual Dutch chemistry (science) curriculum.

By describing this starting point of selecting authentic practices for the design of units in which students should experience the meaningfulness of learning models and modelling, we also contribute to the development of contexts-based units in science education. This method to select and evaluate practices for use as contexts might be of use in other science domains. Furthermore, we have indicated in what way the essential features of those practices will be of use during the design of such context-based curriculum units.

Over the past years, models and modelling has been studied from several perspectives, like students' understanding of specific models in physics and chemistry, the process of modelling, teachers' knowledge and use of models in science education and how modelling can be approached gradually in the classroom (Gilbert and Boulter, 2000; Harrison and Treagust, 1996; Justi and Gilbert, 2002; Treagust et al., 2002; Van Driel and Verloop, 2002). Most of these studies focus primarily on models that already, for historical reasons, have been incorporated in science curricula describing or explaining phenomena regarded as representative for that domain. However, major learning problems related to models and modelling are still apparent. The strategy described in this paper builds on recommendations in literature to focus on the process of modelling and the use of models (Penner et al., 1998; Roth, 1998). Our approach implies that the modelling procedure in an authentic practice determines, to a large extent, the design of a curriculum unit. The selected authentic practices are considered within the students' zone of proximal development, in contrast to many 'typical' traditional research practices from which the issue knowledge can be found in traditional science curricula. The use of a relatively open internet search method as described proved to be successful in finding practices in which students can recognize real-life problems and societal issues (Bennett and Holman, 2002; Edelson, 1998). Furthermore, in a curriculum unit based on the selected practices students are engaged in authentic modelling approach with an explicit attention for motives and purposes to construct models. In our opinion, such an unit significantly promotes students' understanding of the role and functioning of models in society (Gobert and Pallant, 2004). In addition, students are expected to recognise that models and modelling in chemistry matters for society and thus can be relevant for themselves. We consider this as an important goal for chemistry education and science education in general.

Although this study has revealed two promising authentic practices, further research is needed to evaluate the potential benefits of this strategy. This includes an analysis of the adaptation of the selected authentic chemical modelling practices into instructional versions, teacher preparation, classroom practice and outcomes in terms of students' insight in the functioning and meaning of models in science. Preceding the full design of an authentic practice based unit, we consider it appropriate to gain more certainty in the potential success of our efforts. In our view meaningful learning of models and modelling by students can only be achieved if students indeed feel a need for modelling and have some sense of direction in terms of a sequence of modelling activities. Since these values should emerge in the beginning of an unit, we plan to study empirically the start of both selected authentic practice based units in a forum group of students using the method of developmental research (Bulte et al., 2006; Lijnse, 1995). The next step will be designing a complete unit to be tested in real classroom situations. This research phase needs to be accompanied with well planned teacher preparation, since both model use and outlining of the unit will be very different compared to normal chemistry classes. However, given the fact that model-based teaching and learning is regarded as central in science education, it is worth while to explore this strategy, and to evaluate the potential benefits in classroom and the possible contribution to the design of context-based units in science education.

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3

Selection of Authentic Modelling Practices as Contexts for Chemistry Education[1]

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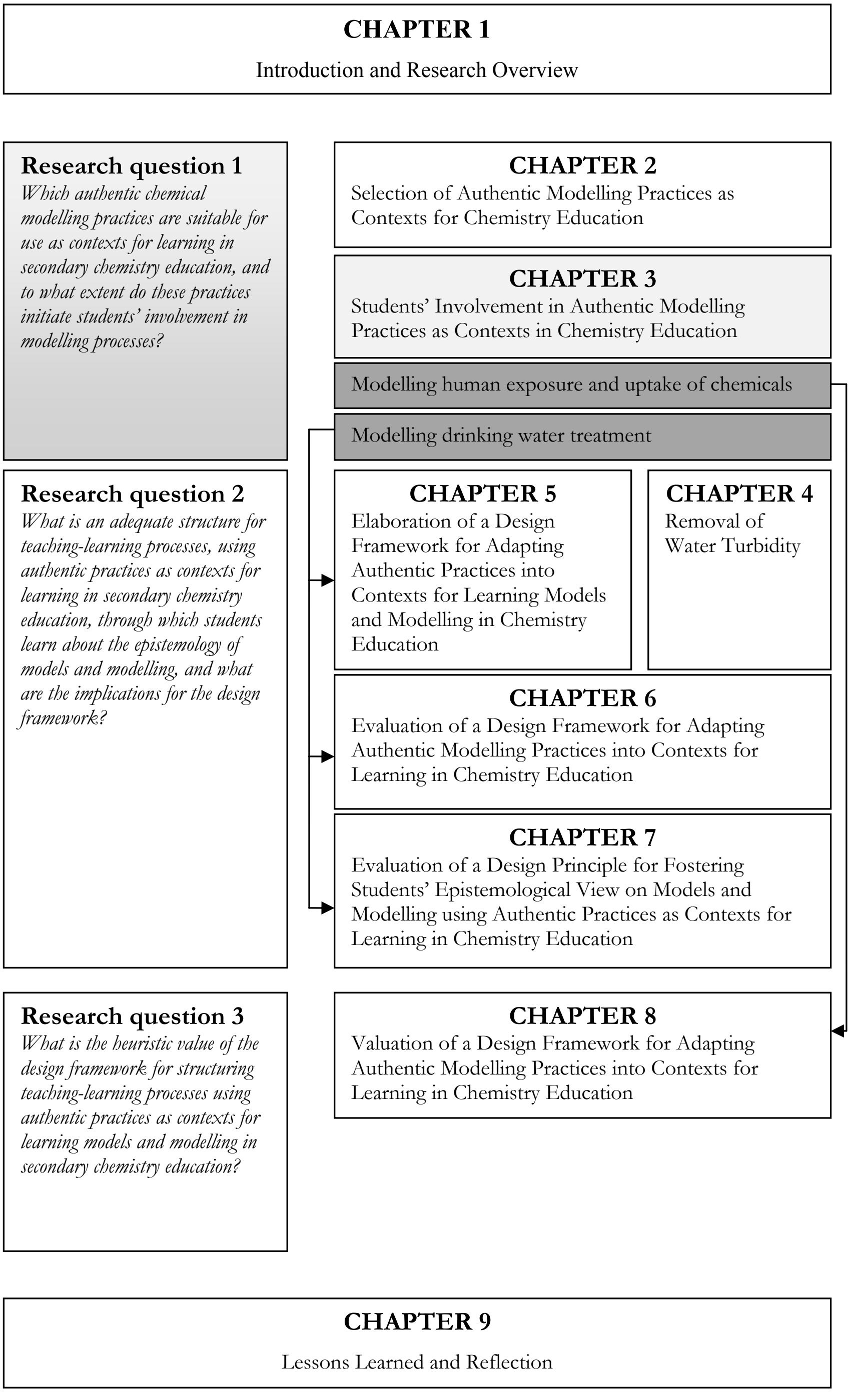
CHAPTER 1
Introduction and Research Overview
Research question 1
Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?
CHAPTER 2
Selection of Authentic Modelling Practices as Contexts for Chemistry Education
CHAPTER 3
Students' Involvement in Authentic Modelling Practices as Contexts in Chemistry Education
Modelling human exposure and uptake of chemicals
Modelling drinking water treatment
Research question 2
What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?
CHAPTER 5
Elaboration of a Design Framework for Adapting Authentic Practices into Contexts for Learning Models and Modelling in Chemistry Education
CHAPTER 4
Removal of Water Turbidity
CHAPTER 6
Evaluation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education
CHAPTER 7
Evaluation of a Design Principle for Fostering Students' Epistemological View on Models and Modelling using Authentic Practices as Contexts for Learning in Chemistry Education
Research question 3
What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?
CHAPTER 8
Valuation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education
CHAPTER 9
Lessons Learned and Reflection

In Chapter 3 we examine to what extent students become involved in modelling processes. For this purpose, learning tasks were designed that related to two practices: (1) modelling human exposure and uptake of chemicals from consumer products, and (2) modelling drinking water treatment. In these learning tasks students orient themselves on the authentic practice at hand and draw up a plan of action for solving a modelling problem. The tasks were enacted with a focus group of students. During the learning process students' interests and ownership were mapped, their familiarity with the issue and perceived complexity were investigated, and the modelling procedures devised by students in response to the modelling problem, as expressed by them, were analysed. It was found that both practices appeal to students, evoke their interest, encourage willingness to work and build on their prior knowledge base and intuitive notions.

The following research questions are addressed:

1. *To what extent does the use of authentic practices as contexts evoke students' interest and initiate ownership?*
2. *To what extent are students familiar with the modelling issues and able to manage the complexity?*
3. *To what extent are students able to express a rudimentary procedure in response to modelling issues, in terms of a sequence of activities accompanied by relevant issue knowledge?*

Abstract

In science education students should come to understand the nature and significance of models. A promising strategy to achieve this goal is using authentic modelling practices as contexts for meaningful learning of models and modelling. An authentic practice is defined as professionals working with common motives and purposes, pertaining to a similar type of procedure and applying relevant knowledge on the modelling issue they work on. In this study we evaluate whether the use of authentic practices initiates adequate students' involvement. This was done by investigating students' interests, ownership, familiarity and complexity. In addition, we evaluated students' expressed modelling procedures in response to the modelling issues. We designed learning tasks which were enacted by a focus group of students. Three primary data sources were used to collect data. Firstly, a group discussion was organised in which students' reflected on both authentic practices. Secondly, students filled in written questionnaires containing items on affective and cognitive aspects. Thirdly, the realised modelling procedures by student were analysed. The results show that students' involvement was successfully initiated, evidenced by motivated students, willingness to continue and the completeness and quality of the realised modelling procedures. The design of the learning tasks proved to be successful in realising this involvement. The results obtained in this study support the strategy of using authentic modelling practices as contexts for meaningful learning of models and modelling.

Introduction

Models are essential both in science and in science education. As such, models are generally viewed as connections between the scientific theory and the world as experienced. Currently, the learning of models and modelling is regarded as an integral part of scientific literacy (Clement, 2000; Gilbert, 2004). Given the fact that modelling is considered an essential element of scientific thinking, there is an urge to design learning environments such that students' understanding of the nature of models is enhanced (Harrison and Treagust, 1998).

In science education, the terms model and modelling are used quite ambiguously (Harrison and Treagust, 2000). Examples of models used are iconic and symbolic models, to depict chemical formulae and chemical equations, mathematical models to represent conceptual relationships of physical properties and processes (e.g. $PV = nRT$) and theoretical models to describe well-grounded theoretical entities (e.g. kinetic theory model of gas volume, temperature and pressure). In this paper we concentrate on models and modelling in chemistry education. We use the term model as some structured representation, including symbolic elements, of the essential characteristics of an idea, object, event, process or system (Gilbert and Boulter, 2000). In addition, we define the act of modelling as the construction, evaluation and revision of a model in response to a particular task (Van der Valk, Van Driel, & De Vos, 2007).

Many studies have revealed that students do not effectively learn about models and modelling (Grosslight, Unger, Jay, & Smith, 1991; Harrison and Treagust, 1996) Students, in general, think of models as copies of reality. Students have problems capturing more advanced features of model understanding, like the purpose of creating models, models as representations of ideas in contrast to reality, the construction of models and the notion that models can be tested and changed in order to inform the development of ideas. There is substantial evidence that the traditional chemistry curriculum does not fully support students' learning of models and modelling. Erduran and Duschl (2004) pointed out some trends within the traditional framework of chemistry teaching that account for this lack of support. Firstly, chemical models are presented to students as final versions of our knowledge, neglecting the tentative nature of models. Secondly, textbooks often present inaccurate 'hybrid' models which cause confusion among students (Carr, 1984). Thirdly, chemical models have been synonymised with the visual ball-and-stick models, resulting in a unilateral view on chemical models from a student's perspective. Finally, chemical experimentation has rarely been implemented as an activity through which models are developed, evaluated and revised. Given these trends how models and modelling are implemented in chemistry education, the motivations, strategies and arguments underlying the development, evaluation and revision of chemical models are overlooked. To overcome these problems, the trajectory of learning of models and modelling needs to be redefined.

Students should become actively involved in modelling processes in which they develop understanding of their models including the evaluation and testing (Penner, Lehrer, & Schauble, 1998; Raghavan and Glaser, 1995). It has been claimed that this aspiration might be realised by designing a learning environment which accurately reflects an authentic science practice that employs models (Edelson, 1998; Roth, 1998). Students need to experience models in processes similar as those used in research laboratories or other settings in which real science takes place (Sadler, 2007).

As appealing the benefits might be, the empirical basis supporting these theoretical claims is limited. In addition, the design knowledge for adapting the characteristic features of authentic practices into contexts for curriculum units is inadequate. Therefore, as part of a larger research project, this study evaluated whether the use of authentic practices as contexts *initiates* adequate students' involvement for learning models and modelling. For this we designed learning tasks which were enacted by a focus group of students.

Theoretical framework

Coherency between modelling activities and issue knowledge can be achieved by defining context as a cultural entity in society (Bulte, Klaassen, Westbroek, Stolk, Prins et al., 2005; Gilbert, 2006; Sadler, 2007). Following this proposition, we use authentic chemical practices as contexts for curriculum units. We define an authentic practice as a homogeneous group of people in society working on real-world problems and issues in a 'community' connected by three characteristic features: common motives and purposes, working according to a similar type of characteristic procedure leading to an outcome and using relevant knowledge about the issue they work on (Westbroek, 2005). The use of authentic practices as contexts relate to the activity theory in education, rooted in the socio cultural tradition (Leont'ev, 1978; Vygotsky, 1978).

However, when using authentic practices as contexts for curriculum units, one needs to acknowledge significant differences between the population of students and that of experts. Any adaptation of an authentic practice will need to address three primary aspects: curriculum structure; teacher preparation; and learner-appropriate resources, such as attitudes, tools and techniques (Edelson, 1998). In this study we focus specifically on the students' involvement. Students' involvement should be initiated at the start of the curriculum unit, in which students orient themselves with the authentic practice at hand. The issues should appeal to students, evoke their interest, encourage willingness to work and build on pre-knowledge and intuitive notions. For establishing adequate involvement of students, three conditions should be satisfied to a sufficient extent. Below each condition is addressed briefly.

Condition A. Connect to students' interest and ownership

We agree with Bennett and Holman (Bennett and Holman, 2002) that the use of recognisable contexts in science education potentially fosters students' interest and ownership. By means of such a context students are expected to become active learners, they are expected to acquire scientific knowledge in a meaningful context and to develop appropriate styles of inquiry and communication. However, experts do have different interests and sense of ownership compared to students. So, the authentic practice as context should evoke students' interest and initiate ownership in order to achieve adequate involvement.

Condition B. Comply with students' familiarity and complexity

Experts have a vast amount of knowledge about an issue. This knowledge covers, amongst other things, the scientific concepts, tools and techniques. We need to account for differences in knowledge between experts and students. The extent to which students are able to cope with the cognitive load of an issue depends primarily on the familiarity with the issue and perceived complexity (Taconis, Ferguson-Hessler, & Broekkamp, 2001). In conclusion, the modelling issue addressed should be sufficiently familiar to students with manageable complexity.

Condition C. Build on students' procedural modelling knowledge

In the past decade considerable interest has developed in the design of modelling processes at all levels of schooling in science education (Clement, 2000; Hodgson, 1995; Ingham and Gilbert, 1991; Raghavan and Glaser, 1995). A common goal of the numerous approaches is to engage learners in modelling processes (Linn, Songer, & Lewis, 1991). However, modelling is a difficult enterprise for students to be engaged in and involves complex thinking. Students frequently tackle a complex issue in a fragmented, uncoordinated way or struggle to complete the task (Hogan and Thomas, 2001; Riley, 1990). Various studies have been carried out that have investigated conceptualizing modelling processes (Buckley, 2000; Webb, 1994). The study of Webb (Webb, 1994) has showed that students are able to express a modelling procedure in general terms, provided that students are familiar and knowledgeable with the issue.

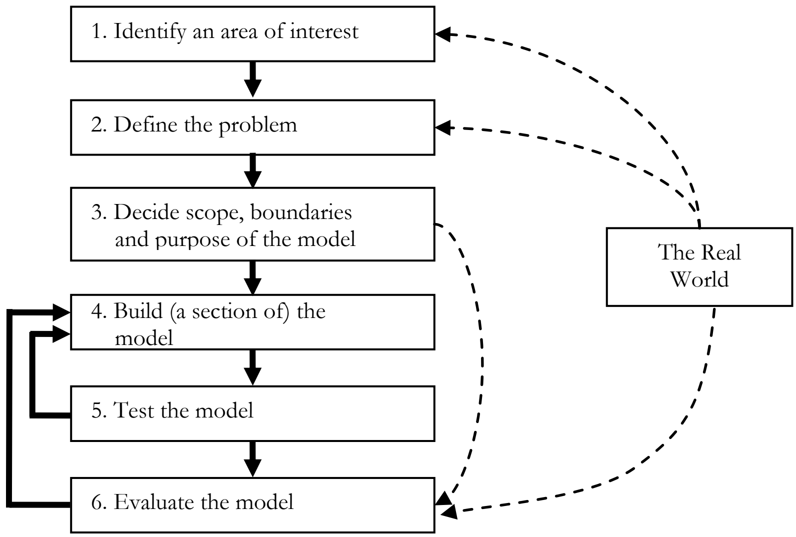

Figure 1. A six-stage modelling process for general application, originating from the Modus project. Bold lines indicate the direction of the process, the dotted lines represent the flow of information (Webb, 1994).

This finding is supported by other studies, showing that the development of modelling ability is heavily context dependent (Carey, 1985). The stages in the modelling process for general application are depicted in Figure 1. In conclusion, in order to initiate students' involvement it is essential that the modelling issue builds on students' procedural modelling knowledge. Students should be able to express, in a rudimentary sense, a modelling procedure in response to the issue. Such a modelling procedure should consist of a series of modelling activities accompanied by relevant issue knowledge.

Scope and research questions

This research study is positioned within the broader perspective to develop and investigate context-based curriculum units in science education. The aim of this study was to investigate to what extent the use of authentic practices as contexts initiates adequate students' involvement for learning models and modelling. Two authentic practices were evaluated. For this we designed learning tasks which were enacted with a focus group of students'. Three research questions are addressed:

1. *To what extent does the use of authentic practices as contexts evoke students' interest and initiate ownership?*
2. *To what extent are students familiar with the modelling issues and able to manage the complexity?*
3. *To what extent are students able to express a rudimentary procedure in response to modelling issues, in terms of a sequence of activities accompanied by relevant issue knowledge?*

The first question elaborates condition A, the second condition B and the third question condition C.

Method

In this section the participants, the authentic practices, the designed learning tasks, the enactment of the learning tasks, the data collection and analysis are described. At the end of this section an overview is given of data sources for each research question.

Participants

In total 18 students, grade 10-11 from three schools in Utrecht, The Netherlands, participated, each receiving financial compensation. The cohort consisted of 12 girls and 6 boys. Each participant was asked to fill in a questionnaire about their view on chemistry education at school and personal reasons to participate. All students studied chemistry at high school. The majority (15) of the students appreciated chemistry. The experimental work was mentioned as the most attractive part, next to explanations of phenomena. The calculation part of chemistry was considered least interesting as well as studying topics hardly linked to the 'real world', such as balancing reaction equations. The average score of the students on chemistry was 6.5 on a scale of 1 (low) to 10 (high). The lowest score was 4.9, the highest 8.0. Chemistry was considered 'difficult' by 9 students and 'easy' by the other 9 students. The experienced difficulty was mainly caused by 'trouble in imagining what chemistry is about'. The main reason to participate in this study was to contribute to the development of new content for chemistry classes and orientation on possible topics for the obligatory science project each science student has to carry out for their final assessment in secondary school.

Authentic chemical modelling practices

In a previous study we selected two authentic chemical modelling practices as contexts for learning of models and modelling: 'Modelling drinking water treatment' and 'Human exposure and uptake of chemicals from consumer products'. The selection was based upon criteria students' interest, ownership, familiarity and complexity. Below both authentic practices, situated in society, are briefly described.

Modelling drinking water treatment

The growing water demand in The Netherlands in the past decades caused an intensified use of existing sources. This tendency resulted in a need for more detailed knowledge of the influence of various process variables on the treatment process. The aim was to develop a tool to predict the quality of drinking water depending on the quality of the raw water and treatment processes. For each treatment step, e.g. activated carbon filtration, the relevant process variables were identified. Next, their influence on the effectiveness was determined, firstly on a qualitative level using relevant chemical or biological knowledge of removal of contaminants and micro organisms, secondly on a quantitative level by gathering empirical data, through laboratory experiments and/or company data. The empirical data are analysed by statistical techniques resulting in mathematical models. For example, the developed models range from percentage-removal based,

like $conc_{out} = \left(1 - \frac{X}{100}\right) conc_{in}$ in which X is the empirical determined removal percentage,

till process models incorporating the influence of process variables,

like $TOC_{out} = const * TOC_{in}^{a} * dose^{b} * pH^{c}$

for predicting the 'total organic carbon' (TOC) removal from raw water during coagulation / flocculation treatment (*const*, *a*, *b* and *c* are empirical determined fit parameters). Each model is accompanied with a 'goodness of fit' indication and a reliability check. The complete treatment process has thus been represented by a series of mathematical models, each representative for one treatment step. Combining the models enables prediction of the quality of drinking water after treatment given a certain raw water quality.

Human exposure and uptake of chemicals from consumer products

Consumer products comprise a large diversity, ranging from shoe polish to detergents and pesticides. All these products may contain hazardous chemicals. When a product is encountered with questionable health risks, an objective quantitative risk assessment is needed. For such assessment one needs to calculate the total uptake of potential hazardous chemicals from consumer products, based on detailed information on the composition of the product itself and on the contact route. For example, for contact route 'mouth' several physical models are available, like single ingestion

$E = \frac{w_f q}{DV_{product}}$ and leaching from product $E(t) = E_0 \exp^{-\left(\frac{RA}{E_0 V} t\right)}$.

In these models E is the amount of compound taken up. Both models contain empirical parameters, like the initial leaching rate (R), parameters specific for the product at hand, such as the initial amount of compound (E_0), weight fraction (w_f), surface (A) and volume (V), and parameters related to type of use, like amount of product (q), dilution (D) and duration (t). When using the proper model fit for a specific contact route, one can predict the total amount of hazardous chemicals released and taken up by a consumer.

Adaptation of the authentic practices into contexts

In this section we describe the adaptation of the selected authentic practices into contexts for chemistry curriculum units. The design of the learning tasks was inspired by previous research on meaningful teaching-learning processes (Cobb, Stephan, McClain, & Gravemeijer, 2001; Lijnse, 1995; Lijnse and Klaassen, 2004). In the first three tasks students orientated on the practice. In the fourth and last task, students were given the open task to draw up a plan of action to solve an exemplary problem themselves. In this plan of action students express a series of modelling activities. In Figure 2 a detailed description is given of the sequence and content of each learning task.

In the practice 'Modelling drinking water treatment', hereafter named unit 'Treatment', students take notice of occasional exceeding of the quality norms of drinking water in The Netherlands. Next, students study recommendations of experts to improve the treatment processes. In the subsequent tasks students zoom in on treatment step coagulation/flocculation of surface water. During coagulation/flocculation suspended matter and colloid particles, causing turbidity of water, are removed together with attached contaminants. Students set up a modelling approach to develop a mathematical model predicting the removal of nickel by coagulation/flocculation as a function of process variables initial nickel concentration, coagulant dose and the pH.

In the practice 'Human exposure and uptake of chemicals from consumer products', hereafter named unit 'Exposure', students orientated on the release and uptake of chemicals from consumer products, like phtalates from kids-toys. Students take notice of advises of experts. Next, students focus on the release and uptake of dyes from kids-toys and plan a modelling approach to predict the total amount of dyes taken up. Students have to think about relevant data related to the contact route, how to collect this data and how to calculate the total amount of dye taken up with use of a proper model.

	Learning tasks	*Modelling drinking water treatments*	*Modelling human exposure and uptake of chemicals in consumer products*
General orientation on the authentic practice. *Condition A:* Evoke students' interest and initiate ownership	Students study newspaper articles individually (task 1) and discuss them in teams (task 2). Teams think of possible measures to take, and the kind of knowledge needed for this kind of problems.	Tree newspaper articles reporting on: 1. High concentrations of heavy metals and pesticides in drinking water. 2. Drinking water companies having problems producing good quality drinking water. 3. Results of a research project on possible improvements of the treatment process.	Tree newspaper articles reporting on: 1. High concentrations of carcinogenic phtalates in kids toys, especially 'Scooby-doo' ropes, cause health risks among children 2. The government emphasizing that more in depth data are needed and research will be initiated. 3. The National Institute of Public Health and Environment starting an investigation on health risks of 'Scooby-doo' ropes.
Condition B: Students are familiar with the issue and able to manage the complexity. Learning tasks 1, 2 and 3.	Teams study a project plan (task 3). They are asked to think over: *1.* *Why* a model is needed. 2. The procedure to develop a model.	Project plan summarizing: 1. Problems drinking water companies have producing drinking water 2. Overview of chemicals and contaminants removed by each treatment step 3. Need for a model to be able to predict and optimize the performance of each treatment step.	Research plan summarizing: 1. A list of chemicals in 'Scooby-doo' ropes causing possible health risks. 2. Overview of exposure routes and update rates. 3. Need for a model to be able to predict the human exposure and uptake of those chemicals.
Study an exemplary problem. *Condition C:* Build on students' existing procedural modelling knowledge Learning task 4.	Each team of students is given the open assignment to draw a plan for one of the problems. (task 4). Students use the solution of an analogous problem as described in a fact sheet as 'leading' example.	Open task: draw up a plan of action for predicting the removal of nickel by treatment step coagulation / flocculation. To facilitate this open task a fact sheet summarizing the removal of organic carbon substances by the treatment step flocculation / coagulation is available. The fact sheet gives an overview of the approach used, the collected experimental data, the developed model and evaluation.	Open task: draw up a plan of action for calculating the exposure and uptake by humans of dye cibracon blue from 'Scooby-doo' ropes. To facilitate this open task a fact sheet summarizing the exposure and uptake of phtalate di-2-ethylhexylphtalate from 'Scooby-doo' ropes is available. The fact sheet gives a contact scenario, an overview the collected experimental data, the model used and finally an advice upon the health risks.
	Additional documents with background information are available.	Additional writings available: 1. Overview of the stages in the treatment process 2. Chemical background on flocculation / coagulation and process variables influencing the performance. 3. Drinking water supply in The Netherlands.	Additional writings available: 1. Overview of dyes and phtalates used in kids toys 2. Different release routes of these chemicals out of kids toys 3. Routes describing the uptake of these released chemicals by the human body.

Figure 2. Overview of the sequence and content of the learning tasks in unit *Modelling drinking water treatment* and unit *Modelling human exposure and uptake of chemicals in consumer products.*

Enactment of the learning tasks

The enactment of the learning tasks took place in the first week of the summer holiday and consisted of four meetings of four hours each. The second author of this paper acted as a teacher. The teacher was well acquainted with the content and the pedagogy, since she was involved in the design of the learning tasks. The enactment started with an introductory meeting. This meeting was organised to avoid hindering effects in second and third meeting, like students not knowing each other or students not being familiar with the type of learning activities. At the start students were grouped in six teams of three persons. Each team member was from one of the three schools and, in addition, consisted of one student with a high average score for chemistry at school, one with a medium and one with a low score. Next, the teams worked on a curriculum unit designed earlier on modelling dose-effect relationships of medicines. The type of learning tasks in this unit was similar to those in the units to be evaluated in the second and third meeting. At the end of the first meeting, students were asked to fill in a written questionnaire focusing on students' interest, ownership, familiarity with the issue and perceived complexity. The outcomes were used to evaluate the quality and to adapt the questionnaire for use in the second and third meeting.

In the second meeting the unit 'Treatment' was enacted, and in the third the unit 'Exposure'. In both meetings the teacher started with a short plenary introduction. Next the students worked in teams on the learning tasks, as depicted in Figure 2. The teacher did give help, feedback and coaching if needed. At the end each student team delivered a plan of action describing a modelling procedure to come to a solution for the modelling issue at hand. At the end of the meeting all students filled in a written questionnaire individually.

In the fourth meeting an evaluative group discussion was held in which students reflected on affective and cognitive aspects in both units.

Data collection and analysis

Given the purpose of this study, the data required are essentially qualitative. The first two research questions were answered using the group discussion as primary data source and the written questionnaire as secondary. The delivered plans of action were used as data source for answering the third research question. Below, each data source is described as well as the analysis procedure.

Group discussion

The teacher invoked and chaired the discussion. Discussion went on until each point of view was clear and every student was given a chance to give his/her opinion. The framework for the semi-structured group discussion is shown in Table 1.

Table 1. Questions to start the semi-structured group discussion

1.	Please indicate your willingness to carry out the ***remaining part of the unit*** '*Modelling drinking water treatment*'? Should we continue with this unit for use in chemistry classes?
2.	Please indicate your willingness to carry out the ***remaining part of the unit*** '*Modelling human exposure and uptake of chemicals in consumer products*'? Should we continue with this unit for use in chemistry classes?
3.	In both units you worked with mathematical models developed in real practices. These models as used as predictive tools. With the knowledge you now have about these models, what do you think of the *reliability* of these models?

The length of the group discussion was approximately 150 minutes. The group discussion was audio taped and transcribed *verbatim*. Next, the discussion was analysed independently by two researchers (first and fourth author of this paper). The analysis was conducted from an interpretative perspective (Smith, 1995). Students' statements from the group discussions items 1 and 2 were coded according to criteria students' interest and ownership. The statements from the group discussion item 3 were coded according to familiarity and complexity. These criteria originated from our previous study in which we selected authentic chemical modelling practices suitable as contexts (Prins, Bulte, Van Driel, & Pilot, 2008).

The inter coder agreement was tested for by calculating the percentage of statements coded equally by both researchers. We regarded 80% as lower limit for a substantial level of agreement (Miles and Huberman, 1994). Next, both researchers analysed all equally coded statements to identify major trends. Finally, all results were discussed in the complete research team.

Written questionnaire

Each student filled in a questionnaire for the units 'Treatment' and 'Exposure'. The questionnaire contained items on the students' interest, ownership, familiarity and complexity. The items in the written questionnaire are shown in Table 2. Afterwards all answers of the students were collected and summarized by one researcher (first author). The results were used to validate the findings from the group discussion.

Table 2. Items in individual written questionnaire for students

1. I would like to carry out the remaining part of the unit and solve the problem?
   Yes - ☐-☐- No
2. Did you ever hear of these kinds of real existing problems before? If yes, what and in what manner?
3. Do you judge the topic studied as interesting | motivating | relevant?
4. Please give your opinion on the difficulty of the unit.
5. Comment on the following statement: In this unit I am able to use own ideas and knowledge.
6. Please indicate what you would like to learn about the employed models?

Plans of action

Each student team delivered a plan of action outlining a modelling procedure (learning task 4). All plans of actions were analysed by two researchers independently (first and fourth author of this paper). Preceding the analysis, both researchers developed and agreed upon a reference modelling procedure as evaluative framework. This framework consisted of a description according to the modelling process for general application (Webb, 1994) on each unit. The reference modelling procedures were used as instruments to identify modelling stages within the plans of action of the student teams, to match these to one of the conceptual modelling stages and to judge the quality. The sequence of the stages in the plans of action was no evaluative criterion, since many modelling processes proceed iterative in which stages are run through several times in mixed order. The reference modelling procedures for each unit are shown in Table 3.

The quality of each modelling stage was judged by comparing the stage description in the plans of action to the corresponding stage description in the reference modelling procedures. The judgements ranged from 1 (low quality) to 5 (high quality).

In case a conceptual modelling stage was absent, a zero was noted. A rater consistency check was conducted by calculating the intraclass correlation coefficient using a two-way mixed effects model (Shrout and Fleiss, 1979). Afterwards, both researchers discussed differences in quality judgements to identify underlying considerations. Finally, both researchers discussed the plans of action to unravel students' views on the modelling issues. All results were discussed in the complete research team.

Table 3. Reference modelling procedures of unit *Modelling drinking water treatment* and unit *Modelling human exposure and uptake of chemicals in consumer products.*

Modelling procedure for general application *Six stages*	Unit *Modelling drinking water treatment*	Unit *Modelling human exposure and uptake of chemicals in consumer products*
Identify the area	Drinking water treatments / removal of metals by coagulation – flocculation	Exposure and uptake of chemicals from consumer products / dye from Scooby-doo
Define the problem	Optimalisation of process variables: required dose of coagulant depending on: starting concentration of metals and pH	Calculate total uptake in human body of dye's from Scooby-doo through uptake route mouth
Decide the scope, boundaries and purpose of the model	Scope: Treatments method coagulation – flocculation Boundaries: Metals (nickel) Coagulant: $FeCl_3$ Purpose: Predict residual nickel concentration in drinking water after treatment step coagulation / flocculation, depending on pH, dose coagulant and starting concentration nickel in water.	Scope: Dye Cibracon Blue in Scooby-doo Boundaries Contact scenario: uptake route mouth. Leakage of dye from product into water Purpose: Calculate total uptake of Cibracon Blue in human body
Build (section of) the model	Conduct series of experiments to quantify: - influence of pH on removal of nickel - influence on dose coagulant on removal of nickel - influence of starting concentration nickel on resisting concentration Use statistical methods to develop mathematical models.	Literature study: Models for describing migration of chemicals from consumer products Toxicological data Conduct experiments to determine initial migration speed of cibracon blue from product to water - PVC material with known initial concentration cibracon blue in water - Measuring concentration cibracon blue in water Determine initial migration speed from experimental data.
Test the model	Test model in new situation: compare model outcome with empirical data	Calculate total uptake of cibracon using initial migration speed and contact scenario Compare with norms for maximum allowed uptake of cibracon blue (toxicological data)
Evaluate the model	Reflect on reliability and validity of developed model Advise on usefulness of model and further steps to conduct	Reflect on reliability of model used to calculate total uptake of cibracon blue. Advise on health risks of uptake of cibracon blue out of Scooby-doo through contact route mouth

Overview data sources on each research question

In Table 4 an overview is given of data sources used on each research question. In case of research question 1 and 2 the group discussion was used as primary data source, while the written questionnaire was used as secondary to validate the findings.

Table 4. An overview of primary and secondary data sources on each research question.

Research questions		Data sources
1	To what extent does the use of authentic practices as contexts evoke students' interest and initiate ownership?	*Primary: Group discussion items 1, 2* *Secondary: Written questionnaire items 1, 3, 5*
2	To what extent are students familiar with the modelling issues and able to manage the complexity?	*Primary: Group discussion item 3* *Secondary: Written questionnaire items 2, 4, 6*
3	To what extent are students able to express a rudimentary procedure in response to a modelling issue, in terms of a sequence of activities accompanied by relevant issue knowledge?	*Plans of action*

Results

The enactment of the learning tasks was conducted completely according to the plan as described in the section Method. All 18 students participated in all four meetings. In this section we present the results for each research question. After every research question the main conclusions will be summarized.

Research question 1: To what extent does the use of authentic practices as contexts evoke students' interest and initiate ownership?
The group discussion revealed that a majority of the students (14 out of 18) experienced both units as interesting. Students especially appraised the high level of authenticity, as evidenced by exemplary comment stated below.

> David[1]: '… the subject, something useful for yourself ….. in normal chemistry classes, you are busy with formula's and so on, and you think: what am I supposed to do with it? And now it is just a real subject'. (GD)[2]

Also statements emphasising the general value of learning models and modelling were articulated, such as 'models are used in all of science', 'good preparation for my studies later on' and 'really want to understand models'.

> Tom: 'You learn about treatment processes …. you are very busy with that [drinking water treatment] …. you have to think of a plan of action yourself …. you really learn to understand the models ….. I liked that very much'. (GD)

As for ownership, the majority of the students appreciated the thinking over experiments to collect empirical data.

> Anna: 'Yes, I found it enjoyable that you had to think creatively about how to conduct the experiments …. you have to think about normal water as replacement of real saliva, and how to simulate chewing and sucking'. (GD)

The independent coding revealed a substantial level of 85% agreement in coding. Two major trends were identified within students' interest: 'appreciation of the clear link between chemical theory and practice' and 'the value of understanding models and learning to construct models'. A major trend within ownership was that both units encourage students to think 'creatively about experiments'.

The written questionnaire confirmed these results. The majority (15) of the students was willing to continue with the unit Treatment, whereas 14 with the unit 'Exposure'. As it comes to ownership, 12 students agreed on the statement that the units promote to use own ideas and knowledge.

> Judy: 'It is less theoretical [compared to normal chemistry class] and with more emphasis on self investigation. You are able to use own knowledge and ideas'. (WQ)[3]

Only three students were not interested in continuation with the unit 'Treatment' and four students in case of the unit 'Exposure'. These students qualified the modelling issues as 'to much mathematics included', 'lack of relevance for personal life' or 'to much overload of new chemistry concepts'. Six students made a reservation regarding ownership, because the units were to much focussed on 'common sense notions and knowledge, in stead of specific issue (chemistry) knowledge'.

Research question 2: To what extent are students familiar with the modelling issues and able to manage the complexity?
Comparison of the independent coding showed a substantial 83% level of agreement. In general, the results revealed that students were familiar with the chemical concepts involved. In addition, students recognized the major steps in the approach of experts to come to a solution, as typified by students' comments below.

> Susan: 'It is more about …. a lot is asked about your own knowledge, general knowledge so to say …. and some things [learning activities] were so obviously logical'. (GD)

> Mary: 'Yes, for example the steps engineers take to come to a solution [Modelling drinking water treatment], those are really logical. Of course, first you have to see what is in it followed by what can be improved. Next you have to figure out how and then you come to a conclusion. That is all really logical'. (GD)

However, as it comes to the mathematical models employed the results showed a more dispersed picture. The main trends emerging from the data were that students were rather unfamiliar with the syntax of the formula's, the construction method and the empirical validation of the models. These trends also were reflected in the students' statements about complexity, the origin and determination of the constants, and the number of process variables and constants involved. Furthermore, the application of the models in analogue situations raised difficulties.

> Tracy: 'I found it difficult to work with [formula], because of the many constants that are different in other situations, so you have to know exactly what those variables do and how to adjust the formula to fit the other substance'. (GD)

These findings were confirmed by the written questionnaire. As for familiarity with the issues, the majority of the students, 13 in case of unit 'Treatment' and 16 in case of unit 'Exposure' were informed by newspaper and/or television. In the case of unit 'Treatment', students came up with statements such as 'Ground and surface water are polluted with chemical contaminants: problems with purification' and 'Process of water treatment: complex with many different steps'. As for the unit 'Exposure', statements were mentioned like 'Kids toys, e.g. Scooby doo ropes, contain hazardous contaminants that are released' and 'Consumer products might contain hazardous chemicals'. In both units students indicated that they would like to learn about 'method to construct these kinds of models' and 'investigate all the variables included in the models'.

Based on these findings, we concluded that students were challenged to extent their knowledge. Students showed willingness for self construction of the models, nevertheless their unfamiliarity with the models. The experienced complexity was mainly focussed on the amount of variables and constants, the origin and determination of the constants and the usability of the models in analogue situations.

Research question 3: To what extent are students able to express a rudimentary procedure in response to modelling issues, in terms of a sequence of activities accompanied by relevant issue knowledge?
The analysis of the student teams' plans of action focused on the completeness and quality of the modelling procedures. We first describe the results in unit 'Treatment'. In Table 5 an overview is presented of the stages present in the delivered plans of action in the unit 'Treatment' as well as their quality.

The judgement showed a substantial consistency between the raters reflected in the intraclass correlation coefficient of 0,88. To exemplify differences in judging and give insight into the underlying considerations, we reflect on the stage 'build (a section of) the model' of team III. The actual stage description was:

> Team III defined the build (a section of) the model as: 'Process variables: dose [coagulant], stirring intensity and residual time. The pH: determine the optimal pH value by conducting experiments. The Fe^{3+} can only work if it stays strongly charged. If the pH would turn alkaline, the Fe^{3+} would turn less charged. The pH should be neutral, we think. That is our pH hypothesis. The ABC values [fit parameters] will be differently [compared to analogue problem]. We determine the ABC values by fitting. After investigation and with experimental results we are able to determine the ABC and develop a formula.'

Table 5. Overview of the results of the analysis procedure conducted by two researchers independently of the plans of action in unit Modelling drinking water treatment.

Stages in modelling procedure[1]	Team[2]											
	I		*II*		*III*		*IV*		*V*		*VI*	
	R1	*R2*	*R1*	*R2*	*R1*	*R2*	*R1*	*R2*	*R1*	*R2*	*R1*	*R2*
Identify the area	5	5	5	5	5	5	5	5	5	5	5	5
Define the problem	4	3	4	5	5	4	4	5	4	1	5	5
Decide the scope, boundaries and purpose of the model	4	5	3	5	3	5	4	5	4	3	4	5
Build (a section of) the model	4	3	4	5	1	5	4	5	4	2	4	5
Test the model	5	5	1	4	2	2	1	4	0	0	0	0
Evaluate the model	5	3	0	0	2	2	1	3	5	1	2	2

[1] Conceptual modelling stages expected to be present and described in the plans of action of student teams.

[2] The judgement results per stage in each plan of action per team. R1 refers to the first researcher, R2 to the second.

0 stage not present, no quality judgement possible

1 very low quality

2 low quality

3 medium quality

4 high quality

5 very high quality

Researcher 1 judged the quality as very low, because no explicit reference was made to investigating the correlations between process variables and residual nickel concentration after coagulation/flocculation treatment. On the contrary, researcher 2 valued the fact that all process variables were mentioned, the arguments on the possible influence of the pH and the notion of 'fitting as means to calibrate a model to serve a new situation'.

Hereafter we reflect on students' views on the modelling issue by summarizing exemplary stages rated with a high quality. All student teams mentioned 'drinking water treatment' and treatment step 'coagulation/flocculation' as problem area (stage 1). In addition, four teams had clear sight on the problem, as illustrated by the citation below from the plan of action of student team IV:

> Team IV defined the problem as: '…calculate the optimal value for each process variables, by varying one at the time while keeping the others constant.'

The second and third stages were all present with sufficient quality. All teams focused on the 'removal of nickel' during coagulation/flocculation using 'coagulant $FeCl_3$'.

Student team II described the building of the model (stage 4) in much detail, as typified by the citation below:

> Team II defined the building of (a section of) the model as: 'We propose the following experiments to find a correlation. We measure the correlation between the starting concentration of heavy metals and the outgoing concentration of heavy metals. This variable we call A. We measure the correlation between the dose of the coagulant and the final concentration of heavy metals. This variable we call B. We measure the correlation between the *pH* and the final concentration of heavy metals. This variable we call C. [cont'd]. We do a series of small experiments to discover the correlations. After this we develop a good formula, and conduct extensive experiments.'

However, starting from the fifth stage, the testing of the model, the quality decreased. Only student team I described stages 5 and 6 with sufficient quality.

> Team I defined the testing of the model as: 'Develop a formula on small scale [by performing laboratory experiments] and evaluate this [formula] in practice.'

> Team I defined the evaluation of the model as: 'Discuss [the results]. Check the hypothesis, the conditions and reliability [of the model].'

We now turn to the unit 'Exposure'. In Table 6 the results for the unit 'Exposure' are shown.

Table 6. Overview of the results of the analysis procedure conducted by two researchers independently of the plans of action in unit Modelling human exposure and uptake of chemicals in consumer products.

Stages in modelling procedure[1]	Team[2]											
	I		*II*		*III*		*IV*		*V*		*VI*	
	R1	*R2*	*R1*	*R2*	*R1*	*R2*	*R1*	*R2*	*R1*	*R2*	*R1*	*R2*
Identify the area	5	5	5	5	5	5	5	5	5	5	3	3
Define the problem	5	4	5	5	5	3	4	3	5	5	3	3
Decide the scope, boundaries and purpose of the model	4	5	5	5	4	4	4	3	5	5	2	3
Build (a section of) the model	4	5	3	4	4	4	4	4	4	4	4	4
Test the model	4	4	4	4	0	0	4	2	5	4	4	4
Evaluate the model	4	5	3	5	0	0	3	4	4	5	3	3

[1] Conceptual modelling stages expected to be present and described in the plans of action of student teams.

[2] The judgement results per stage in each plan of action per team. R1 refers to the first researcher, R2 to the second.

0 stage not present, no quality judgement possible
1 very low quality
2 low quality
3 medium quality
4 high quality
5 very high quality

The inter-rater consistency was sufficiently, reflected by the intraclass correlation coefficient of 0,71. To exemplify differences in rating, we reflect on the stage 'test the model' of team IV.

> Team IV defined the test the model as: 'Check the existing formulas by filling in data. If not, use the data to develop a new formula. Calculate the average value [uptake] with use of the developed formula and toxicological data. Evaluate the risks.'

Researcher 1 judged the quality as high, since explicit reference was made to data from 'external sources', such as experiments and toxicological data. However, researcher 2 rated low quality, because the contact scenario was only mentioned implicitly. Besides, the uptake was not differentiated to the type of consumer, such as children or adults.

All teams had clear sight on the area and the exemplary problem, as typified by citations like 'exposure to chemicals/dye's from Scooby-doo ropes' and 'calculate the total uptake of cibracon'. All teams explicitly described the contact scenario, part of the third modelling stage, as typified below:

> Team I defined the decision on the scope, boundaries and purpose of the model as: 'Determine the contact scenario: determine the weight, duration of the contact and contact surface in the mouth.'

The results revealed that the student teams had a clear sight on modelling activities to perform in the fourth stage, building (a section of) the model. Team III described the fourth stage as follows:

> Team III defined the decision on the scope, boundaries and purpose of the model as: '… about dyes much data is available. From this data one is able to calculate the upper limit for uptake in milligram per kilogram body weight without any running into health risks [toxicological data]. The contact scenario is the same [mouth], but the initial leakage rate R is different. We first determine how much gram of dyes is in 100 gram of Scooby-doo rope (…). We determine the volume and surface of that 100 gram of Scooby-doo rope. We use real human saliva instead of water, to determine the uptake of dyes. We do plot the data in a diagram (…).'

In addition, four teams extensively described the experimental setup, all focused on measuring the initial leakage rate. In the final stages, although on average less in quality than the first four stages, five teams explicitly mentioned that the calculated total uptake must be compared with the legally set maximum allowed uptake.

We present two exemplary descriptions of stages test the model and evaluate the model:

> Team V defined the testing of the model as: '… with the model and the contact scenario one can calculate the uptake. This total uptake should be compared to the norm, revealing a conclusion ….'
>
> Team II defined the evaluation of the model as: '… draw conclusions and relate to data and norm. The exact conclusion has to be based on the results. We have to point out whether potential harmful or not ….'

The findings on units 'Treatment' and 'Exposure' suggest that student teams were well able to articulate a modelling procedure. They showed to be able to couple modelling activities with relevant issue knowledge, while constantly having the purpose of the modelling in mind. Another aspect emerging from the data was the difference in quality between the first four modelling stages and the last two. Apparently, the student teams had a clear sight on the modelling actions to perform until the testing and evaluation of the model.

Conclusions and discussion

This study has evaluated students' involvement in modelling processes using authentic practices as contexts. The results reveal that students were interested in both units. Most of the students appreciated the approach, the authenticity of the modelling issues and the challenges to devise a solution themselves. As it comes to ownership, the results indicate that both units in potential do allow students to act relatively autonomously. In short, both units meet condition A to a large extent. As for the cognitive domain, it can be concluded that students were sufficiently familiar with the chemical concepts involved. However, students were unfamiliar with the employed mathematical models. In addition, the amount of the variables involved and unknown origin of the constants raised the complexity. Despite this unfamiliarity with the models and perceived complexity, there were enough indications that students were able to cope with the cognitive load. We concluded that both units do fulfil condition B sufficiently. This conclusion on the cognitive domain is supported by the completeness and quality of the expressed modelling procedures by the student teams (condition C). A noticeable aspect was that the final modelling stages, the testing and evaluation of the model, were of less quality than the preceding stages. Students were aware of the fact that the models had to be tested and evaluated, but they were not able to give content for these stages. In retrospect, it is not surprising since these stages are relevant later on in the modelling (and learning) process, so probably were, at present, beyond students' scope. When (in a next study) a complete curriculum unit is designed, in which students' gradually

proceed through the full modelling process, one should account for supplying, in time, students with necessary tools and resources for model testing and evaluation. Despite the lower quality of the final modelling stages, these two units also meet condition C to a sufficient extent.
The results suggest that authentic practices as context might benefit students' learning of models and modelling. By starting with an orientation on authentic modelling practices, students are provided with a broad route about 'where to go' and 'points to consider'. Furthermore, it facilitates students to connect modelling activities with relevant issue knowledge. In our opinion, the latter is conditional to achieve adequate students' involvement in modelling processes. However, the results obtained in this study are subject to limitations. Firstly, it should be noted that these authentic practices were selected after a thorough analysis and judgement (Prins et al., 2008). Whether the results can be generalised to other authentic practices, in other science domains, is subject for further studies. Secondly, the realized involvement is partly due to adequately designed learning tasks (Figure 2). The first learning tasks were directed towards an orientation by means of items reporting about societal issues. Two items reported about the issues and one item pointed towards an approach followed in practice to come to a solution. Apparently, such an orientation did evoke students' interest, contributed to perceived relevance and provided students a view to a solution. In our opinion, these three aspects contributed as well to the students' ownership. It thus seems relevant in the introduction phase to articulate to students not only the actuality and relevance of the issue, but also to mention the route to a solution. The final learning task compromised the drawing up of a plan of action to solve an exemplary problem themselves. This open task was facilitated by delivering an already solved analogous problem belonging to the same authentic practice. The analogous problem provided students with the necessary guidelines while providing them with opportunities to introduce own ideas and thoughts. Such a learning task, fostering students to think of a sequence of modelling actions to conduct, proved to be successful. This learning task offers an instrument to enable students to look ahead, which is important for effective engagement in modelling processes. Thirdly, the enactment has taken place outside the classroom. Although the sample of participants might be considered as a fair reflection of an average population of high school chemistry class (grade 10-11), one needs to account for different circumstances. The fourth limitation relates to the teacher preparation. Proper preparation of the teacher is critical. The use of models and the outlining of the unit will be different from what happens in traditional chemistry classes. In the present study the teacher (second author) was engaged in developing the learning tasks. The teacher therefore was well informed with the content and pedagogy of both units.

In conclusion, these two authentic modelling practices might indeed serve as appropriate contexts for involving students in a modelling process. The next steps in this research will be focusing on design strategies for complete curriculum units, based on these authentic practices, followed by testing and evaluation in classroom. The design of complete curriculum units will be conducted in close cooperation with teachers. The challenge is to design a sequence of the learning tasks such that students do see the point of what they are doing at every step in the unit (Lijnse and Klaassen, 2004). To achieve such a sequence of learning tasks, the activity pattern of the experts in the authentic practice provides heuristic guidelines. At the end of such units we need to design learning activities to induce reflection of students' on their own attended modelling process. During such reflection activities students should learn about essential model characteristics, like purpose, boundaries and limitations, reliability and validity.

Many research studies have been conducted on students' understanding of models and modelling. In general they call for greater emphasis on the role and purpose of models in science. In the present study an effort has been made to contribute to the knowledge about this emphasis. Meaningful learning of models and modelling requires a context in which modelling activities and issue knowledge are closely related. Such coherency might be realised by using authentic chemical modelling practices as sources of inspiration. The results obtained in this study so far confirmed this hypothesis. In subsequent studies we aim to further contribute to the development and elaboration of design knowledge for adapting authentic practices into curriculum units to construct meaningful learning trajectories.

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Endnotes

[1] All names used in this research study are pseudonyms.

[2] All of the references here are to the specific data source used, where GD stands for Group Discussion.

[3] All of the references here are to the specific data source used, where WQ stands for Written Questionnaire.

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4

Removal of Water Turbidity[1]

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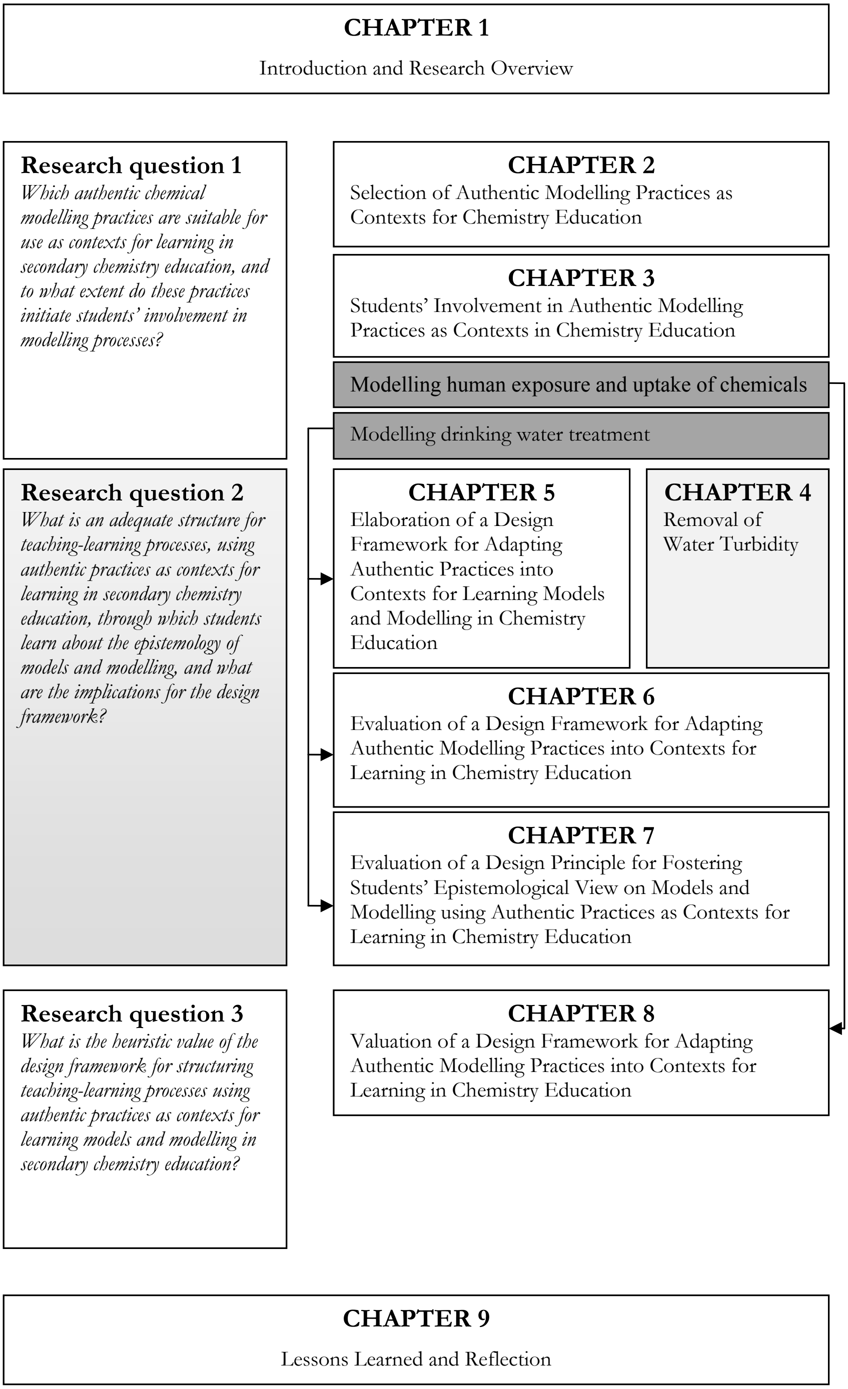
1 Prins, G. T., Wigmans, A., Bollen, T. P. F., Bulte, A. M. W., & Pilot, A. (Submitted). Removal of water turbidity.


CHAPTER 1
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Research question 1
Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?
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CHAPTER 3
Students' Involvement in Authentic Modelling Practices as Contexts in Chemistry Education
Modelling human exposure and uptake of chemicals
Modelling drinking water treatment
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What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?
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Elaboration of a Design Framework for Adapting Authentic Practices into Contexts for Learning Models and Modelling in Chemistry Education
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What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?
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Valuation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education
CHAPTER 9
Lessons Learned and Reflection

In Chapter 4 we report the design of a laboratory experiment. The laboratory experiment is incorporated in a teaching-learning process using the authentic practice of modelling drinking water treatment as a context for learning. In this practice empirical data are collected for the construction, revision, validation or calibration of models. In order to collect data in the classroom, it was necessary to devise a laboratory experiment that would be feasible in practice and perceived by the students as authentic. The laboratory experiment involves the removal of fine silt, causing water turbidity, by the treatment step coagulation/flocculation. The focus is to determine the influence of various process variables, such as dose coagulant, starting turbidity and temperature, on the turbidity of the water after treatment.

Instructor side

This Activity explores the optimum coagulant dosage for removal of water turbidity. Students conduct multiple coagulation experiments using a turbid clay suspension and ferric chloride as coagulant, and analyze the end turbidity of the supernatant qualitatively. The main learning objective is to become aware of the dynamics of (water treatment) processes, in terms of multiple varying process variables affecting the outcomes.

Background

Much of our water for domestic use originates from surface water such as lakes and rivers. Traditionally, the treatment process consists of four major steps. In the first step the water is aerated and the larger particles are allowed to settle. In the second step clay particles and colloids, causing turbidity, are removed by coagulation and flocculation. Thirdly, the water is filtered (in some cases multiple times), using sand and/or activated charcoal. In the fourth step the water is disinfected, either by adding chemicals (ozone or chlorine) or by techniques like UV light. In a previous edition of this *Journal* an experiment demonstrating the purification of water using a filtration column containing layers of gravel, sand and activated charcoal was published (1). In addition, an experiment focusing on the purification of water using lime and alum, thus forming $Al(OH)_3$ precipitates incorporating small particles, is available (2). In practice, the optimum dosage of coagulant for the removal of suspended matter needs to be determined experimentally. Variables like the nature of turbidity, *pH* and temperature influence the coagulation (3). This authentic setting is simulated in the present Activity.

About the Activity

We use fine chamotte clay, 0.5 mm type K-30000, available in general tinker stores. In addition, we use water with high alkalinity (hydrogen carbonate HCO_3^- > 275 mg/L), *pH* = 7. Prepare the clay suspension in a (large) container. Stir the clay into the water using a sturdy wooden stick. Mix until the suspension turns opaque. Leave the suspension to rest for about 60 minutes. Clay residue will settle at the bottom of the container. Gently pour the upper layer of the suspension into a second (clean) container. Be careful not to pour in the lower layer of the suspension with the clay residue. This should be left behind. Each (team of) student(s) needs approximately 300 mL of suspension. Instructors should test the filter paper students use in step 1 to make sure the clay suspension runs through. The clay suspension should run through. The ferric chloride solution (0,1 g Fe^{3+} / mL) has to be made freshly, using standard $FeCl_3 \cdot 6H_2O(s)$. The turbidity measurement is conducted qualitatively by evaluating the visibility of a black cross on paper through the mass of liquid using tap water and the original turbid clay suspension as references. Alternatively you might consider using a turbidity sensor connected to a computer with a lab interface (4).

Integrating the Activity into Your Curriculum

This Activity fits well in themes on water quality and (waste) water treatment. Confronted with the clay suspension, the majority of the students will suggest filtration as suitable method to remove turbidity. The students can experience for themselves that filtration is not effective, thus urging for some other treatment. In explaining the mechanism of coagulation students are guided to use the concept reducing repulsive forces between negatively charged clay particles by adding strongly positive charged ions. Instructors might broaden the scope of this Activity and turn it into a student research project. The dosage of aluminum sulfate next to ferric chloride might be researched and/or the influence of other process variables, e.g. temperature or *pH*.

Answers to Questions

1. The positive ion Fe^{3+} reduces repulsive forces between negatively charged clay particles. The clay particles approach each other and aggregate.
2. Adding too little coagulant results in high residual turbidity. Adding a surplus, however, is not advisable for economic reasons (costs of coagulant), environmental effects (sludge production) and public health considerations (quality of drinking water).
3. A strategy is to conduct a series of experiments using waters with varying starting turbidity. Summarize the data in plots or tables of residual turbidity depending on starting turbidity and coagulant dosage.

References, Related Activities, and Demonstrations *(accessed April 2009)*

1. Jacobsen, Erica K. Water filtration. *J. Chem. Educ.* 2004, 81(2), 224.
2. Borgford, Christie L.; Summerlin, Lee R. *Chemical Activities, Teacher Edition*; American Chemical Society: Washington, DC, 1988, pp 179-181.
3. Everett, D.H. Basic principles of Colloid Science, *Royal Society of Chemistry Paperbacks*, 2007, chapters 1-3, pp. 1-53.
4. Turbidity sensor from Vernier Software & Technology. *http://www.vernier.com/*

Student Activity side

Much of the water we use at our homes originates from rivers and lakes. This water may be contaminated with soil, toxic substances, harmful bacteria and other impurities. To make the water suitable for consumption, it has been through a whole series of treatments. One of the first steps is to remove suspended matter that causes turbidity, such as clay particles. In this activity, you will investigate the coagulation/flocculation treatment method to remove suspended matter.

Try this

You will need: turbid clay suspension (obtain from your instructor), ferric chloride solution (0,1 g Fe^{3+} / mL), magnetic stirrer and stir bar, five 100 mL beakers, three 50 mL beakers, one 100 mL Erlenmeyer flask, one 100 mL graduated cylinder, 1 mL pipette or syringe, funnel, non-analytical filter paper, stop watch and a black plain core pin.

_1. Filter a *small portion* of the clay suspension using the funnel with filter paper. Collect the filtrate in the conical flask. Observe the clay suspension. What is your conclusion?

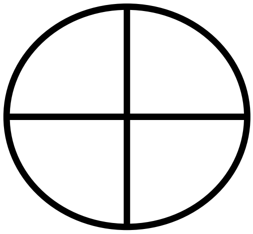
Be Safe! Do NOT taste or drink any of the water, including the suspension or flocculated supernatant in this activity. Harmful contaminants may remain.

_2. Pour 50 mL clay suspension into a 100 mL beaker using the graduated cylinder. Add a stir bar and place the beaker on the magnetic stirrer. Mix the solution rapidly (maximum rpm). While mixing, add 1 mL of ferric chloride solution using the pipette or syringe. Continue to mix for precisely 1 minute. Why, do you think, is it important to stir thoroughly?

_3. Lower the stirring rate to ¼ of the maximum rpm. Continue to mix for precisely 5 minutes. Observe the clay suspension. Think of (a) reason(s) why the stirrer rate was lowered.

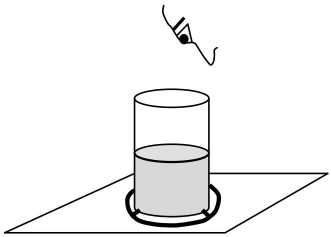
_4. Turn off the magnetic stirrer and gently place the beaker on the desk. Remove the stir bar and leave the flocculated solution to rest for precisely 20 minutes. In the meantime, continue with step _5.

_5. Draw three equally sized black crosses on three separate pieces of paper. Pour 25 ml original turbid clay suspension into one of the 50 mL beakers using the graduated cylinder and place the beaker on top of a black cross. Fill another 50 mL beaker with 25 mL tap water. Place this second beaker also on top of the second black cross. Test the visibility of the black crosses by looking through the mass of liquid from the top. What is your conclusion? Keep both beakers as references.



_6. After 20 minutes analyze the flocculated supernatant for turbidity. Gently fill the third 50mL beaker with 25 mL supernatant using the graduated cylinder. Take care not to disturb the sludge at the bottom of the beaker. Place the beaker on top of the third black cross. Test the visibility of the black cross and compare with the references. What is your conclusion?

_7. Determine the dosage of ferric chloride needed to produce clear water. Repeat steps 2-4 and 6, but change the amount of ferric chloride. Record the added amount. Compare your results with others and discuss.



Questions

1. Explain why adding a coagulant like ferric chloride results in clay particles forming flocs.
2. Think of (a) reason(s) why it is important to know the amount of coagulant needed to produce clear water.
3. Under natural circumstances, the starting turbidity of the surface water also varies. Drinking water companies adjust the dosage of coagulant to the actual turbidity of the surface water taken in. How would you investigate the influence of the starting turbidity on the turbidity after treatment? How would you incorporate the effects of coagulant dosage?

Information from the World Wide Web *(accessed April 2009)*
Water treatment process. *http://www.epa.gov/safewater/kids/watertreatmentplant/*
Coagulation/flocculation.
http://www.waterspecialists.biz/html/about_coagulation___flocculati.html
Turbidity: *http://en.wikipedia.org/wiki/Turbidity*

5

Elaboration of a Design Framework for Adapting Authentic Practices into Contexts for Learning Models and Modelling in Chemistry Education[1]

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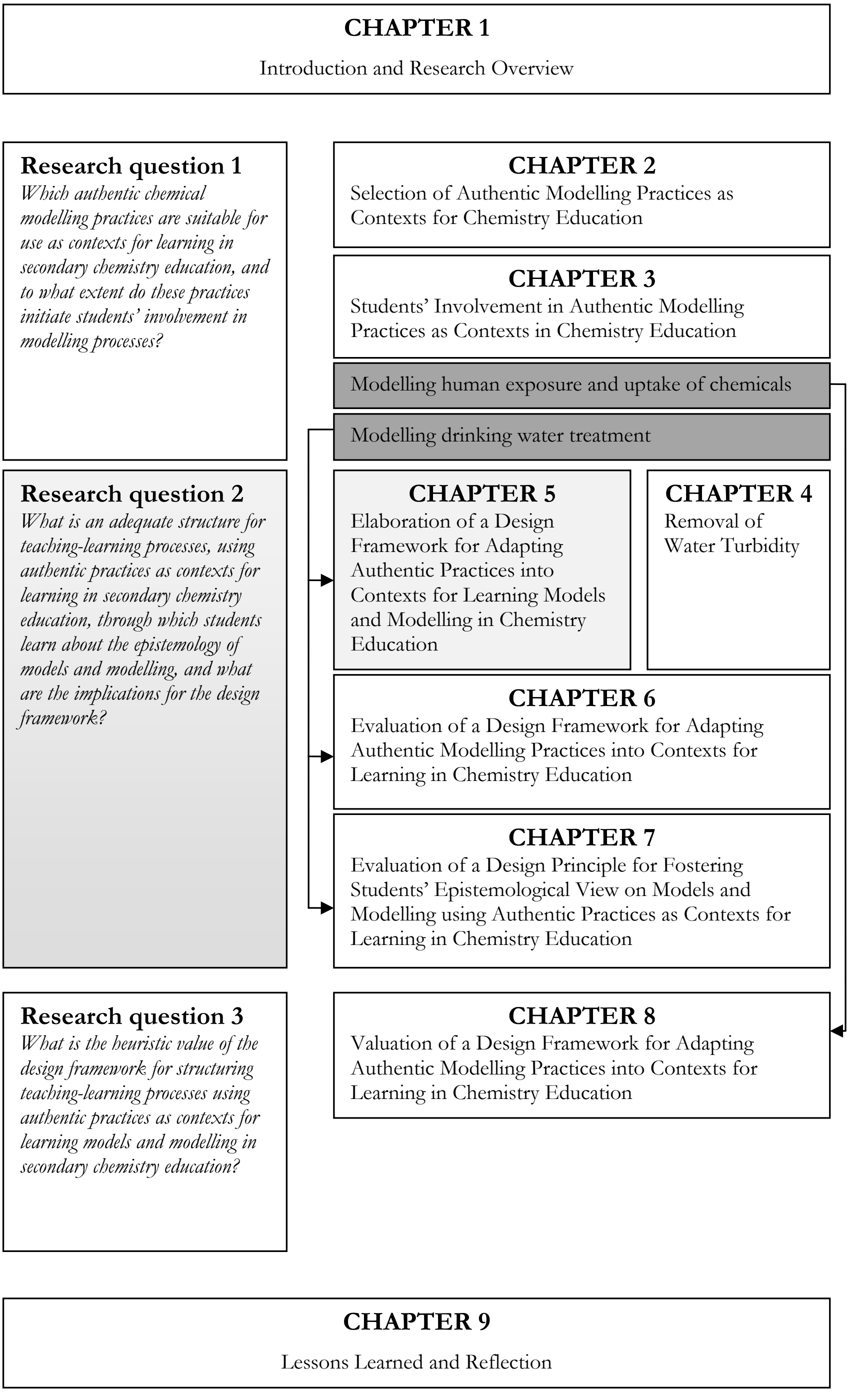
1 Prins, G. T., Bulte, A. M. W. & Pilot, A. (Submitted). Elaboration of a Design Framework for Adapting Authentic Practices into Contexts for Learning Models and Modelling in Chemistry Education.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Lessons Learned and Reflection

In Chapter 5 we describe the initial design of a teaching-learning process using an authentic practice for modelling drinking water treatment as a context for learning. The knowledge involved is captured in a design framework, a synthesis of design principles, learning phases and instructional functions. The emphasis was on the elaboration of three design principles, labelled 'context', 'content modelling' and 'chain of activities'. Design principles are theoretically and empirically grounded constructs linking *strategy components* (e.g., *what*, *when* and *how* to do in the teaching-learning process) with *intended pedagogic effects* (e.g., students see the point of modelling and achieve improved understanding of epistemic notions), underpinned by *arguments* (e.g., literature on educational research, empirical findings from previous applications and/or practical considerations). The principle of *context* deals with involving learners in a focal event embedded in its cultural setting. This implies the setting, the behavioural environment, the specific language and the extra-situational background knowledge, such that students become engaged in a modelling activity. The principle of *content modelling* deals with focusing learners on the essential generic content regarding models and modelling. The principle of *chain of activities* deals with constructing a sequence of teaching-learning activities such that learners constantly know *why what* to do at every step in the process.

The research question addressed is:
What are the characteristics of a design framework for structuring teaching-learning processes using authentic chemical modelling practices as contexts for learning models and modelling in secondary chemistry education?

Abstract

In science education students should come to understand the nature and significance of models. A promising route to achieve this goal is to involve students in a domain of science that employs models. The current study explores the use of authentic modelling practices as contexts for learning. An authentic practice is defined as professionals working with common motives and purposes, according to a similar type of procedure and applying relevant knowledge to the modelling issue on which they are working. In this study, design principles providing heuristic guidelines for the adaptation of authentic practices into contexts for learning are elaborated according to a stepwise procedure by a design team consisting of six experienced chemistry teachers and three researchers. The design principle of 'context' deals with involving learners in a focal event embedded in its cultural setting, such that students become engaged in a modelling activity. The design principle of 'content modelling' deals with focussing learners on the essential generic content regarding models and modelling. The design principle of 'chain of activities' describes the construction of an ongoing sequence of teaching-learning activities such that learners constantly know 'why what' to do at every step in the process. The three design principles are synthesised into a design framework. The design framework contributes to a knowledge base about designing context-based chemistry education.

Introduction

Models are essential in both science and science education. Models are generally viewed as connections between the scientific theory and the world as experienced. Currently, the learning of models and modelling is regarded as an integral part of scientific literacy (Clement, 2000; Gilbert, 2004). Given the fact that modelling is considered an essential part of scientific thinking, there is a need to design learning environments such that students' understanding of the nature of models is enhanced (Harrison and Treagust, 1998).

In science education, the terms model and modelling are used quite ambiguously (Harrison and Treagust, 2000). In this paper we concentrate on models and modelling in chemistry education. We use the term 'model' for some structured representation, including symbolic elements, of the essential characteristics of an idea, object, event, process or system (Gilbert and Boulter, 2000). Examples of models used are iconic and symbolic models that depict chemical formulae and chemical equations, mathematical models that represent conceptual relationships of physical properties and processes (e.g. $PV = nRT$) and theoretical models that describe well-grounded theoretical entities (e.g. kinetic theory model of gas volume, temperature and pressure). Modelling is defined as the construction, evaluation and revision of a model in response to a particular task (Van der Valk, Van Driel, & De Vos, 2007).

Many studies have revealed that students do not learn about models and modelling effectively (Grosslight, Unger, Jay, & Smith, 1991; Harrison and Treagust, 1996). The majority of students think of models as either toys or copies of reality. Students, in general, have difficulty capturing the more advanced features of understanding models, like the purpose of models, models as representations of ideas in contrast to reality, and the notion that models can be tested and changed in order to inform the development of ideas. It has been claimed that these problems might be overcome if students are engaged in modelling processes similar to those used in the research or technology settings in which real science takes place (Edelson, 1998; Sadler, 2007). In such a process it is expected that students will be involved in the construction, testing and evaluation of models, and learn about model characteristics like purpose, reliability and validity. This vision of learning is underpinned by the situated nature of learning (Brown, Collins, & Duguid, 1989) and activity theory in education (Engestroem, 1987; Leont'ev, 1978). Following this proposition, the challenge is to adapt an authentic modelling practice into a context for learning to foster the learners' understanding of models and modelling.
However, at present we lack a specific knowledge base for adapting authentic modelling practices into contexts for learning. In adapting an authentic modelling practice into a context for learning, it is seductively easy to focus on scientific knowledge, tools and techniques at the expense of other aspects, like the attitudes, procedures and social interactions of two different populations of experts and learners. In this paper we will focus on the elaboration of design principles (Van den

Akker, Gravemeijer, McKenny, & Nieveen, 2006), providing heuristic guidelines for adapting authentic modelling practices into contexts for learning. The design principles are synthesised into a design framework. To ensure the validity of the emerging design framework, it has been developed by six experienced chemistry teachers in close cooperation with three researchers. The empirical evaluation of the design framework is beyond the scope of this article and is described elsewhere (Prins, Bulte, & Pilot, Submitted-a). The aim of this paper is to contribute to the development of a knowledge base for adapting authentic modelling practices into contexts for learning.

Theoretical framework

Our strategy to adapt authentic practices into contexts for learning stems from and relates to two pedagogic orientations, namely the situated nature of learning and activity theory in education. Each orientation is briefly discussed below. Next we focus on the adaptation of authentic practices into contexts for learning. We end this section by formulating three design principles providing heuristic guidelines for adaptation of authentic practices into contexts for learning.

Pedagogic orientations

In response to Dewey's (1964) recommendations, authenticity has become an objective for innovation in science education. A number of research studies have shown that students often fail to apply knowledge taught in school in real-world settings. Brown, Collins and Duguid (1989) argue that knowledge is situated, being in part a product of the activity, practice and culture in which it is developed. This view of knowledge affects our understanding of learning, as expressed by the following:

> Authentic activity… is important for learners, because it is the only way they gain access to the standpoint that enables practitioners to act meaningfully and purposefully. (Brown et al., 1989, p. 36).

If we manage to design a learning environment reflecting a real-world setting, the learners will see more opportunities to apply the new learning. A well known pedagogic approach commonly associated with the situated nature of knowledge is cognitive apprenticeship. Cognitive apprenticeship supports learning by enabling students to acquire, develop, and use cognitive tools in authentic situated activity. Furthermore, cognitive apprenticeship aims to enculturate students into authentic practices through activity and social interaction. In cognitive apprenticeship the notion of learning is viewed as an emerging property of the whole person's legitimate peripheral participation in communities of practice (Lave, 1996).

Activity theory, rooted in the sociocultural tradition, describes society in terms of connected social practices as manifestations of activity (Leont'ev, 1978; Vygotsky, 1978). In its simplest form, an activity is defined as the engagement of a subject in pursuit of a certain goal or objective. The subject refers to the individual or group whose agency is chosen as the point of view in the analysis. The object refers to the 'raw material' or 'problem space' at which activity is directed and which is moulded and transformed into outcomes. Activity theory regards the 'activity' as the primary 'unit of knowledge'. Human activity is driven by an object-related motive and carried out within a community. The activity consists of (a chain of) actions, which in turn are realized through operations. Activity is mediated by instruments created by humans, such as tools and language and social relations (Engestroem, 1987).

The associated pedagogic approach is that a learner enters into a cognitive apprenticeship with the teacher who interprets the practice (Gilbert, 2006). From the socially accepted attributes of a given practice, the teacher's task is to identify those attributes that are recognised and mastered by students, and those attributes that lie in the 'zone of proximal development' of the students (Confrey, 1995). The recognised and mastered attributes form the starting point of the learning process. These attributes can be used to introduce the social practice and facilitate students' involvement. The attributes identified within the 'zone of proximal development' embody the notion of learning.

Although the two pedagogic orientations originate from different perspectives, both encourage the use of authentic activity in education. Within the classroom, the teacher provides cognitive apprenticeship and he/she is the primary source of tuition. This indicates the need for a well thought out adaptation of authentic practices in order to design meaningful contexts for learning.

Design principles for adapting authentic practices into contexts for learning

Any adaptation of an authentic practice into a context for learning involves a variety of issues regarding, for example, involvement of students, sequence and content of teaching-learning activities. The educational design process can be characterized as an iterative cyclic process reflected in the different curriculum representations, such as ideal, formal, perceived, operational, experiential and attained representations of a curriculum unit (Van den Akker, 1998). The design knowledge involved resides mainly in the formal representation of a curriculum unit, consisting of the following products:

- A set of explicit learning aims and standards
- A design framework, a synthesis of design principles, phases in the teaching-learning process and instructional functions.
- A curriculum unit, consisting of (a sequence of) teaching-learning activities, study materials, teaching guidelines, etc.

A design framework provides heuristics for structuring teaching-learning processes.

For the phases in the teaching-learning process and instructional functions, we use an 'instructional version of authentic practice'. This phasing emerged from research on the feasibility of an 'authentic practice based curriculum unit' in classrooms (Bulte, Westbroek, De Jong, & Pilot, 2006), inspired by previous research on meaningful teaching-learning processes (Cobb, Stephan, McClain, & Gravemeijer, 2001; Kortland, 2001; Lijnse, 1995; Lijnse and Klaassen, 2004; Westbroek, 2005). The phasing is depicted in Table 1.

Inspired by McKenny, Nieveen and Van den Akker (2006), we define design principles as tools providing heuristic guidelines on how to realise intended pedagogic effects within a certain educational setting in as much detail as needed. We see this in terms of strategy components to be applied by the designer in the teaching-learning process (it is up to the teacher to enact those strategies in the classroom with sufficient quality), pedagogic effects (specified educational activities and learning outcomes, for students to achieve, to measure among students) and arguments underpinning the coupled strategy components and pedagogic effects. These should be based on theoretical knowledge, empirical experiences based on earlier applications of the curriculum unit(s) and/or practical (tacit) considerations from the designer(s). Figure 1 depicts a conceptualised scheme of a design principle.

The validity of a design principle is bound to a certain educational setting and restricted by a set of conditions, e.g., the science domain and the age of the students. There are three design principles which we have labelled context, content modelling and chain of activities. The three design principles are described below.

Table 1. Phasing of the teaching-learning process and instructional functions using authentic practices as contexts for learning.

Phase		Instructional functions
I: Orientate on the practice	***a)***	Connect to the prior conceptual knowledge base
	b)	Connect to the prior procedural knowledge base
	c)	Evoke motivation to study the problems posed in the practice
	d)	Evoke a motive to zoom in on an example problem
II: Zoom in on an example problem	***e)***	Make explicit and build on the prior conceptual knowledge base
	f)	Make explicit and build on the prior procedural knowledge base
	g)	Evoke a motive to solve the example problem
III: Solve the example problem	***h)***	Proceed through the sequence of activities and learn/apply knowledge until a satisfactory solution for the example problem can be presented
IV: Evoke a motive to express the findings	***i)***	Induce a motive to express the learned conceptual and procedural knowledge used to solve the example problem
V: Express and reflect on the findings	***j)***	Make explicit the learned conceptual and procedural knowledge
	k)	Draw up a project plan for solving a similar problem posed in the practice

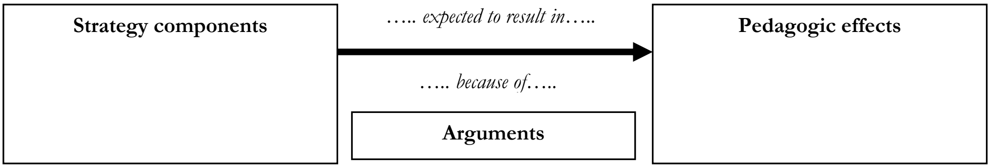

Figure 1. A design principle linking strategy components and pedagogic effects, underpinned by arguments.

Design principle 'context'

The design principle of *context* deals with involving learners in a focal event embedded in its cultural setting (Gilbert, 2006). This implies the setting, the behavioural environment, the specific language and the extra-situational background knowledge, such that students become engaged in a modelling activity. In adapting an authentic modelling practice, we need to account for significant differences between experts, who in general are well-informed in the field in which they are employed, and learners, who lack basic affinity and essential background information. In addition, the school environment is completely different from the environments in which experts work, in aims and cultural role and function in society. In short, what is authentic for experts is not equally authentic for learners. Hence, one of the first stages in adapting an authentic modelling practice is a careful analysis of the attributes that are already known and mastered by students, and the attributes that are within the 'zone of proximal development' of students. Using this information, students need to be introduced to the practice such that content-related motives for modelling will arise.

Design principle 'content modelling'

The design principle of *content modelling* deals with learners focussing on the essential generic content regarding models and modelling. Using authentic chemical modelling practices as contexts for learning, it is tempting to regard the experts' knowledge as the intended learning outcomes for students. However, while some of what the experts do is very specific for their work and is best taught by 'on-the-job' training, there is also likely to be a core of generic content which is common to all modelling practices within the chemistry domain (Gott, Duggan, & Johnson, 1999). This generic content includes the advanced model features like purpose, reliability, goodness of fit and validity, and the modelling procedure applied. This generic content related to models and modelling should be identified within the authentic modelling practice and should embody the main learning gain of the curriculum unit.

Design principle 'chain of activities'
The design principle of *chain of activities* deals with constructing a sequence of teaching-learning activities such that learners constantly know *why what* to do at every step in the process. In general, experts know *why what* to do at every stage in the chain of modelling activities. Experts have clear content-related motives to go from one activity to the next, inspired by relevant background information. The challenge is to construct a chain of teaching-learning activities such that students also can see *why what* to do at every stage (Lijnse and Klaassen, 2004). The experts' modelling procedure provides a basic outline for the sequence of teaching-learning activities (Prins, Bulte, Van Driel, & Pilot, 2008). Next, each activity needs to be evaluated from the students' perspective according to the problem-posing approach (Klaassen, 1995).

Scope and research question

This research project is positioned within the broader perspective of developing and investigating context-based curriculum units in science education. The aim of this project was to develop a design framework with particular emphasis on the three design principles. The authentic chemical modelling practice at hand is 'Modelling drinking water treatment' (Prins et al., 2008), intended for secondary chemistry education (age 16–17 years, grades 10 and 11) in the Netherlands. The design framework was developed by a design team consisting of six experienced chemistry teachers and three researchers (the authors of this paper). The empirical testing and evaluation of the design framework, in light of the overall functioning of the curriculum unit in the classroom, is beyond the scope of this paper and is described elsewhere (Prins et al., Submitted-a). The central research question addressed here is:
What are the characteristics of a design framework for structuring teaching-learning processes using authentic chemical modelling practices as contexts for learning models and modelling in secondary chemistry education?

Method

In this section we describe the research approach, participants, data collection and analysis. Given the purpose of the study, the data collected is essentially qualitative. Furthermore we present a brief description of the authentic practice 'Modelling drinking water treatment'.

Design-based research approach
We follow a cyclic design-based research approach (Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003; Lijnse, 1995). In this study the first cycle is reported, in which design principles are

elaborated and synthesised to a design framework. The authentic practice 'Modelling drinking water treatment' is used as the context for learning. The arguments and considerations concerning 'why the unit will function as expected' are essential for understanding the functioning of curriculum unit in class. The current paper aims to capture this meta- knowledge in a design framework. By doing so, the knowledge becomes available for other educational designers and practitioners. We triangulated different data sources, summarised the data in an outline of the curriculum unit, and presented a preliminary version of the curriculum unit to the participants for a member check (Creswell, 2007). The participants played a major role in directing as well as examining and judging rough drafts of the curriculum unit.

Participants, data collection and analysis

The design team consisted of three researchers (the three authors of this paper) and six experienced chemistry teachers. In this paper we use the word 'design team' to denote the three researchers and six teachers, and 'researchers' to denote the three researchers. All teachers had over 10 years experience in secondary chemistry education from grade 8 to grade 12. The teachers all planned to use the curriculum unit in their own classrooms. The design team came together in the period from April to December 2006. Four meetings of three hours each were organised, in which the first two learning phases (I: orientation of the practice; II: zoom in on an example problem), the last two learning phases (IV: evoke a motive to express the findings; V: express and reflect on the findings), and the third learning phase (III: solve the example problem) were elaborated consecutively, and finally a preliminary version of the curriculum unit was discussed.

In the first meeting, the design team studied the motives and purposes, the modelling procedure and situated knowledge of the practice 'Modelling drinking water treatment'. The first author of this paper, introduced the authentic practice and pointed out major characteristics. Next, the design team evaluated the authentic practice leading to a selection of attributes already mastered and known by students. Finally, each of the teachers in the design team delivered a written draft summarising their views and ideas to engage students in an adapted version of the authentic practice. After this meeting, the researchers analysed the (raw) data. The preliminary interpretations and conclusions were brought back to the entire design team in the fourth and final meeting to check the accuracy and credibility of the account.

In the second meeting the design team focussed on the intended learning gain regarding models and modelling based on a broad outline of the authentic practice, as introduced in the first meeting. All the teachers in the design team again described their views and ideas, which were analysed by the researchers. Again, the preliminary interpretations and conclusions were brought back to the entire design team in the final meeting to check the accuracy and credibility of the account.

In the third meeting the design team focussed on the chain of modelling activities that students should conduct. The first author of this paper made a prototypical sequence of teaching-learning activities which was elaborated by the design team. The prototypical teaching-learning activities were all broadly formulated, thus leaving space for teachers' own contributions. At the end all the teachers in the design team reflected individually upon the prototypical teaching-learning activities. The preliminary interpretations and conclusions were brought back to the entire design team in the fourth and final meeting to check the accuracy and credibility of the account.

In the fourth and final meeting, a preliminary version of the curriculum unit was discussed, evaluated and commented upon by the design team. The preliminary version was constructed by the first author of this paper, based on interpretations and conclusions from the previous meetings. The complete discussion was audio-taped and transcribed *verbatim*. Next, the data was analysed independently by two researchers (the first and second authors of this paper). The analysis was conducted from an interpretative perspective (Smith, 1995). Firstly, all strategy components, pedagogic effects and arguments were coded according to 'context', 'content modelling' or 'chain of activities'.

Agreement between the coders was tested by calculating the percentage of statements concerning the strategy components coded equally by both researchers. We regarded 80% as the minimal level for a substantial level of agreement (Miles and Huberman, 1994). All strategy components were discussed by the researchers to identify intended pedagogic effects and underlying argumentation. Finally, the emerging design principles were synthesised into a design framework and discussed by the researchers.

Authentic practice 'Modelling drinking water treatment'

In this section, we describe the authentic practice 'Modelling drinking water treatment' in broad terms. This practice has been studied in detail in our previous study (Prins et al., 2008).

Motives for modelling drinking water treatment

The quality of drinking water is an important area within public health care. Different kinds of organic compounds, heavy metals and micro-organisms need to be removed to produce safe drinking water. Several treatment methods are available for this purpose, such as sand filtration and activated carbon filtration. In the Netherlands, the government and the drinking water production companies expect a growing demand for drinking water due to an increase of 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. The latter results in a need for more detailed knowledge of the influence of various process variables on the treatment process. In response to this need the National Institute of Public Health and the

Environment (RIVM) developed a 'Tool for the Analysis of the Production of Drinking Water' (known as TAPWAT) with the following goals (Versteegh, Van Gaalen, Rietveld, Aldenberg, & Cleij, 2001):

- To predict, on a global scale, the quality of drinking water (including health risk levels by micro-organisms) given a certain raw water quality.
- To determine the probability of the occurrence of pathogenic micro-organisms 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 concerning public health risks.

Situated and modelling knowledge involved
In TAPWAT each treatment step is represented by a mathematical model. A mathematical model is a systematic attempt to translate conceptual understanding of a real-world system into mathematical terms. The models fulfil three basic functions:

1. Models are used for the design of water treatment units, because with their help the parameters of the treatment plant (e.g. filter area and depth) can be calculated more accurately.
2. Models are used to improve the operation of water treatment processes. By simulating different scenarios models enable operators to adjust operational parameters like coagulant doses, filter loading rates, backwashing conditions and frequency etc. to optimal levels.
3. Models are applied to improve the automation and process control systems, because they allow predictions and use computers to simulate different patterns of control actions to find the most appropriate one.

The models developed range from percentage-removal based, empirical and mechanistic models for all treatment units. The choice of which level of complexity to use was made based on available theoretical and empirical data. The process models were tested using data from full-scale water treatment plants in the Netherlands. The generic modelling procedure consisted of three main steps. For each treatment step the relevant process variables were identified. Next, their influence on the removal effectiveness was determined, firstly on a qualitative level and secondly on a quantitative level, by gathering empirical data, through laboratory experiments and/or using real company data. Finally, the gathered data was analysed using statistical techniques.

The complete treatment process has thus been represented by a series of mathematical models enabling prediction of the quality of drinking water after treatment given a certain raw water quality. In Figure 2 the modelling procedure as applied by experts and the relevant situated knowledge in each stage are shown.

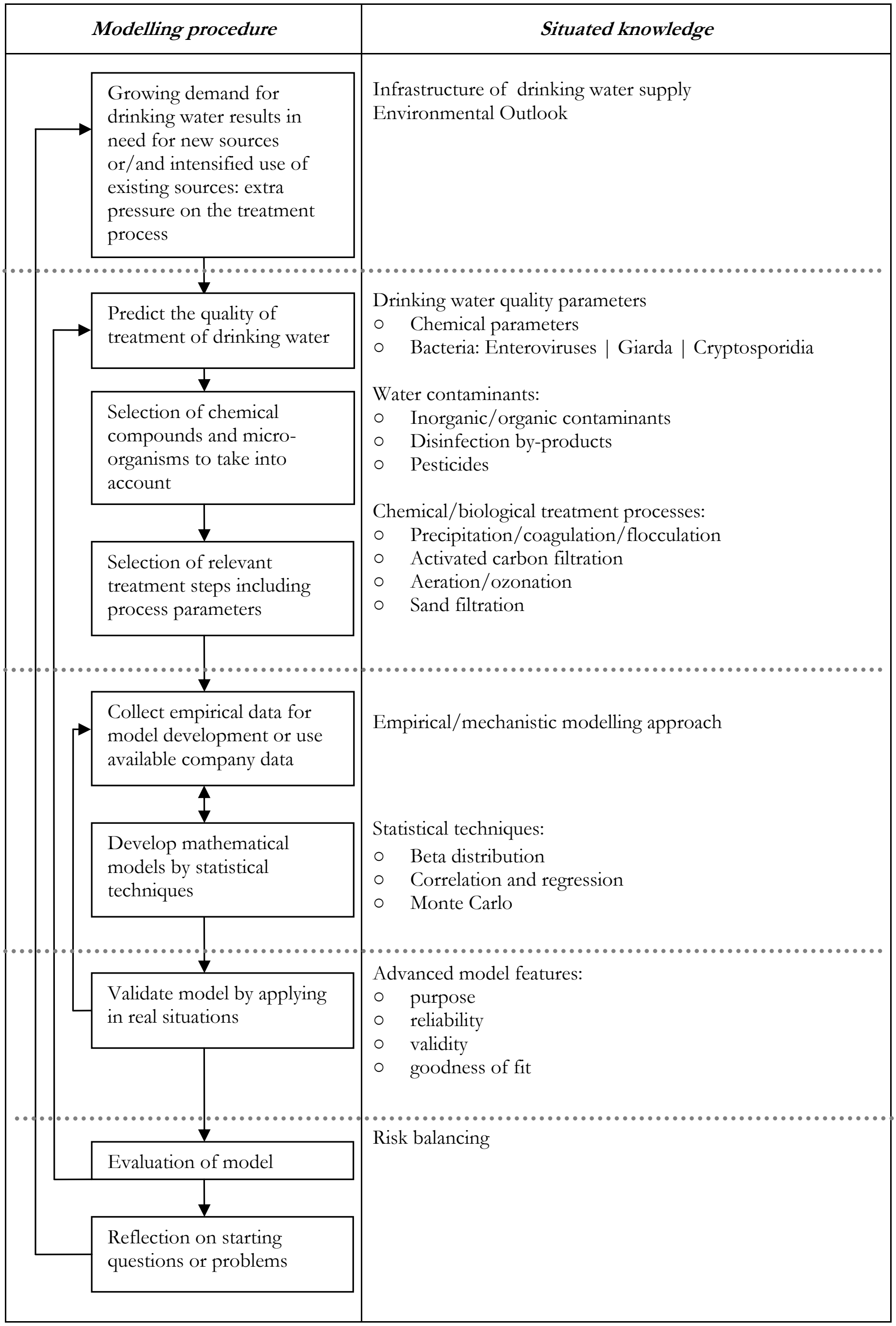

Figure 2. The modelling procedure and situated knowledge in the authentic practice 'Modelling drinking water treatment'. Arrows indicate the direction of the modelling process.

Context for learning

As might become clear from above description, the TAPWAT tool comprised a large project. The project was initiated and guided by multiple, partly overlapping, motives and goals. Preceding adaptation of this practice into a context for learning, we decided to reduce the complexity (Prins, Bulte, Van Driel, & Pilot, 2009). We focussed merely on the quality of drinking water as a function of the treatment process and raw water quality. As an example case, we concentrated on the removal of water turbidity by coagulation/flocculation. This quality parameter and treatment step was chosen because laboratory work in the classroom is practically feasible (Prins, Wigmans, Bollen, Bulte, & Pilot, Submitted). 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 series of experiments manipulating each process variable in a controlled way. The resulting data is analysed by a regression. The end turbidity as a function of process variables can be described with a multiple regression model, such as (Rietveld, 1999):

- Linear: $Y = a + b_1 X_1 + ...$
- Power: $Y = a(X_1^{b_1}).....$

The regression model is evaluated on characteristics such as purpose, goodness of fit, reliability and validity. The applied modelling approach can be typified as ‘data driven’ or ‘black-box’ modelling. The regression model explains the empirical data and observed process behaviour, but not the underlying mechanism(s) for coagulation/flocculation. This pre-made choice regarding the focus and content for the context for learning formed the starting point of the present study.

Results

In this section we describe the elaboration of the five learning phases. The design team thought of and discussed strategies to apply in their classes. For the sake of clarity, we reflect on the major decisional points, underlying arguments and alternatives that arose in the four meetings. In the second half of this section we present the emerging design principles. The independent coding of the transcript showed a substantial level of 87% agreement.

Learning phase I: Orientate on the practice

The design team identified two attributes with which students were expected to be familiar: the existence of quality norms for drinking water imposed by law and the basics of the process of water treatment, e.g., techniques like filtration, sedimentation aeration etc. It was decided to focus on *occasional exceeding* of the quality parameters imposed by law [SC 1][1]. The Dutch government regularly publishes data concerning the quality of drinking water in the Netherlands, including occasional exceeding (Versteegh and Te Biesebeek, 2003). By using such ‘official data’, it was expected that students would grasp the societal relevance of the exercise and this would induce a broad interest in the practice at hand. It was expected that such an orientation would also activate students' prior knowledge regarding the process of drinking water treatment. This decision, however, was questioned. An alternative pathway proposed was to focus students immediately on modelling water treatment and the approach experts apply, as exemplified by the following statement.

> *Teacher 1: 'Today in the news: the quality of drinking water in the Netherlands is of excellent quality … why not start directly with introducing the modelling programme students are supposed to work with?' [M1, WR]*[2].

The major argument for the alternative pathway was that, even if an orientation on occasionally-exceeded quality norms resulted in students raising questions about what is done in practice to prevent outruns, it does not focus students on *modelling water treatment*. However, the majority of the design team (four out of six) emphasised the potential benefits of providing a reason to study water treatment, before turning to modelling water treatment.

> *Teacher 2: 'Through such an orientation students realise that not all quality norms are always within reach. Such a notion induces, most probably, questions, amongst students, related to the (possible) cause(s) of exceeded quality norms. By presenting several exceeded quality norms [not only water turbidity], students recognise that the type of problem is not isolated or unique. It underlines the societal relevance and the need to come to a solution.' [M4, PD].*

Next, the design team discussed how to connect to the prior procedural modelling knowledge and how to evoke a motive for modelling. It was proposed to use a *shortened and rewritten* version of the original project plan 'modelling water treatment' (Versteegh et al., 2001) as study material for students [SC 1]. In the shortened and rewritten version the multilayered and complex project concerning 'modelling of water treatment' was 'simplified' to a single-cause straightforward modelling problem:

- reason (*why*): prevent exceeding of quality norms
- objective (*what*): model the quality of drinking water as a function of the process variables of the treatment process and quality of certain raw water
- by means of (*how*): examine all treatment units and parameters separately to find relations between in- and outgoing concentrations of contaminants, and describe the relation with a mathematical formula.

It was expected that such a strategy would offer students a first indication of the learning property. The design team unanimously expected that the shortened and rewritten version would provide an in-depth orientation on the practice and would focus students on modelling the influence of process variables.

Teacher 3: 'The objective of the unit will become clear. (…) I would strive for an exchange of findings and opinions between groups of students, so that different aspects of the practice will become clear to everybody.' [M1, WR].

Teacher 4: 'The students will get acquainted with the researchers and their approach: how do they cope with these kind of problems? How would you do it yourself?' (M1, WR].

By applying above strategies in learning phase I, it was expected that students would have a broad idea about the *why*, *what* and *how* related to modelling water treatment, although in a rudimentary sense. The next challenge was to involve students in modelling an example problem themselves, e.g., a distinct parameter and treatment unit. The design team thought of specific content-related motives that would initiate students' engagement in modelling turbidity removal by coagulation/flocculation. It was decided to let students discover that turbidity is one of the parameters with the highest number of crossings, thus motivating an explicit focus on removal of turbidity by coagulation/flocculation.

Learning phase II: 'Zoom in' on an example problem

Building on learning phase I, the design team faced the challenge of engaging students further to model turbidity removal by coagulation/flocculation. The design team was of the opinion that the content-related motive would not deliver prolonged engagement of students. After discussion, the design team decided to treat the students as junior employees [SC 2] of the Institute of Public Health and the Environment, and give them a specific assignment, namely to model the removal of turbidity as a function of the process variables of coagulation/flocculation.

Teacher 1: 'The Institute of Public Health and the Environment should be introduced. What is the aim of this organisation? Students then receive the task as being junior employees.' (M4, PD).

Earlier studies have proved that providing students with a rich, whole assignment fosters active involvement and leads to division of labour, inducing mutual dependency and discourse. It was decided that the assignment would mention distinct tasks to conduct, each task in correspondence with a particular stage in the teaching-learning process [SC i]. In addition, the expected end product was mentioned, namely a factsheet. A factsheet gives a compendious and practical overview of the (main) activities and outcomes of a (research) project. Factsheets are used in many practices as a communication tool [SC 6]. It was decided that a factsheet would be an appropriate end-product and suit the students' role as junior employees.

To elicit students' prior knowledge, the design team decided to use a factsheet of a worked-out analogous problem, namely modelling the removal of trichloroethylene by activated carbon filtration, as an advanced organiser (Ausubel, 1968). The factsheet of the analogous problem was composed using shortened and rewritten versions of research articles reporting the modelling of adsorption processes by activated carbon filtration. Studying the analogous modelling problem should lead students to (1) draw up a modelling procedure to apply and (2) focus on a set of advanced features to judge the quality of the models to be developed [SC A]. The modelling procedure to be identified by the students consisted of the following (major) consecutive stages:

1. Select relevant process variables;
2. Experimental research;
   a. Conduct experiments under controlled circumstances;
   b. Measure the outgoing concentration as function of ingoing concentration and the relevant process variables;
3. Regression to analyse correlations and describe these in mathematical formulas.

The advanced features to be identified, such as purpose, goodness of fit, validity and reliability, are the criteria to evaluate the developed regression models. To focus students explicitly on the advanced model features, it was decided that the factsheet of the worked-out analogous problem should also contain a separate section dealing with the advanced model features mentioned.

Teacher 5: '… Insert a separate paragraph [in the factsheet of the analogous problem] for the aspects of reliability and validity, so that students will take notice of these criteria early on and again at the end of their learning process.' [M4, PD].

All members of the design team were confident with the above strategy. The way of learning was embraced and was expected to evoke further engagement among the students.

Teacher 1: 'Nice way to work! […] Students will find it difficult to focus on the generic modelling approach, but it is very instructive.' [M2 WR; M4 PD].

Teacher 5: *'While drawing up a plan of action, a student should notice a lack in knowledge. [for learning models and modelling], the analogue factsheet illustrates the development of a mathematical model out of a series of empirical data, and how to evaluate the reliability of such model. [This is what students should learn by doing themselves…].' [M2, WR].*

The design team agreed on a basic structure for the factsheet, as shown in Figure 3.

Project Modelling drinking water treatment *Factsheet Turbidity removal by Coagulation/Flocculation* Name of researchers: .... Name of teacher: .... Delivery date: ....
Introduction & purpose
The operation of coagulation/flocculation on industrial level
Process variables
Experimental research
Empirical data
Regression
Goodness of fit, reliability & validity
Advice on future research
Literature
List of concepts

Figure 3. The basic structure of the factsheet to be delivered by students reporting the main findings and activities conducted concerning modelling turbidity removal by coagulation/flocculation.

Learning phase III: Solve the example problem

The modelling procedure, consisting of the three main stages described above, can be typified as an 'empirical' ('data driven' or 'black-box') modelling approach. It was concluded in our previous study that this modelling procedure is basically in line with students' prior procedural modelling knowledge (Prins et al., 2009). Hence, the teaching-learning activities in phase III were outlined according to the three stages [SC ii]. However, in phase III the challenge is to find ways to keep students 'on track' and leading to desired (learning) outcomes. Below we discuss strategies for achieving the aim of students seeing the point of extending their knowledge going from one activity to the next.

In the first stage – select relevant process variables – the design team noted that students lacked the necessary background knowledge on coagulation/flocculation. Therefore, the design team decided to let students conduct a literature study on coagulation/flocculation treatment. Therefore two 'mock' articles were suggested [SC 3]: one dealing with the working of coagulation/flocculation (A) and one with the chemistry underlying coagulation/flocculation mechanisms (B). In addition, it was suggested that teachers demonstrate turbidity removal by coagulation/flocculation in class [SC 4] to emphasise the essentials of the modelling problem.

It was assumed that the above strategies would illuminate the major characteristics of the process and the relevant process variables to be examined, being; dose coagulant, starting turbidity, temperature, *pH* and salt concentration. A main argument for this was that it resembles the way experts search for information. Experts also gather new knowledge and insights by studying relevant articles and reports. Such a strategy fits the role played by students as junior employees. However, regarding article B, there was discussion about how much theoretical insight was needed on the chemistry underlying coagulation/flocculation processes. The chemistry involved was considered difficult for students, and the added value of studying it was questioned.

> *Teacher 6: '[Please] summarize that colloids are negatively charged and brought together by the positive ferric ion in a few sentences and deliver a list stating all relevant process variables. Leave all the rest for the more interested students. More is not needed, is it? I do find the chemistry related to coagulation/flocculation processes even hard to understand myself!' [M4, PD].*

Consequently, it was decided that article B was optional, and need only be consulted by students willing to know more details about coagulation/flocculation. Both 'mock' articles were to be presented to students as 'real' professional writing.

> *Teacher 5: 'Also note the names of the authors at the top of the articles, so that students experience the writings as authentic.' [M4, PD].*

After the selection of relevant process variables, the students proceed to the experimental stages. They conduct experiments under controlled circumstances and measure the outgoing concentration as function of ingoing concentration and the relevant process variables. To ensure controlled circumstances in the classroom it was decided to use prescripts for the laboratory experiments to be conducted for each process variable (dose coagulant, starting turbidity, temperature, *pH* and salt concentration). In each series of experiments, the end turbidity was measured as function of one of the process variables, leaving the others at constant value. The design team explicitly made the choice to investigate in class all five process variables, although a minor (no) influence was expected from the variables temperature and salt concentration. The design team considered it worthwhile that students should experience that some process variables apparently have no influence and thus need no further study ('negative' result).

> *Teacher 1: 'That is also a very important result. I will emphasise that in class and compliment students on that, so that they will not be disappointed.' [M3, WR].*

The final stage comprised the analysis of the data by regression to analyse correlations and describe these in mathematical formulas. Regression as a statistical technique was expected to be unfamiliar to students, so the design team decided to provide guidance by means of a manual [SC 3]. In this manual the method was explained and illustrated using Microsoft Excel software as a computer tool. Students were supposed to draw scatter plots of all process variables, select the one which showed (obvious) correlation with the end turbidity, fit several regression models to find the best, and finally conduct multiple regression to construct one mathematical formula describing end turbidity as function of relevant process variables [SC B]. This gradual formalisation of concrete (visible) observations in mathematical formulas is known as emergent modelling (Gravemeijer, 1999). The design team considered the multiple regression a heavy cognitive task for students. However, it was expected that students, after having experienced and conducted single regression, would grasp the central idea of multiple regression and be able to perform the task with the necessary guidance.

> *Teacher 1: 'I do find the method to start with single regression models more instructive than performing a multiple regression immediately by means of MS Excel. For students, much happens below surface.' [M4, PD].*

It was expected that phase III as outlined above would be meaningful from students' perspective, given that each teaching-learning activity builds on the previous one and prepares for the next one (Klaassen, 1995). The design team evaluated the modelling procedure from students' perspective and constructed a learning pathway (Lijnse and Klaassen, 2004). Figure 4 depicts the structure of the learning pathway of students in learning phase III, in terms of knowledge, motives and modelling activities.

To ensure that students stay on track, it was decided to organise class meetings after each modelling stage. In these meetings the assignment was recalled and the progression was discussed [SC iii].

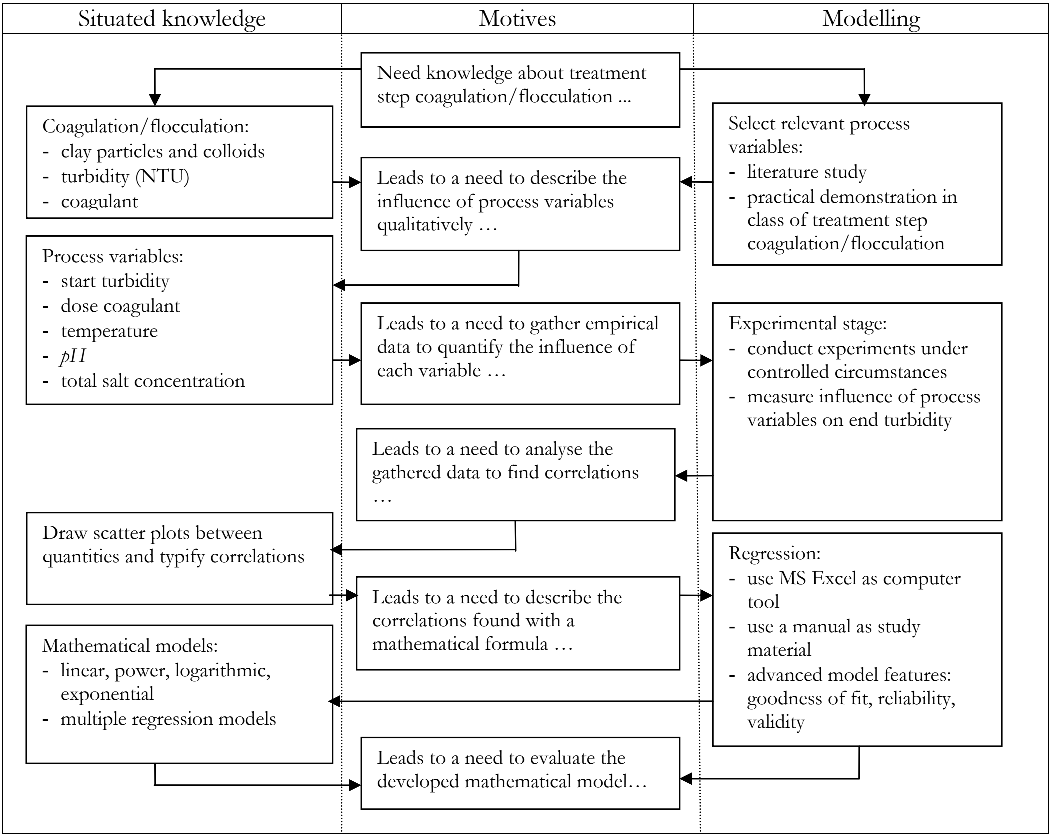

Figure 4. Structure of the teaching-learning process in phase III in terms of situated knowledge and modelling activities coupled by motives. The arrows indicate the direction of the process.

Learning phase IV: Evoke a motive to express the findings

The primary aim of the fourth learning phase is to induce a motive among students to make their findings explicit. The design team decided to build in a teaching-learning activity in which students evaluated the developed multiple regression models and to what extent the example problem has been solved [SC iv]. It was expected that this strategy would induce a motive for a critical reflection on the performed modelling activities.

> *Teacher 6: 'You cannot just postulate the advanced features in a factsheet. You must show how you have gathered the results, what you actually have done, what went wrong, did you deviate from the plan of action …' [M4, PD].*

Learning phase V: Express and reflect on the findings

In learning phase V the findings should be made explicit and reflected upon. The main strategy was to report all the main results in a factsheet, including a list of concepts [SC 5]. The 'list of concepts' was introduced in learning phase II as a method to keep track of the situated knowledge related to the coagulation/flocculation treatment. The idea was that students would regularly update their list of concepts, and deliver a final version at the end of the learning process. This list of concepts was incorporated into the factsheet. It was considered that students would regard this as a natural part of their roles as junior employees, as typified by the statement below:

> *Teacher 1: 'Construct a list of concepts for yourself [student] and the community [class]. For yourself it is important to learn these concepts, for the community it is important that everybody uses the same concepts and understands them equally.' [M4, PD].*

As for reflection, the design team faced the challenge of focussing students on the *generic* modelling procedure and the advanced model features, and emphasising that the learned knowledge is also usable in other (related) modelling issues. In essence, the design team discussed two possible routes:

A. Students, in their role as junior employees, should advise another project team on modelling a different quality parameter and treatment step.
B. Students, in their role as junior employees, should advise another project team upon future research on the removal of turbidity by coagulation/flocculation.

Both routes imply a recall of the activities conducted. For each route several arguments were given, both for and against. Route A would put students in the position to focus on generic content.

> *Teacher 1: 'For example, project team disinfection [another treatment step] has asked the project team coagulation/flocculation to advise on the [modelling] approach to apply. So, students look back to their formulated plan of action and adapt this to accommodate the new situation based on own experiences. [This would deliver an] advice on two levels: a [generic] modelling approach and a relevant list of concepts.' [M4, PD].*

However, according to the design team, route A bears the risk that students would consider the new treatment step as a completely new situation in which the learned knowledge is hardly usable. This argument would favour route B, in which treatment step coagulation/flocculation remains object of study.

> *Teacher 4: '[A suggestion might be to] focus students on examining one not yet identified process variable of coagulation/flocculation … that is much closer to*

students' capability than taking another treatment step, with the risk that students will respond in a very broad and non-specific manner.' [M4, PD].

The disadvantage of route B mentioned was that students could get the idea that the applied modelling procedure is specific for the treatment step of coagulation/flocculation. Considering all arguments, the design team decided to apply route B as the major strategy [SC C].

The design team decided to bring up different kinds of aspects for future research on coagulation/flocculation not identified so far, like other coagulants, process variables etc. It was expected that this would lead students to identify, select and describe the generic content regarding models and modelling.

Elaboration of the design principles

The data was analysed to reveal the substance of the three design principles of *context*, *content modelling* and *chain of activities* in terms of strategy components, pedagogic effects and arguments. The design principle of *context* deals with involving learners in a focal event embedded in its cultural setting (Gilbert, 2006). This implies the setting, the behavioural environment, the specific language and the extra-situational background knowledge, such that students become engaged in a modelling activity. Therefore, the practice should be presented such that students recognise the subject dealt with. In addition, the example problem should appeal to students in such a way that they themselves see routes to solve the problem. The design team applied a couple of strategies which, in combination, are expected to result in a prolonged engagement of students in the adapted practice. Figure 5 depicts the strategies applied, the expected pedagogic effects and the underlying arguments.

Strategy components

1 Provide students with a broad orientation base:
- occasional exceeding of legal set quality norms of drinking water
- adapted version of the authentic project plan concerning 'Modelling drinking water treatment'

2 Give students a specific role and task:
- role play as junior employees of the 'Institute for Public Health and the Environment'
- model the removal of turbidity by coagulation/flocculation

3 Select the essential situated knowledge and supply it to students by means of articles and/or manuals:
- article 'Coagulation/flocculation treatment'
- article 'Mechanisms of coagulation'
- manual 'Correlation & regression'

4 Visualise for students the example problem on which they are going to work:
- demonstrate treatment step of coagulation/flocculation

5 Organise students to ensure that they keep track of situated knowledge:
- construct a list of concepts

6 Select an end product, matching the example problem, to assess students' performance:
- write a factsheet 'Modelling turbidity removal'

… *expected to result in* ….

… *because of* ...

Pedagogic effects

1 Students show familiarity with water treatment and legally imposed quality norms (***a***). Students are able to situate the authentic practice in its cultural setting, and are motivated to study the problems posed (***c***)

2 Students are willing to and show ownership of work on modelling turbidity removal by coagulation/flocculation (***d***)

3 Students take notice of and understand situated knowledge (***h***), such as colloids, coagulant, turbidity, charge neutralisation, sweep flocs and process variables

4 Students are able to materialise the situational (theoretical) knowledge from articles regarding coagulation/flocculation (***h***)

5 Students construct a list of concepts related to water treatment, specifically concerning coagulation/flocculation (***j***)

6 Students display the main findings and the learned conceptual and procedural knowledge (***j***)

Arguments

1 The design argued that the use of an adapted version of the authentic project plan as teaching material emphasises the societal relevance and evokes students' broad interest. In addition, it provides students with a view on the *what* (construct a mathematical model), *how* (modelling treatment process) and *why* (exceeding of quality norms). Later on in the teaching-learning process students are supposed to advise on a modelling approach for another (similar) problem based on their own experiences.

2 It is found that addressing students as junior employees with a whole task fosters active involvement and leads to division of labour inducing mutual dependency and discourse. The design team expected that the relatively high number of turbidity crossings would motivate students to focus specifically on turbidity removal by coagulation/flocculation.

3 The design team argued that the use of articles and/or manuals fosters a sense of authenticity and facilitates 'just in time' information delivery. In addition, it offers opportunities to select and communicate the essential situated knowledge in a compact and orderly way. It corresponds to the common way of information search by experts.

4 The design team argued that through visualisation the essentials of the example modelling problem would become apparent for students.

5 The design team was of the opinion that a list of concepts is a suitable tool to record situated conceptual knowledge to ensure mutual understanding. The construction of the list of concepts should be a recurring event in the teaching-learning process and an integral part of the end product.

6 The design team regarded a factsheet, summarising the main results and findings, as an appropriate end product to assess. Moreover, it suits the role of students as junior employees.

Figure 5. Conceptualised scheme of the design principle 'context'. The numbers connect strategy components with expected pedagogic effects and underlying arguments. The italic letters in the 'Pedagogic effects' box refer to the instructional functions in Table 1.

The design principle of *content modelling* deals with focussing learners on the essential generic content regarding models and modelling. A pitfall in adapting an authentic modelling practice into a context for learning is to incorporate too much specific situated knowledge. The challenge is to avoid cognitive overload among students. It is necessary to select the essential concepts needed to cope with the example problem without 'oversimplifying' the problem. In addition, the desired learning outcome is to foster students' understanding of models and modelling, so the focus should lie on the generic content related to models and modelling. An important aspect in the proposed strategies was to point out to students that turbidity removal is but one of the problems posed in the practice. It was expected that students would bear in mind that the learning gain is also usable for other quality parameters and treatment steps. Combining all strategies, pedagogic effects and accompanying arguments leads to the filling-in of the design principle, as depicted in Figure 6.

Strategy components

A Supply students with a worked-out analogous modelling problem as leading example:
- factsheet 'modelling trichloromethane removal by activated carbon filtration'

B Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand:
- perform experiments
- construct scatter plots
- analyse and typify correlations
- perform single and multiple regression

C Let students advise on a modelling procedure to apply to similar problem:
- advise on future research on modelling treatment step coagulation/flocculation

… expected to result in …

… because of …

Pedagogic effects

A Students activate and enrich their prior knowledge base:
- mention epistemic values 'goodness of fit', 'reliability' and 'validity' (***e***)
- draw up a modelling procedure (***f***)

B Students show understanding of (***h***):
- accuracy of measurements
- global trends and correlations
- lines of best-fit through scatter plots
- single and multiple regression models
- epistemic values 'goodness of fit', 'reliability' and 'validity'

C Students evaluate and reflect on the epistemic values and formulate a generic modelling procedure for a similar problem (***k***)

Arguments

A It is found that supplying students with an advanced organiser informs students' views on activities to conduct and (type of) knowledge to learn/apply. The design team argued that a worked out analogous modelling problem, originating from the authentic practice at hand, serves as an advanced organiser. It provides students with a view on epistemic values to take into account and the end product to deliver.

B It is found that emergent modelling, e.g., gradually formalising empirical data in mathematical models, is a suitable way to guide students through levels of abstraction. The design team argued that multiple regression should be preceded by single regression to reduce complexity and foster students' understanding.

C The design team argued that, through advising on a modelling procedure for a similar problem, students would be placed in a position to focus on the generic content regarding models and modelling, e.g., a modelling procedure and the epistemic values.

Figure 6. Conceptualised scheme of the design principle 'content modelling'. The capital letters connect strategy components with expected pedagogic effects and underlying arguments. The italic letters in 'Pedagogic effects' refer to the instructional functions in Table 1.

The design principle of *chain of activities* deals with constructing a sequence of teaching-learning activities such that learners constantly know *why what* to do at every step in the process. The challenge is to match students' prior knowledge with the sequence of teaching-learning activities. An important strategy component was to use the modelling procedure in the authentic practice as a backbone for the sequence of teaching-learning activities. Combining all the strategies, pedagogic effects and accompanying arguments led to the filling-in of the design principles, as depicted in Figure 7.

Strategy components

i Give students a clear assignment concerning the example problem to work on and formulate tasks that coincide with the main stages in the teaching-learning process

ii Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration:
- select relevant process variables
- conduct experiments under controlled circumstances
- analyse data by correlation & regression

iii Plan work meetings with students after each main stage in the teaching-learning process to look ahead on future activities:
- recall the assignment and record progress

iv Let students evaluate to what extent the example problem has been solved:
- summarise all findings and evaluate the constructed regression model

… *expected to results in…* → … *because of* …

Pedagogic effects

i Students have a motive to learn/apply knowledge to solve the example problem at hand (***g***)

ii Students are aware about *why what to do* at every point in the teaching-learning process. Students see the point of every teaching-learning activity in the sequence leading to an outcome (***h***)

iii Students have a broad outlook on the future modelling stages: each stage couples to the previous and prepares the next one (***h***)

iv Students have a motive to make explicit all findings to inform others (***i***)

Arguments

i The design team argued that prolonged engagement is established by providing students with a clear assignment. Moreover, receiving an assignment fits the students' role as junior employees.

ii It is found that the experts' modelling procedure complies with students' notions regarding solving the example problem. The design team decided to evaluate each modelling stage from students' perspective to construct an ongoing sequence of teaching-learning activities.

iii The design team argued that planning regular meetings after each main modelling stage keeps students 'on track'. Students record the tasks already accomplished and future tasks, while keeping the purpose of the modelling in mind.

iv The design team considered an explicit evaluation phase a suitable precursor for reporting all main results and findings. Students understand that all reported results and findings, as well as proposals for future work, need to be underpinned.

Figure 7. Conceptualised scheme of the design principle 'chain of activities'. The captions connect strategy components with expected pedagogic effects and underlying arguments. The italic letters in the 'Pedagogic effects' box refer to the instructional functions in Table 1.

Conclusion and discussion

This study described the adaptation of an authentic practice ‘Modelling drinking water treatment’ into a context for learning for upper secondary chemistry education. We have reported in detail the major design issues and decisions taken. The knowledge involved has been captured in three design principles. In the following, the design principles are synthesised with the learning phases and instructional functions in a design framework. We reflect on the characteristics of the design framework and formulate criteria for empirical testing in class. Furthermore, we discuss the use of authentic practices as contexts for learning.

Meaningful learning of models and modelling might be achieved if we manage to engage students actively in modelling processes (Schwarz and White, 2005). For this to take place, students should see modelling as a coherent whole activity in terms of motives, activities and knowledge. However, designing a meaningful teaching-learning process from students’ perspective using an authentic practice as context is no trivial task. The challenge is to adapt authentic practices for the population of students within the constraints of the classroom, while maintaining their coherency. In this study we elaborated three design principles, embodying strategy components in order to reach pedagogic effects underpinned by arguments. The design principles are synthesised with the ‘instructional version of authentic practice’ (Bulte et al., 2006) in order to construct a design framework. The emerging design framework is depicted in Table 2. For the sake of clarity, we highlight only the strategy components, leaving out the intended pedagogic effects and underlying arguments. As becomes clear, each design principle covers multiple learning phases. So, the design principles should not be viewed as complete isolated entities. They can be regarded as functional parts in the design which can be studied separately, thus reducing the overall complexity. Such an approach keeps research on educational designs manageable (Schunn, 2008).

The design framework provides heuristics for structuring teaching-learning processes. The validity of the design framework is subject to certain conditions. It is only valid for using authentic modelling practices as contexts for learning in pre-academic chemistry education. In addition, the authentic practice to be adapted should be feasible for use in secondary chemistry education (Prins et al., 2008). The heuristic value of the design framework needs to be evaluated on (at least) two levels. Firstly, the value needs to be studied in light of the overall functioning of the curriculum unit in class (Prins et al., Submitted-a). At present, the design framework has only been justified by expert judgement, e.g., experienced chemistry teachers and researchers. Secondly, the applicability of the design framework for adapting other authentic practices into contexts for learning needs to be studied (Prins, Bulte, & Pilot, Submitted-b). Currently, the design framework is based on the adaptation of only one authentic chemical modelling practice.

Table 2. A design framework, a synthesis of design principles, learning phases and instructional functions, providing heuristics for structuring teaching-learning processes using authentic modelling practices as contexts for learning.

Design Framework			
Learning phases / Instructional functions	***Design principles***		
	Context	***Chain of activities***	***Content modelling***
I: Orientate on the practice ***a)*** Connect to the prior conceptual knowledge base ***b)*** Connect to the prior procedural knowledge base ***c)*** Evoke motivation to study the problems posed in the practice ***d)*** Evoke a motive to zoom in on an example problem	**Strategy component 1:** Provide students with a broad orientation base **Strategy component 2:** Give students a specific role and task		
II: Zoom in on an example problem ***e)*** Make explicit and build on the prior conceptual knowledge base ***f)*** Make explicit and build on the prior procedural knowledge base ***g)*** Evoke a motive to solve the example problem		**Strategy component i:** Give students a clear assignment concerning the example problem to work on and formulate tasks that coincide with the main stages in the teaching-learning process	**Strategy component A:** Supply students with a worked-out analogous modelling problem as leading example
III: Solve the example problem ***h)*** Proceed through the sequence of activities and learn/apply knowledge until a satisfactory solution for the example problem can be presented	**Strategy component 3:** Select the essential situated knowledge and supply it to students by means of articles and/or manuals **Strategy component 4:** Visualise for students the example problem on which they are going to work **Strategy component 5:** Organise students to ensure that they keep track of situated knowledge	**Strategy component ii:** Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration **Strategy component iii:** Plan work meetings with students after each main stage in the teaching-learning process to look ahead on future activities	**Strategy component B:** Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand
IV: Evoke a motive to express the findings ***i)*** Induce a motive to express the learned conceptual and procedural knowledge used to solve the example problem		**Strategy component iv:** Let students evaluate to what extent the example problem has been solved	
V: Express and reflect on the findings ***j)*** Make explicit the learned conceptual and procedural knowledge ***k)*** Draw up a project plan for solving a similar problem posed in practice	**Strategy component 6:** Select an end product, matching the example problem to assess students' performance		**Strategy component C:** Let students advise on a modelling procedure to apply to similar problem

The procedure for the elaboration of the design principles and formulation of the design framework functioned well. The participating chemistry teachers were confident with the procedure. The role of the teachers was clear at all stages. The fact that all the teachers planned to apply the curriculum unit in their own class indicated that they felt empowered to teach the unit. Many curriculum innovation projects emphasise the essential role of teachers as developers of curriculum materials. At the same time, many projects struggle to find ways to involve teachers so that they can contribute in a valuable way. In this respect, the applied procedure might also be used as a basic format for fostering teachers' expertise regarding context-based science units. However, it should be taken into account that this authentic practice was selected after a thorough analysis and judgement (Prins et al., 2008). We started with a well documented authentic practice. That meant the design team could immediately focus on adapting the authentic practice into a context for learning, instead of figuring out what the practice is all about and then revealing its essentials. Such a starting point is a prerequisite for the applied procedure.

Many research studies have been conducted on students' understanding of models and modelling. In general they call for greater emphasis on the role and purpose of models in science. In the present study an effort has been made to contribute to a knowledge base regarding the design of context-based chemistry education. The results of this study underline that authentic practices are valuable sources of inspiration. We are well aware of the fact that different teaching-learning processes can be designed using authentic practices as contexts for learning. Therefore, we recommend that the arguments and considerations underlying the adaptation of authentic practices into contexts for learning are explicitly described, in order to understand their learning effects in class.

The next steps in this research will be to develop a complete curriculum unit, followed by empirical testing and evaluation of the curriculum unit in the classroom. By doing so, this research project aims to contribute to the further development and elaboration of a knowledge base for adapting authentic practices into contexts for learning, based on theoretical notions enriched with practical considerations from classroom, in order to construct meaningful learning trajectories.

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Endnotes

[1] All references are to specify strategy components identified, where SC 1, 2, … etc. stands for the strategy components within design principle context, SC A, B, … etc. stands for strategy components within design principle content modelling, and SC i, ii, … etc. stand for strategy components within design principle chain of activities.

[2] All references used are to specific data sources used, where M1, 2, 3, 4 denotes a meeting, WR for written reflection and PD for the plenary discussion.

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6

Evaluation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education[1]

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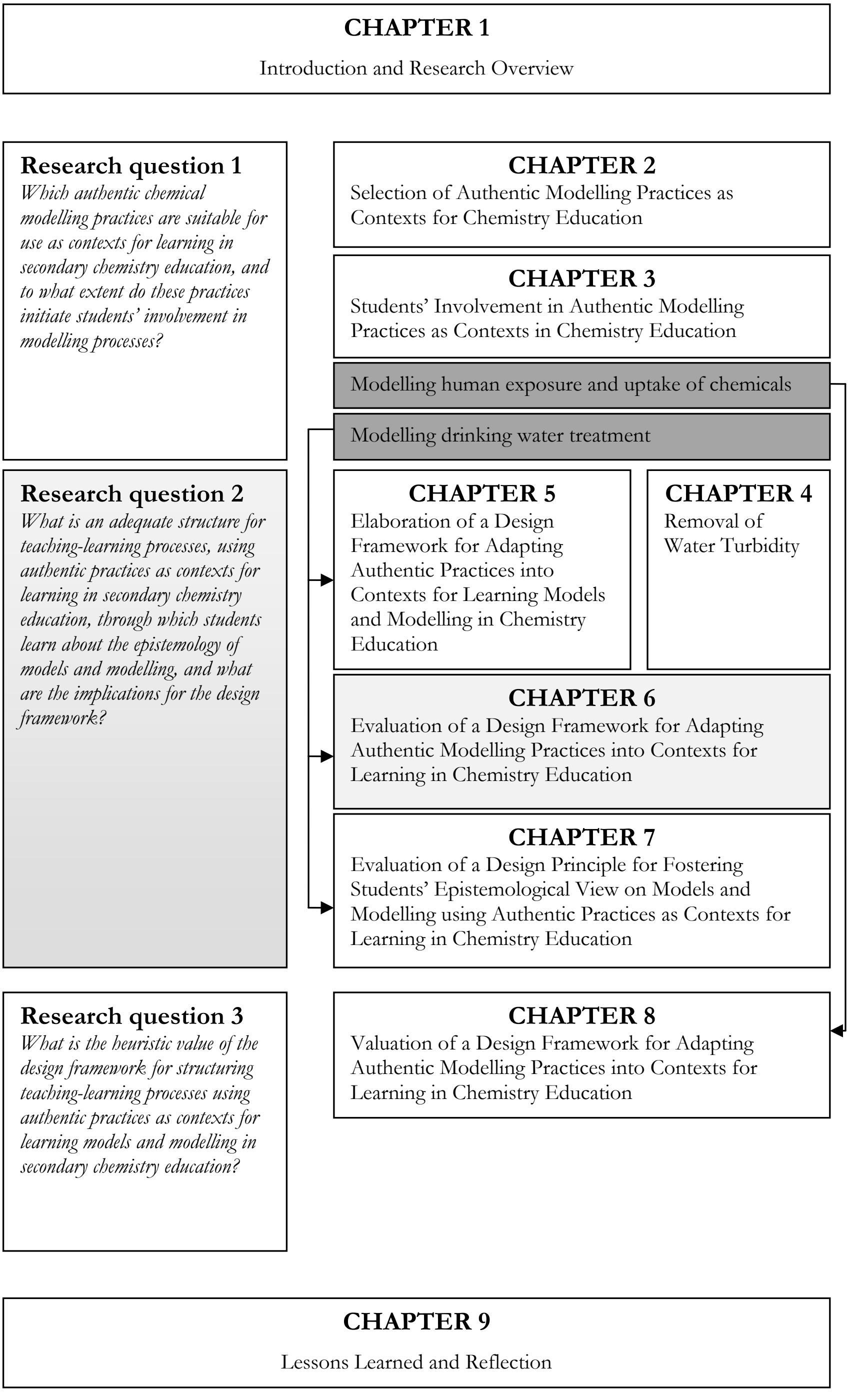

CHAPTER 1
Introduction and Research Overview
Research question 1
Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?
CHAPTER 2
Selection of Authentic Modelling Practices as Contexts for Chemistry Education
CHAPTER 3
Students' Involvement in Authentic Modelling Practices as Contexts in Chemistry Education
Modelling human exposure and uptake of chemicals
Modelling drinking water treatment
Research question 2
What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?
CHAPTER 5
Elaboration of a Design Framework for Adapting Authentic Practices into Contexts for Learning Models and Modelling in Chemistry Education
CHAPTER 4
Removal of Water Turbidity
CHAPTER 6
Evaluation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education
CHAPTER 7
Evaluation of a Design Principle for Fostering Students' Epistemological View on Models and Modelling using Authentic Practices as Contexts for Learning in Chemistry Education
Research question 3
What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?
CHAPTER 8
Valuation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education
CHAPTER 9
Lessons Learned and Reflection

Chapter 6 focuses on the empirical testing and evaluation of the design framework, with emphasis on the design principles, in light of the overall functioning of the teaching-learning process in the classroom. In two experimental cycles, data were collected by means of classroom observations, interviews, audio-taped discussions, completed worksheets and written questionnaires. The results gave rise to major changes in the design framework, especially concerning the filling-in of the design principle content and the instructional functions regarding an evaluation of and reflection on the applied modelling procedure.

The central research questions addressed are:

1. *To what extent does the designed teaching-learning process, using an authentic practice as a context for learning in secondary chemistry education, lead to intended pedagogic effects and understanding of models and modelling?*
2. *What are the implications for the design framework?*

Abstract

In science education students should come to understand the nature and significance of models. A promising route to achieve this goal is to involve students in a domain of science that employs models. This paper reports the design of a curriculum unit using the authentic chemical practice 'Modelling drinking water treatment' as the context for learning and the evaluation of its application in the classroom. An authentic practice is defined as professionals working on an issue guided by common motives and purposes, according to a similar type of procedure and applying relevant knowledge. The knowledge base concerning the adaptation of the authentic practice into a context for learning was captured in a design framework, consisting of learning phases, instructional functions and design principles. Throughout the field tests, research data was collected by means of classroom observations, interviews, audio-taped discussions, completed worksheets and written questionnaires. Students were able to reflect on the model aspects of goodness of fit and reliability, and showed awareness of the empirical foundation of the developed model. However, inducing meaningful reflection on the modelling procedure proved to be difficult. The findings were used to reconsider the design framework. This study contributes to the acquisition of a knowledge base concerning the design of context-based chemistry education.

Introduction

Models are essential in both science and science education. In this context, models are generally viewed as connections between the scientific theory and the world as experienced. Currently, the learning of models and modelling is regarded as an integral part of scientific literacy (Clement, 2000; Gilbert, 2004). Given the fact that the process of modelling is considered an essential element of scientific thinking, there is a need to design learning environments such that students' understanding of the nature of models is enhanced (Harrison and Treagust, 1998).

In education, the terms model and modelling are used quite ambiguously (Harrison and Treagust, 2000b). In this paper we concentrate on models and modelling in chemistry education. We use the term model for some structured representation, including symbolic elements, of the essential characteristics of an idea, object, event process or system (Gilbert and Boulter, 2000). Examples of models used in chemistry education are iconic and symbolic models that depict chemical formulae and chemical equations, mathematical models that represent conceptual relationships of physical properties and processes (e.g. $PV = nRT$) and theoretical models that describe well-grounded theoretical entities (e.g. kinetic theory model of gas volume, temperature and pressure). Modelling is defined as the construction, evaluation and revision of a model in response to a particular task (Gobert and Buckley, 2000).

Many studies have revealed that students do not learn about models and modelling effectively (Grosslight, Unger, Jay, & Smith, 1991; Harrison and Treagust, 1996, 2000a). The majority of students think of models as either toys or copies of reality. Students, in general, have problems capturing more advanced features of model understanding, like the purpose of creating models, models as representations of ideas in contrast to reality and the notion that models can be tested and changed in order to inform the development of ideas. Many science curricula aim to foster students' understanding of models and modelling. However, there is substantial evidence that most current curricula offer little opportunity for reaching this goal (Erduran and Duschl, 2004; Justi and Gilbert, 2002).

It has been claimed that this aspiration might be realised by designing teaching-learning processes that reflect authentic science practices that employ models (Edelson, 1998; Gobert and Buckley, 2000; Roth, 1998). Students need to experience models in processes similar as those used in research laboratories or other authentic practices in which real science takes place (Sadler, 2007). Furthermore, the purpose and functioning of models becomes relevant for students if the learning of models and modelling is situated in a context that is recognisable from a students' perspective (Bennett and Holman, 2002).

Following this proposition, we use authentic chemical modelling practices as contexts for learning. We define an authentic practice as a homogeneous group of people in society working on real-world problems and societal issues in a 'community' connected by three characteristic features; common motives and purposes, working according to a characteristic procedure leading to an outcome, and using relevant knowledge about the issue on which they are working (Bulte, Klaassen, Westbroek, Stolk, Prins et al., 2005). In an authentic practice the modelling activities and knowledge involved form a coherent connection. The design challenge, however, is to maintain this coherency within the constraints of the classroom. The authentic practice adapted for use in chemistry education should reflect a similar set of the three characteristic features for two essentially different populations, namely the experts and the learners. In addition, a teacher, guiding the students, has to be acquainted with both the authentic practice and the adaptation thereof into a context for learning.

In the present paper we report on the application in class of a curriculum unit using the authentic practice 'Modelling drinking water treatment' as the context for learning. The evaluation is focussed upon the evaluation of a design framework consisting of learning phases, instructional functions and three design principles (Van den Akker, Gravemeijer, McKenny, & Nieveen, 2006). The design principle of *context* deals with involving learners in a focal event embedded in its cultural setting (Gilbert, 2006). This implies the setting, the behavioural environment, the specific language and the extra-situational background knowledge, such that students become engaged in a modelling activity. The design principle of *content modelling* deals with focussing learners on the essential generic content regarding models and modelling, for example, the advanced model features and modelling approach. The design principle of *chain of activities* deals with constructing a sequence of teaching-learning activities such that learners constantly know *why what* to do at every step in the process (Klaassen, 1995; Lijnse and Klaassen, 2004). We will discuss the design principles, report on the observed outcomes in the classroom and evaluate the current completion of the design framework. The aim of this paper is to contribute to a knowledge base for adapting authentic modelling practices into meaningful contexts for learning.

Theoretical framework

In this section the authentic practice 'Modelling drinking water treatment' is described. Next, the design framework, providing heuristics for structuring teaching-learning processes, is portrayed.

Authentic practice 'Modelling drinking water treatment' as a context for learning

The use of authentic practices as contexts for learning stems from and relates to activity theory in education, rooted in the sociocultural tradition (Leont'ev, 1978; Vygotsky, 1978). An adaptation of an authentic practice into a context for learning will need to address at least three primary issues: (1) curriculum structure, (2) teacher preparation and (3) learner-appropriate resources, tools and techniques (Edelson, 1998). Below, we briefly describe the authentic practice 'Modelling drinking water treatment'.

In the Netherlands, the government and the water companies expect a growing demand for drinking water due to an increase of the population and the level of prosperity. To meet this extra demand, new sources for the production of drinking water need to be found, or the use of existing sources needs to be intensified. The latter results in a need for more detailed knowledge of the influence of various process variables on the treatment process. Therefore, for each treatment step, the significant process variables were identified using relevant physical, chemical or biological knowledge of removal of contaminants and micro organisms. Next, their influence on the effectiveness of removal was determined, through laboratory experiments and/or using real company data, and described in mathematical models. The developed models range from models based on percentage-removal to process models incorporating the influence of process variables, including mechanistic models, underpinned by physical-chemical principles and empirical ('black-box') models, describing process behaviour with statistical models. The complete treatment process has thus been described by a series of mathematical models, each representing one treatment step. Combining the models for all treatment units enables prediction of the quality of drinking water after treatment given a certain raw water quality. The modelling of the drinking water treatment is conceptualised in Figure 1.

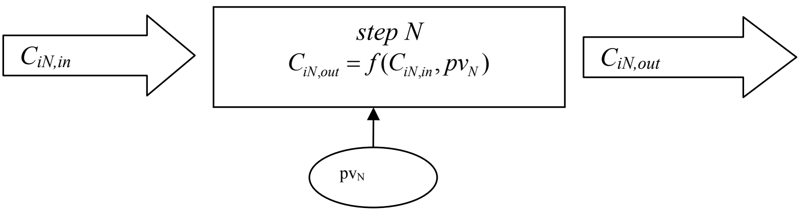

Figure 1. Conceptualised scheme of modelling the drinking water treatment process. The block arrows indicate the flow of water with contaminants to be removed in step N. $C_{iN, in}$ denotes the incoming amount of contaminant i at the start treatment by step N, while $C_{iN, out}$ denotes the residual amount of contaminant i after step N. The removal efficiency in each step is affected by process variables, symbolised by pv_N. The quantitative relation between output, input and process variables can be formalised by a formula $C_{iN,out} = f.(C_{iN,in}, pv_N)$

Design framework for a curriculum unit

As much as the designers attempt to draw upon existing theories for teaching and learning, when they adapt an authentic practice into a context for learning, the necessary strategies, pedagogic effects and argumentation may be lacking. The educational design process can be characterised as an iterative cyclic process reflected in the different curriculum representations, such as ideal, formal, perceived, operational, experiential and attained representations of a curriculum unit (Van den Akker, 1998). The design knowledge involved resides mainly in the formal representation of a curriculum unit, consisting of three products:

- A set of explicit learning aims and standards
- A design framework, that is a synthesis of design principles, phases in the teaching-learning process and instructional functions.
- A curriculum unit, consisting of (a sequence of) teaching-learning activities, study materials, teaching guidelines, etc.

A design framework provides heuristics for structuring teaching-learning processes. In a previous study (Prins, Bulte, & Pilot, Submitted-a) we developed a design framework using the practice 'Modelling drinking water treatment' as the context for learning. This was done by a design team consisting of six experienced chemistry teachers and three researchers (the authors of this paper). Below we first describe the design principles, and secondly the design framework. The curriculum unit itself is described in the Method section.

Inspired by McKenny, Nieveen, and Van den Akker (2006), we define design principles as theoretically and empirically grounded constructs linking strategy components, e.g., what to do, precisely how to do it, when in the sequence, with what tools and how enacted, the intended pedagogic effects (e.g. students see the point of modelling), and arguments (e.g. literature on educational research, empirical findings based on earlier applications of the curriculum unit(s) and/or practical (tacit) considerations of the designers). The heuristic value of a design principle is bound to a certain educational setting and restricted by a set of conditions, such as the science domain and the characteristics of the students. There are three design principles, which we have labelled *context*, *content modelling* and *chain of activities*. The three design principles are described below.

Design principle 'context'

The design principle of *context* deals with involving learners in a focal event embedded in its cultural setting (Gilbert, 2006). This implies the setting, the behavioural environment, the specific language and the extra-situational background knowledge, such that students become engaged in a modelling activity. In adapting an authentic practice, we need to account for significant differences between experts, who in general are well-informed in the field in which they are employed, and learners, who lack basic affinity and essential background information.

Strategy components

1 Provide students with a broad orientation base:
- occasional exceeding of legal set quality norms of drinking water
- adapted version of the authentic project plan concerning 'Modelling drinking water treatment'

2 Give students a specific role and task:
- role play as junior employees of the 'Institute for Public Health and the Environment'
- model the removal of turbidity by coagulation/flocculation

3 Select the essential situated knowledge and supply it to students by means of articles and/or manuals:
- article 'Coagulation/flocculation treatment'
- article 'Mechanisms of coagulation'
- manual 'Correlation & regression'

4 Visualise for students the example problem on which they are going to work:
- demonstrate treatment step of coagulation/flocculation

5 Organise students to ensure that they keep track of situated knowledge:
- construct a list of concepts

6 Select an end product, matching the example problem, to assess students' performance:
- write a factsheet 'Modelling turbidity removal'

… *expected to result in* ….

… *because of* …

Pedagogic effects

1 Students show familiarity with water treatment and legally imposed quality norms (***a***). Students are able to situate the authentic practice in its cultural setting, and are motivated to study the problems posed (***c***)

2 Students are willing to and show ownership of work on modelling turbidity removal by coagulation/flocculation (***d***)

3 Students take notice of and understand situated knowledge (***h***), such as colloids, coagulant, turbidity, charge neutralisation, sweep flocs and process variables

4 Students are able to materialise the situational (theoretical) knowledge from articles regarding coagulation/flocculation (***h***)

5 Students construct a list of concepts related to water treatment, specifically concerning coagulation/flocculation (***j***)

6 Students display the main findings and the learned conceptual and procedural knowledge (***j***)

Arguments

1 The design argued that the use of an adapted version of the authentic project plan as teaching material emphasises the societal relevance and evokes students' broad interest. In addition, it provides students with a view on the *what* (construct a mathematical model), *how* (modelling treatment process) and *why* (exceeding of quality norms). Later on in the teaching-learning process students are supposed to advise on a modelling approach for another (similar) problem based on their own experiences.

2 It is found that addressing students as junior employees with a whole task fosters active involvement and leads to division of labour inducing mutual dependency and discourse. The design team expected that the relatively high number of turbidity crossings would motivate students to focus specifically on turbidity removal by coagulation/flocculation.

3 The design team argued that the use of articles and/or manuals fosters a sense of authenticity and facilitates 'just in time' information delivery. In addition, it offers opportunities to select and communicate the essential situated knowledge in a compact and orderly way. It corresponds to the common way of information search by experts.

4 The design team argued that through visualisation the essentials of the example modelling problem would become apparent for students.

5 The design team was of the opinion that a list of concepts is a suitable tool to record situated conceptual knowledge to ensure mutual understanding. The construction of the list of concepts should be a recurring event in the teaching-learning process and an integral part of the end product.

6 The design team regarded a factsheet, summarising the main results and findings, as an appropriate end product to assess. Moreover, it suits the role of students as junior employees.

Figure 2. Conceptualised scheme of the design principle 'context'. The numbers connect strategy components with expected pedagogic effects and underlying arguments. The italic letters in the 'Pedagogic effects' box refer to the instructional functions in Figure 5.

In addition, the school environment is completely different from the environments in which experts work, in aims and cultural role and function in society. Figure 2 depicts the filling-in of the design principle of context.

Design principle 'content modelling'

Using authentic practices as contexts for learning, it is tempting to regard the experts' activities and applied knowledge as the intended learning outcomes for students.
However, 'what a (group of) expert(s) do' cannot be taken as representative of what is needed for employment in chemistry-based practices as a whole. There is likely to be a core of generic content which is common to all chemistry-based practices (Gott, Duggan, & Johnson, 1999). Using an authentic modelling practice as the context for learning models and modelling, students should focus on the applied generic modelling approach and epistemic values. The design principle of *content modelling* deals with focussing learners on the generic content regarding models and modelling. Figure 3 depicts the filling-in of the design principle of content modelling.

Strategy components

A Supply students with a worked-out analogous modelling problem as leading example:
- factsheet 'modelling trichloromethane removal by activated carbon filtration'

B Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand:
- perform experiments
- construct scatter plots
- analyse and typify correlations
- perform single and multiple regression

C Let students advise on a modelling procedure to apply to similar problem:
- advise on future research on modelling treatment step coagulation/flocculation

… expected to result in …

Pedagogic effects

A Students activate and enrich their prior knowledge base:
- mention epistemic values 'goodness of fit', 'reliability' and 'validity' (***e***)
- draw up a modelling procedure (***f***)

B Students show understanding of (***h***):
- accuracy of measurements
- global trends and correlations
- lines of best-fit through scatter plots
- single and multiple regression models
- epistemic values 'goodness of fit', 'reliability' and 'validity'

C Students evaluate and reflect on the epistemic values and formulate a generic modelling procedure for a similar problem (***k***)

… because of …

Arguments

A It is found that supplying students with an advanced organiser informs students' views on activities to conduct and (type of) knowledge to learn/apply. The design team argued that a worked out analogous modelling problem, originating from the authentic practice at hand, serves as an advanced organiser. It provides students with a view on epistemic values to take into account and the end product to deliver.

B It is found that emergent modelling, e.g., gradually formalising empirical data in mathematical models, is a suitable way to guide students through levels of abstraction. The design team argued that multiple regression should be preceded by single regression to reduce complexity and foster students' understanding.

C The design team argued that, through advising on a modelling procedure for a similar problem, students would be placed in a position to focus on the generic content regarding models and modelling, e.g., a modelling procedure and the epistemic values.

Figure 3. Conceptualised scheme of the design principle 'content modelling'. The capital letters connect strategy components with expected pedagogic effects and underlying arguments. The italic letters in 'Pedagogic effects' refer to the instructional functions in Figure 5.

Design principle 'chain of activities'

The design principle of *chain of activities* deals with constructing a sequence of teaching-learning activities such that learners constantly know *why what* to do at every step in the process. Experts have clear motives for performing modelling activities. These motives are inspired by the experts' background knowledge of the issues and their previous experiences with (similar) objects. In adapting an authentic practice into a context for learning, the challenge is to construct a sequence of teaching-learning activities such that students see *why what* to do at every point (Klaassen, 1995; Lijnse and Klaassen, 2004). The experts' chain of activities provides heuristic guidelines for sequencing teaching-learning activities (Prins, Bulte, Van Driel, & Pilot, 2009). In the second stage the chain of teaching and learning activities needs to be evaluated from the students' perspective according to the problem posing approach (Klaassen, 1995). Figure 4 depicts the filling-in of the design principle of chain of activities.

Strategy components

i Give students a clear assignment concerning the example problem to work on and formulate tasks that coincide with the main stages in the teaching-learning process

ii Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration:
- select relevant process variables
- conduct experiments under controlled circumstances
- analyse data by correlation & regression

iii Plan work meetings with students after each main stage in the teaching-learning process to look ahead on future activities:
- recall the assignment and record progress

iv Let students evaluate to what extent the example problem has been solved:
- summarise all findings and evaluate the constructed regression model

… expected to results in…

… because of …

Pedagogic effects

i Students have a motive to learn/apply knowledge to solve the example problem at hand (***g***)

ii Students are aware about *why what to do* at every point in the teaching-learning process. Students see the point of every teaching-learning activity in the sequence leading to an outcome (***h***)

iii Students have a broad outlook on the future modelling stages: each stage couples to the previous and prepares the next one (***h***)

iv Students have a motive to make explicit all findings to inform others (***i***)

Arguments

i The design team argued that prolonged engagement is established by providing students with a clear assignment. Moreover, receiving an assignment fits the students' role as junior employees.

ii It is found that the experts' modelling procedure complies with students' notions regarding solving the example problem. The design team decided to evaluate each modelling stage from students' perspective to construct an ongoing sequence of teaching-learning activities.

iii The design team argued that planning regular meetings after each main modelling stage keeps students 'on track'. Students record the tasks already accomplished and future tasks, while keeping the purpose of the modelling in mind.

iv The design team considered an explicit evaluation phase a suitable precursor for reporting all main results and findings. Students understand that all reported results and findings, as well as proposals for future work, need to be underpinned.

Figure 4. Conceptualised scheme of the design principle 'chain of activities'. The captions connect strategy components with expected pedagogic effects and underlying arguments. The italic letters in the 'Pedagogic effects' box refer to the instructional functions in Figure 5.

For the phases in the teaching-learning process and instructional functions, we used an 'instructional version of authentic practice'. This phasing emerged from research on the feasibility and effects of an 'authentic practice based curriculum unit' in the classroom (Bulte, Westbroek, De Jong, & Pilot, 2006), inspired by previous research on meaningful teaching-learning strategies (Kortland, 2001; Westbroek, 2005). The design framework consists of a synthesis of the 'instructional version of an authentic practice' with the three design principles. The design framework gives a compendious overview of the placement of the strategy components in the teaching-learning process. Although the design principles are formulated as separate entities, there is overlap at some points. Therefore, the functioning of each design principle has to be evaluated in light of the overall functioning of the curriculum unit. Figure 5 depicts the design framework. For the sake of clarity, we highlight only the strategy components, leaving out the expected pedagogic effects and underlying arguments.

Design Framework			
Learning phases / Instructional functions	***Design principles***		
	Context	***Chain of activities***	***Content modelling***
I: Orientate on the practice ***a)*** Connect to the prior conceptual knowledge base ***b)*** Connect to the prior procedural knowledge base ***c)*** Evoke motivation to study the problems posed in the practice ***d)*** Evoke a motive to zoom in on an example problem	**Strategy component 1:** Provide students with a broad orientation base **Strategy component 2:** Give students a specific role and task		
II: Zoom in on an example problem ***e)*** Make explicit and build on the prior conceptual knowledge base ***f)*** Make explicit and build on the prior procedural knowledge base ***g)*** Evoke a motive to solve the example problem		**Strategy component i:** Give students a clear assignment concerning the example problem to work on and formulate tasks that coincide with the main stages in the teaching-learning process	**Strategy component A:** Supply students with a worked-out analogous modelling problem as leading example
III: Solve the example problem ***h)*** Proceed through the sequence of activities and learn/apply knowledge until a satisfactory solution for the example problem can be presented	**Strategy component 3:** Select the essential situated knowledge and supply it to students by means of articles and/or manuals **Strategy component 4:** Visualise for students the example problem on which they are going to work **Strategy component 5:** Organise students to ensure that they keep track of situated knowledge	**Strategy component ii:** Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration **Strategy component iii:** Plan work meetings with students after each main stage in the teaching-learning process to look ahead on future activities	**Strategy component B:** Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand
IV: Evoke a motive to express the findings ***i)*** Induce a motive to express the learned conceptual and procedural knowledge used to solve the example problem		**Strategy component iv:** Let students evaluate to what extent the example problem has been solved	
V: Express and reflect on the findings ***j)*** Make explicit the learned conceptual and procedural knowledge ***k)*** Draw up a project plan for solving a similar problem posed in practice	**Strategy component 6:** Select an end product, matching the example problem to assess students' performance		**Strategy component C:** Let students advise on a modelling procedure to apply to similar problem

Figure 5. A design framework, a synthesis of design principles, learning phases and instructional functions, providing heuristics for structuring teaching-learning processes using authentic modelling practices as contexts for learning.

Scope and research questions

This research study is positioned within the broader perspective to develop and investigate context-based curriculum units in science education. The aim of this study is to evaluate the design framework providing heuristics for structuring teaching-learning processes. Doing so, this study contributes to a knowledge base for the use of authentic chemical modelling practices as contexts for learning. For this we enacted an authentic practice based curriculum unit in class (for students in grades 10 and 11, age 16–17 years). The central research questions addressed are:

1. *To what extent does the designed teaching-learning process, using an authentic practice as a context for learning in secondary chemistry education, lead to intended pedagogic effects and understanding of models and modelling?*
2. *What are the implications for the design framework?*

Method

In this section we describe the design research approach, the curriculum unit, the participants, data collection and analysis. Given the purpose of the study, the data collected are essentially qualitative.

Design research approach

Our design research approach (Lijnse, 1995) strongly resembles what Cobb, Confrey, DiSessa, Lehrer, and Schauble (2003) described as 'design experiments' conducted in the classroom. This approach implies the design of a teaching-learning process, accompanied by a set of argued expectations of how the process is expected to take place and why it should operate according to the expectations (Bulte et al., 2006). The design of a teaching-learning process initially is based on theoretical aspects and the valuations of the design team. Next, the designed teaching-learning process is enacted in several research cycles, focused on testing, reflecting and adjusting the process, in close cooperation with teachers. The teaching-learning process is tested in a small-scale case study, with a classroom and its teacher as the unit of analysis (Cobb, Stephan, McClain, & Gravemeijer, 2001).

The curriculum unit using an authentic practice as context for learning

In this section we describe the curriculum unit using the authentic practice 'Modelling drinking water treatment' as the context for learning.

Broad overview

In the curriculum unit, students first take notice of the quality norms of drinking water in the Netherlands and that these are occasionally exceeded. The quality of drinking water is an issue of which Dutch students are expected to have some knowledge. Students are familiar with the basics of the treatment process and the existence of quality parameters imposed by law. Next, students study the recommendations of experts on how to model the treatment process to be

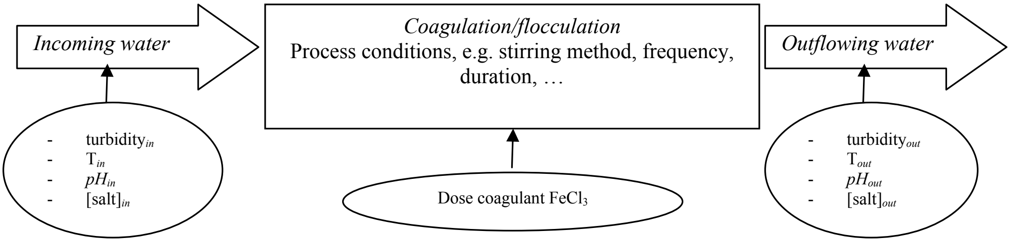

Figure 6. Conceptualised scheme of the modelling of the removal of turbidity by coagulation/flocculation. The block arrows indicate the flow of water. $Turbidity_{in}$ denotes the incoming turbidity, while $Turbidity_{out}$ denotes the residual turbidity. The removal efficiency is affected by various process variables, such as dose $FeCl_3$, acidity (*pH*), temperature and total salt concentration.

able to predict the quality of drinking water given a certain raw water quality and treatment process. Students identify the turbidity caused by suspended matter and colloids as one of the quality parameters occasionally exceeded. This motivates students to 'zoom in' on the treatment step of coagulation/flocculation, in which the particles causing turbidity are removed. Students start with a literature study on coagulation/flocculation. This literature study is accompanied by a practical demonstration in class. Next, students focus on chemical process variables affecting the efficiency of turbidity removal: starting turbidity, dose coagulant ($FeCl_3$), acidity (*pH*), temperature and the total salt concentration. The influence of each of these process variables is investigated by performing small-scale laboratory experiments in class (Prins, Wigmans, Bollen, Bulte, & Pilot, Submitted). Afterwards students perform a regression to find correlations between the end turbidity and the process variables. During this process, students are supposed to be able to reflect meaningfully on the purpose and advanced model features of goodness of fit, reliability and validity. The modelling of the removal of turbidity by coagulation/flocculation is conceptualised in Figure 6.

In the authentic practice, the experts have developed a multiple power regression model describing the correlation between end turbidity and process variables: $turbidity_{end} = const * turbidity_{start}^{A} * dose^{B} * pH^{C}$, in which *const* and exponentials *A*, *B* and *C* are empirically determined fit parameters (Rietveld, 1999). In class, students need not arrive at the same regression model. The gathered data during laboratory work determines which process variables are taken into account and which regression model fits the data. The applied modelling approach, in the authentic practice as well as in class, can be typified as empirical (or black box / data-driven) with the aim to describe correlations with mathematical formulas in order to predict process behaviour.

Table 1. Overview of the content and sequence of the teaching-learning activities (TLA) in learning phases I and II.

Phase	Designed teaching and learning activities (TLA)
I: Orientate on the practice	*Broad orientation on the quality of drinking water* **TLA 1:** Bringing up prior knowledge related to legally set quality norms for drinking water. Students read newspaper items reporting about occasional exceeding of the quality norms of drinking water.
	Broad orientation on drinking water treatment **TLA 2:** Students study an adapted version of an authentic project plan summarising the modelling approach proposed by experts to optimize the drinking water treatment process.
	Zoom in on turbidity removal by coagulation/flocculation **TLA 3:** Students notice that the quality parameter for turbidity has been exceeded. Turbidity is removed by treatment step coagulation/flocculation.
II: Zoom in on an example problem	*Give students role of junior employee and analyse assignment* **TLA 4:** Students are given the role of junior employee with the assignment to solve an example problem: model the removal of turbidity by coagulation/flocculation. Students analyse the assignment and start making a list of known and unknown concepts.
	Enrich the prior procedural (modelling) knowledge **TLA 5:** Students receive a factsheet summarising the modelling procedure and outcomes of an analogous problem: modelling trichloromethane removal by activated coal filtration. Students study the factsheet and extract the applied modelling procedure.

Content and sequence of the teaching-learning activities

In this section, we highlight the content and sequence of the teaching-learning activities (TLA) per learning phase.

The initial teaching-learning activities aim to engage students and induce a motive for modelling turbidity removal by coagulation/flocculation. Furthermore, a modelling procedure to apply should be evoked from students, although this will be in a rudimentary form, as well as the students' views on the (type of) knowledge to learn. In Table 1 the first two learning phases are described in terms of teaching-learning activities.

In phase III, students proceed with the modelling procedure (as roughly outlined by the students themselves in TLA 5) whilst extending the relevant knowledge and refining steps of the procedure. The sequence of teaching-learning activities should be meaningful from the students' perspective. That is, every teaching-learning activity should fit the students' views about 'what to do next'. Figure 7 depicts the sequence and content of the teaching-learning activities coupled by motives to proceed from one activity to the next (Lijnse and Klaassen, 2004).

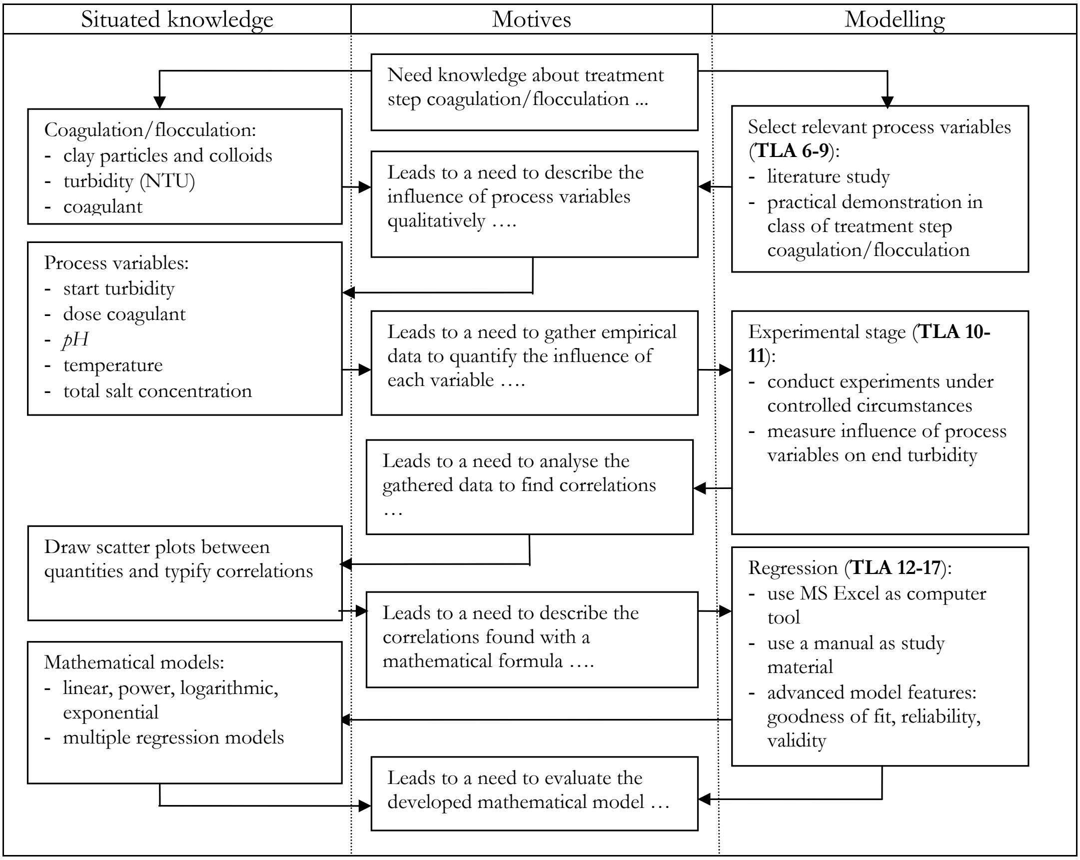

Figure 7. Overview of the sequence and content of the teaching-learning activities (TLA) in learning phase III. The arrows indicate the direction of the learning process.

In the first modelling stage, the relevant process variables are selected. After this, students study coagulation/flocculation by means of an article. This article describes the way the treatment is conducted in an industrial setting, the coagulants used and the relevant process variables. It also illuminates the difficulties of removing small clay particles and how to measure turbidity. In class, the teacher illustrates the acquired (theoretical) knowledge with a plenary demonstration of the clearance of turbid water by coagulation/flocculation. In the second modelling stage, students hypothesise about the influence of the identified process variables, and conduct experiments under controlled conditions according to laboratory prescripts (Prins, Wigmans et al., Submitted). In each series of experiments the influence of one of the chemical process variables is investigated, leaving the others unchanged. In the third modelling stage, students analyse the gathered dataset and perform a regression, facilitated by a manual as study material and Microsoft Excel software. The empirical data is plotted in scatter diagrams showing the end turbidity versus the investigated process variable. Students interpret the results and typify the correlations. Next, students conduct a regression. Students fit several mathematical models and reflect on their goodness of fit, reliability and validity. After each modelling stage students update their list of known and unknown content-related concepts, as started in TLA 4.
The fourth and fifth learning phases aim at reflection and making explicit the newly learned knowledge. Students write a factsheet on ‘modelling turbidity removal by coagulation/flocculation’. Finally students prepare a written advice on future research on coagulation/flocculation, in which the generic content regarding models and modelling becomes apparent. Table 2 gives an overview of the teaching-learning activities in the last two phases.

Application in classroom
The curriculum unit was put into practice at six different schools in the Netherlands. In two schools the designed teaching-learning process was tested in detail. Both of these schools can be characterised as rural schools with few students from ethnic minorities. In these two schools, 36 students in total participated, from grades 10 and 11, aged 16–17 years. The curriculum unit comprised eight lessons of 50 minutes, excluding time for private study. The students were grouped into nine teams of four persons. The teachers were well acquainted with the content and pedagogy of the curriculum unit, since they were involved in its design.

Data collection and analysis
The data collection and analysis is concentrated around the teaching-learning activities. The teaching-learning activities are the operational constructs of the strategy components in the design principles. The resulting pedagogic effects of the teaching-learning activities should comply with the intended pedagogic effects, as described in the design principles.

Table 2. Overview of the content and sequence of the teaching-learning activities (TLA) in phases IV and V.

Phase	Designed teaching and learning activities (TLA)
IV: Motivate students to express the findings	*Make an inventory off the main results* **TLA 18:** Students evaluate the developed multiple regression models on advanced model features goodness of fit, reliability and validity. In addition, they recall and evaluate the applied modelling procedure.
V: Express and reflect on the findings	*Report on the project by writing a factsheet* **TLA 19:** Student write a factsheet 'Modelling turbidity removal by coagulation/flocculation', summarizing the main findings, applied modelling procedure, conclusions and advice. *Generalise the applied modelling procedure* **TLA 20:** Students receive a task to outline a modelling procedure for future research on coagulation/flocculation.

The analysis consisted of three stages. In the first stage, preceding the actual data analysis, two researchers (first and second author of this paper) developed and agreed upon a frame of reference as a coding scheme. This frame of reference consisted of a set of expected students' notions per (cluster of) teaching-learning activity(ies). These students' notions are concrete completions of the intended pedagogic effects. In Appendix A the frame of reference is described.

In the second stage, the empirical data was analysed by both the researchers independently. The attained students' notions and attitudes were compared with those expected, as articulated in the frame of reference. If there was a high level of agreement, the corresponding strategic component was deemed to be fully accomplished. In case of medium or low agreement, the corresponding strategic component was deemed to be partially accomplished, or low accomplished, respectively. The level of accomplishment was determined by a two-step procedure. Firstly, for each student team, a strategy component was deemed fully achieved if at least 80% of the expected notions were realised (Miles and Huberman, 1994). If between 20 and 80%, partial, and if between 0 and 20%, low accomplishment was scored. Secondly, the results from all student teams on each strategy component were combined. A particular strategy component itself was deemed fully accomplished if at least 80% of all student teams produced results where at least 80% of the expected notions were realised. A strategy component was deemed low if it was partly accomplished or less in 80% of all student teams. In case of a score somewhere between these two extremes, the strategy component was judged partly accomplished. A rater-consistency check was conducted by calculating the intraclass correlation coefficient using a two-way mixed effects model (Shrout and Fleiss, 1979).

In the third stage, the findings and results were discussed by the whole research team to identify underlying considerations, to unravel students' perspectives and to reflect on the strategy components applied.

The collected data sources were audio-taped conversations of student teams at work, individual written questionnaires, written answers of student teams and field notes. In all cases, the audio-taped conversations of student teams at work and the individual questionnaires were used as primary sources. The other data were used to confirm the trends noticed. Below, we briefly describe each data source and specific analysis procedure.

Primary data sources

Audio-taped conversations of student teams at work

The conversations of the student teams at work during all eight lessons of the curriculum unit were audio-taped. Next, the conversations were transcribed *verbatim* and coded from an interpretative perspective (Smith, 1995) by both the researchers independently using the frame of reference to reveal students' notions.

Individual written questionnaires

Each student filled in a written questionnaire after each learning phase. The questionnaire contained two questions, as shown in Table 3. The major purpose of the written questionnaire was to check to what extent students experienced an ongoing line of teaching-learning activities. All the answers were collected and summarised by one researcher (first author). For the first question we used the 80% level as the determining criterion (Miles and Huberman, 1994). A (cluster of) teaching-learning activity(ies) was deemed high if valued highly by at least 80% of the students. On the contrary, if valued low by at least 80% of the students, the overall assessment of the activity was low. Between these extremes the assessment was medium.

Secondary data sources

Written answers of student teams

All written answers per teaching-learning activity were coded by two researchers (first and second author) independently using the frame of reference to reveal students' notions. The results were used to validate the findings from the audio-taped conversations.

Field notes

During the complete enactment of the curriculum unit in both schools field notes were made by one researcher (first author). The major purpose of the field notes was to check to what extent the strategy components embodied in the teaching-learning activities were enacted in class as intended.

Table 3. Questions in the written questionnaire for students

1.	Please judge (high – medium – low) each teaching-learning activity on the following aspects. - Instructiveness - Appreciation - Relevance
2.	Formulate the activities which should be done next to solve our modelling problem?

Results

In this section we describe the results of the practice of the curriculum unit in class. In answer to the first research question, we describe the overall functioning of the unit in class per learning phase, exemplified with empirical data. Next, in answer to the second research question, the realisation of the design principles is discussed with respect to the strategy components and corresponding pedagogic effects.

Learning phase I

The orientation on the quality norms of drinking water and occasional exceeding thereof proved to be a successful starting point (TLA 1). Most of the student teams were surprised that the quality of ground- and surface water varied across years and seasons. The students showed themselves to be familiar with drinking water treatment in a rudimentary sense, and with some quality norms of drinking water, such as clarity, taste and smell. When discussing possible measures to take to prevent exceeding of the norms, basically two options were brought to the fore: *prevent pollution of the raw water* and/or *improve the treatment processes*. However, the majority (7 out of 9) of the teams were of the opinion that the treatment process most probably was already '*at its best, since drinking water companies have implemented all their knowledge and experience*'. The approach proposed by experts (TLA 2) raised questions, such as '*Don't they already know everything about the treatment process?*' or '*What possibly can still be optimised?*' Students showed awareness of process variables, as typified by the class discussion below. The teacher invoked a discussion about process variables of the treatment step 'disinfection'.

T: .. so, there are a lot of process variables that influence the quality of water. As an example, think with me, which circumstances, which variables, do influence the process? You try to disinfect the water, that means you throw something in it that kills bacteria, that's what it basically is, and eventually the water does fulfil the quality norms. Which circumstances, related to the quality of water entering the treatment process or things you do with the water, affect the result?
S1: Yes, but there are no substances allowed that can't be removed by disinfection.
D: Could you mention an example?
S1: Yes. For instance, mud.
D: Yes, these kind of substances are removed in other steps. Now we are just looking at the step of

disinfection. What affects, after you did perform the disinfection and you received clean drinking water, which things affect the end results, affects the quality of drinking water, concerning the concentration of bacteria, regardless of the specific quality norms?
S2: Chlorine?
D: There is no chlorine in the water, is there?! Do you mean the chlorine you added?
S2: Yes.
D: All right. So, the amount of chlorine added. Well, that is one process variable with an obvious effect.
S3: The amount of ozone gas that you …
D: Ozone gas also, That is an alternative to chlorine. Ozone or chlorine to remove the bacteria. But, there is still one obvious process variable not mentioned so far.
S4: The amount of bacteria itself
D: Of course! The amount of bacteria itself. Now we have identified two process variables.

In TLA 3 the student teams identified turbidity removal by coagulation/flocculation as one of the 'problematic' parameters. However, it did not induce a specific content related motive to zoom in on turbidity removal by coagulation/flocculation. In addition, in TLA 3 it became clear that most of the student teams (6 out of 9) were unable to position coagulation/flocculation treatment in the complete trajectory of drinking water treatment.

Learning phase II

Learning phase II started by asking students to take on the role of junior employees of the Institute for Public Health and the Environment and supplying them with an assignment: modelling turbidity removal by coagulation/flocculation. As a means to begin the assignment, it was intended that student teams should start to construct a list of known and unknown concepts (TLA 4). However, in class it was apparent that the majority (8 out of 9) started to make such a list only after the literature study on coagulation/flocculation (TLA 6). Next, the teams studied a factsheet reporting a worked-out analogous problem, namely the modelling of the removal of trichloromethane by activated carbon filtration (TLA 5). This activity was expected to lead students to three pedagogic effects: (1) draw up a modelling procedure, (2) become acquainted with the end product to be judged, and (3) notice advanced features to evaluate the models. The observation in class revealed that the majority of the student teams (7 out of 9) indeed came up with a modelling procedure, as typified in Table 4.

The second pedagogic effect was also fulfilled to a large extent. Later on in the teaching-learning process, students explicitly used this leading example to organise and describe their own findings. The third pedagogic effect, however, was not realised. The majority of the teams (8 out of 9) did not record the advanced model features of goodness of fit, reliability and validity.

Table 4. The modelling procedure as expressed by student team 2 in teaching-learning activity 5.

Sequence of activities to perform		*Description*
1	*Explorative study*	*Search for ways to optimise coagulation / flocculation*
2	*Literature study*	*To understand the operation*
3	*Diagram*	*For visualising the problem*
4	*Process variables*	*Which variables could be influenced to optimise the process*
5	*Qualitative description of the influence*	*Investigate which factor have which effect*
6	*Experimental research*	*Conduct laboratory experiments*
7	*Measuring*	*Describe results in diagrams and tables*
8	*Regression analysis*	*Develop a mathematical model.*

At the end of phase II the majority (8 out of 9) of the teams were aware of 'optimalisation of coagulation/flocculation' to 'enhance turbidity removal' by means of 'modelling the influence of process variables'. This awareness provided a motive to understand more about turbidity and the operation of coagulation/flocculation, as typified by the written questionnaires (see Table 5).

Learning phase III

In the next steps, student teams proceeded with the problem of 'modelling turbidity removal by coagulation/flocculation'. The sequence consisted of 13 activities in total. In this section we will concentrate on the key activities: listing of all process variables and hypothesising their influence (TLA 7), the experimental investigation (TLA 10, 11), the selection of process variables that showed correlation with the end turbidity (TLA 13) and finally the regression analysis (TLA 14, 15).

Table 5: Extent of meaningfulness of the teaching-learning activities as valuated by the students, and their outlook on modelling activities to conduct.

Learning phase	Teaching-learning activities	Students' valuation			Students' outlook on activities to conduct to solve the example modelling problem after each learning phase
		Instructiveness	*Appreciation*	*Relevance*	
I: Orientate on the practice	1	Low	Medium	High	- Study the coagulation/flocculation process in detail
	2	Low	Medium	High	- Perform experiments to improve the treatment process
	3	Medium	Medium	Medium	- Think about measurements to take to foster the efficiency
II: zoom in on an example problem	4, 8, 14, 17	Medium	Medium	Medium	- Determine the dose coagulant under different circumstances - Investigate the influence of process variables
	5	High	High	High	- Find out the optimal values for each process variable
III: solve the example problem	6, 7, 9	High	High	High	- Find out how coagulation/flocculation works and what causes turbidity
	10, 11	High	High	high	- Conduct experiments to measure the influence of the process variables
	12, 13, 15, 16	Medium	Medium	Medium	- Combine the results and perform regression
IV: motivate students to express the findings	18	High	High	High	- Evaluate the model - Calculate the optimal process conditions for coagulation/flocculation
V: express and reflect on the findings	19	Medium	High	High	- Report the findings - Write a factsheet
	20	Low	Low	Low	

The practical demonstration of coagulation/flocculation in class proved successful in focussing students' attention on modelling the influence of process variables. During the class discussion on the process variables (TLA 7), it became apparent that three process variables were easily understood by the students. The starting turbidity of the water and the dose coagulant were obvious and needed no further explanation. Also the temperature was easily taken, probably because, in the students' view the temperature affects all processes. However, the process variables acidity (*pH*) and total salt concentration caused difficulties, as exemplified by the following class discussion.

D: The next one, that is the total salt concentration. Can anyone explain the influence to me?
Some S: Positive influence.
D: Also positive. Ah, you do not agree?
Minority S: Negative.
D: Please explain to me why a positive influence is expected?
S9: Well, it has got something to do with the charge. Eh …

To really understand the influence of process variables acidity (*pH*) and total salt concentration, one needs to study theories describing interactions between charged particles. However, in class the teachers did not pay explicit attention to the theory of coagulation mechanisms, although an article on 'Mechanisms of coagulation' was available in the teaching materials. The teachers valued the coagulation chemistry too abstract and complex for students of grade 10-11 to understand, and thus introduced all five chemical process variables without further explanation. Due to this lack of understanding, the empirical investigation of the influence of the acidity (*pH*) and total salt concentration was not perceived as meaningful by the majority of the teams (7 out of 9) (TLA 10, 11). During the laboratory work the students just accepted that these variables do affect coagulation/flocculation, as typified below.

S25: But, why do we investigate the pH of the water?
D: Because it affects the final turbidity. It is one of the process variables.
S25: But I don't see why. We just need to find the amount of coagulant needed to clear the water, isn't it?
D: Of course, but the pH is also influencing the final result, and it is necessary to determine this.
S25: Explain to me in what way the pH affects the final turbidity.
D: Well, you know about the colloid particles being negatively charged?
S25: Yes.
D: And the working compound is the positively charged ferric ion?
S25: Yes.

D: Well, suppose the media is very acidic. What would happen with the total negative charge of the colloid particles? Think about that. On the contrary, suppose the water has high alkalinity. What would happen?

The empirical investigation of process variables of starting turbidity, dose coagulant and temperature proceeded according to expectations. After the empirical data was collected, the students made scatter plots with the aim of selecting those process variables that show correlation with the end turbidity. During the class discussion about 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. The dominant explanation for process variables not showing any correlation was that errors occurred during the laboratory work, instead of concluding that the influence of these process variables might be negligible in the range tested.

In the subsequent activities, the teams performed a regression to find suitable mathematical models describing the observed correlations (TLA 14, 15). Firstly, every process variable showing correlation was analysed separately. Secondly, a multiple regression was applied. These teaching-learning activities were accompanied by short lectures on regression. The regression was presented as a tool, no explicit attention was paid to the underlying mathematical theories and considerations. Starting from the scatter plots, the majority of the student teams (7 out of 9) intuitively felt the need to find the best fitting line and formula. Goodness of fit as the deciding criterion was easily accepted. The multiple regression was considered a hard calculation, but manageable. It became apparent that the large majority (7 out of 9) of the teams understood the general idea behind the multiple regression method – to develop one mathematical model accounting for the influence of several process variables.

Learning phase IV

Students applied the goodness of fit criterion to evaluate the resulting multiple regression model (TLA 18). The majority (8 out of 9 teams) showed themselves to have acquired an understanding of the reliability of the developed model, as typified by statements in their factsheet, such as from student team 2:

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

As mentioned above, goodness of fit was used extensively as the deciding criterion. However, students did not show understanding of the significance of the goodness of fit criterion related to the number of measurements. The validity was mentioned and described only by a minority (2 out of 9) of the student teams. One student team (student team 5) deleted suspicious measurements to obtain a better goodness of fit.

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 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.*

Besides, 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 leave out all measurements falling outside the major trend.

In addition, the student teams extrapolated the results outside the range without any hesitation, an indication that most of the teams were not aware of the limited validity of the regression models. Finally, in phase IV no motivation was observed among most of the student teams (8 out of 9) to make explicit the findings in a factsheet. At this point, it became apparent that pretending the students were junior employees did not result in motivation for students to communicate their findings to the community.

Learning phase V

In the final two teaching-learning activities, students made their findings explicit. Firstly, students got the assignment to write a factsheet on 'modelling the removal of turbidity by coagulation/flocculation', comprising all the activities conducted and results (TLA 19). Secondly, students recommended a modelling procedure for future research on optimising coagulation/flocculation. In this activity a generic modelling procedure should become explicit (TLA 20).

The factsheets prepared (9 in total) were of good quality. Students recalled the example factsheet 'modelling 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 sedimentation and mentioned the process variables identified and their hypothetical influence. While describing the purpose of the modelling, it became apparent that the majority of the teams (6 out of 9) thought of 'optimalisation' as the primary aim, contrary to 'describing the relation between process variables'. In our opinion, this exemplifies the difference between a practical and theoretical orientation.

Table 6. An overview of the extent of realisation (full, partial or low) per design principle and strategy component, and major considerations concerning the functioning.

Design principles	Strategy components	# of students teams: Full	Partial	Low	Major considerations
CONTEXT	1 Provide students with a broad orientation base	5	2	2	- Include an orientation on the complete trajectory of treatment of ground- and surface waters.
CONTEXT	2 Give students a specific role and task	1	5	3	- Role play as junior employees did not induce prolonged engagement or sense of ownership as intended, or a motivation to communicate the findings to the community (writing a factsheet).
CONTEXT	3 Select the essential situated knowledge and supply it to students by means of articles and/or manuals	7	1	1	- Pay attention to the coagulation mechanisms when planning to investigate empirically the influence of acidity (pH) and total salt concentration.
CONTEXT	4 Visualise for students the example problem on which they are going to work	9	-	-	- Visualisation greatly fosters students' view on the modelling problem and induces a modelling procedure. Conceptualise the exemplary problem as an input-output system. Incorporate this strategy in design principle content modelling.
CONTEXT	5 Organise students to ensure that they keep track of situated knowledge	4	3	2	- Fosters students' understanding of key concepts. Introduce in teaching-learning process when needed.
CONTEXT	6 Select an end product, matching the example problem, to assess students' performance	9	-	-	- Students easily adopt the factsheet, it fits the example problem/ assignment. It proves an adequate tool for assessment.
CONTENT MODELLING	A Supply students with a worked-out analogous modelling problem as leading example	8	1	-	- Brings into focus among students the (type of) knowledge to learn, the modelling procedure and epistemic values to evaluate the models.
CONTENT MODELLING	B Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand	8	1	1	- Consider paying more attention to the mathematics underlying regression. Focus on linear and power models only in order to smoothen the learning path from single to multiple regression.
CONTENT MODELLING	C Let students advise on a modelling procedure to apply for a similar problem	-	2	7	- Advice on a similar modelling problem does not evoke reflection on the modelling procedure and approach. Consider applying the model in a real-world setting.

CHAIN OF ACTIVITIES	i Give students a clear assignment concerning the example problem to work on and formulate tasks that coincide with the main stages in the teaching-learning process	8	1	-	- Explicitly pay attention to the end product to be delivered by students. The explicit formulation of sub tasks might be left out. It does not add to a proper orientation base.
	ii Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration	8	1	-	- Students' experienced an ongoing line of teaching-learning activities. There was consistency in the sequence of teaching-learning activities.
	iii Plan work meetings with students after each main stage in the teaching-learning process to look ahead to future activities	2	4	3	- By recalling the assignment during the work meeting, students constantly have the purpose of the modelling in mind.
	iv Let students evaluate to what extent the example problem has been solved	1	2	6	- Does not motivate students to make the findings explicit. Reconsider the placement of the instructional functions regarding evaluation and reflection in the teaching-learning process.

As for the planned reflection on the modelling procedure (TLA 20), it appeared that the majority of the teams (6 out of 9) had many difficulties in setting up a generic modelling procedure for future research on coagulation/flocculation. Students could list some conceptual stages, such as ‘identify process variables’, ‘laboratory work’ and ‘regression’, but were not able to provide these stages with relevant content. In addition, no reflection on the modelling approach was notified. In general, students saw little value in reflection.

Perceived meaningfulness of the chain of teaching-learning activities

After each learning phase, each student filled in a questionnaire in which they evaluated the teaching-learning activities conducted on the aspects of instructiveness, appreciation and relevance, and presented an outlook on the activities to conduct to solve the exemplary modelling problem. The findings show that the majority of the students constantly have sight on *why what* to do during all stages in the teaching-learning process. The results are presented in Table 5.

Realisation of the design principles

All the results of the enactment of the curriculum unit in class were discussed by the research team to identify underlying considerations and unravel students’ perspectives, in order to reflect on the strategy components applied. The judgement showed a substantial consistency between the raters, reflected in the intraclass correlation coefficient of 0.75. In Table 6 all results on the extent of realisation of the design principles are summarised. In addition, major considerations per strategy component are presented.

Implications for the design framework

The acquired findings were used to evaluate the design framework underlying the curriculum unit. Below, we reflect first on the functioning of the design principles of *context*, *content modelling* and *chain of activities*. Next, we turn to the design framework.

Design principle ‘context’

As became clear, most of the students were familiar with the basics of water treatment, such as the techniques applied. However, they were not familiar with the specific treatment step of coagulation/flocculation, or the position it takes in the complete treatment trajectory. This might be overcome by adding to the orientation base the task to outline the treatment process for both ground- and surface water.

No significant effect was measured as a result of addressing the students as junior employees, nor does it motivate students to communicate their findings to the community by writing a factsheet. In retrospect, it is sufficient to give students a whole risk task, e.g., a recognisable example problem posed in the authentic practice in line with students’ abilities. Next, students should be provided with a view on *why*, *how* and *what* to do in response to the problem, in order to establish a proper engagement.

The situated knowledge was delivered to students through adapted articles and/or manuals. In general, this strategy component proved to function well. The regression procedure ran smoothly in class. No hindering effects were observed, for instance, due to lack of mathematical background knowledge. However, regarding the present curriculum unit, a change is needed in the way the process variables are introduced and identified. The process variables of dose coagulant, starting turbidity and temperature were accepted by students unquestioningly. For modelling these process variables, no in-depth knowledge on coagulation mechanisms is needed. However, the process variables acidity (*pH*) and total salt concentration were not easily distinguished. To identify the latter two, a thorough understanding of coagulation mechanisms is needed at a molecular level. The ferric cat ion precipitates easily with the hydroxyl ion. So, the dominant coagulation mechanism, either charge neutralisation or sweep (precipitation) coagulation, depends heavily on the actual acidity (*pH*) of the water. The more salt water contains, the more effectively the negative charge of the particles is shielded, and the more easily the particles aggregate. In retrospect, we see two alternatives:

1) Only take into account three process variables, namely starting turbidity, dose coagulant and temperature, or
2) Take into account all five process variables, and consequently pay explicit attention to coagulation mechanisms.

The practical demonstration of coagulation/flocculation was intended to illustrate the theoretical information about coagulation/flocculation from the literature. However, the data showed that the practical demonstration of coagulation/flocculation treatment in class resulted in a number of desirable pedagogic effects. The demonstration concretised the problem thus providing students with a valuable problem orientation. Students became focused on 'the influence of process variables' and were triggered to think of a modelling procedure to quantify the influence. Hence, to strengthen students' engagement and focus on modelling right from the start, it seems advisable to incorporate the practical demonstration as a separate strategy component in learning phase I and in the design principle of *content modelling*. In addition, next to the visualisation, it seems advisable to conceptualise the example problem as a generic 'input-output' system, as shown in Figure 1. By doing so, students might grasp the broader applicability of the modelling procedure for input-output systems.

As for the list of concepts, in retrospect this list of concepts becomes useful later on in the learning process, thus favouring a postponed introduction. The factsheet, finally, proved a adequate tool for students to make explicit their findings. It suits the example problem. Summarising all implications, we come to an altered filling-in of the design principle of context, as depicted in Figure 8.

Strategy components

1 Provide students with a broad orientation base:
- **outline the treatment of surface water**
- occasional exceeding of legal set quality norms of drinking water
- adapted version of the authentic project plan concerning 'Modelling drinking water treatment'

2 **Give students a rich, whole task**:
- model the removal of turbidity by coagulation/flocculation

3 Select the essential situated knowledge and supply it to students by means of articles and/or manuals:
- article 'Coagulation/flocculation treatment'
- article 'Mechanisms of coagulation'
- manual 'Correlation & regression'

4 Organise students to ensure that they keep track of situated knowledge:
- construct a list of concepts

5 Select an end product, matching the example problem, to assess students' performance:
- write a factsheet 'Modelling turbidity removal'

… expected to result in …

… because of …

Pedagogic effects

1 Students show familiarity with water treatment and legally-imposed quality norms (***a***). Students are able to situate the authentic practice in its cultural setting, and are motivated to study the problems posed (***c***)

2 Students are willing to and show ownership of work on modelling turbidity removal by coagulation/flocculation (***d***)

3 Students take notice of and understand situated knowledge (***h***), such as colloids, coagulant, turbidity, charge neutralisation, sweep flocs and process variables

4 Students construct a list of concepts related to water treatment, specifically concerning coagulation/flocculation (***j***)

5 Students write a factsheet displaying the main findings and the learned conceptual and procedural knowledge (***j***)

Arguments

1 Previous applications of the curriculum unit have proved that the use of an adapted version of the authentic project plan as teaching material emphasises the societal relevance and evokes students' broad interest. In addition, it provides students with a view on the *what* (construct a mathematical model), *how* (modelling treatment process) and *why* (exceeding of quality norms). **The design team argued that it is important to provide students with a broad overview of the subject dealt with in order to position the example problem.**

2 It is found that providing students with a rich, whole task fosters active involvement and leads to division of labour inducing mutual dependency and discourse.

3 Previous applications of the curriculum unit showed that the use of articles and/or manuals fosters students' sense of authenticity and facilitates 'just in time' information delivery. In addition, it offers opportunities to select and communicate the essential situated knowledge in a compact and orderly way. It corresponds to the common method of information search by experts.

4 Previous applications of the curriculum unit proved that a list of concepts is a suitable tool to record situated conceptual knowledge to ensure mutual understanding. The construction of the list of concepts should be a recurring event in the teaching-learning process and an integral part of the end product.

5 Previous applications of the curriculum unit revealed that a factsheet, summarising the main results and findings, is an appropriate end product to assess.

Figure 8. Altered conceptualised scheme of the design principle 'context'. The numbers connect strategy components with expected pedagogic effects and underlying arguments. Alterations of the previous filling-in (see Figure 2) are shown in bold. The italic letters in 'Pedagogic effects' refer to the instructional functions in Figure 11.

Design principle 'content modelling'
Study of the worked-out analogous problem resulted in the identification of the major modelling activities to conduct. In addition, it gave students a view of the end product they were to deliver. In our opinion, the factsheet functioned well as an advanced organiser (Ausubel, 1968).

As for the evaluation of advanced model features, no explicit reference was made in phases IV and V to the initial reason for modelling turbidity removal, e.g., the occasional exceeding of the quality parameter for turbidity. Therefore, we propose that the model evaluation might be enriched if students are given the task of using their own developed model to calculate the dose coagulant needed to produce clear water, and to evaluate the model outcomes. Another distinct feature was that no explicit reflection was made upon the modelling approach and procedure followed. The present strategy applied – letting the students advise on future research related to coagulation/flocculation – did not evoke reflection on the generic content related to modelling. To induce reflection, we need to reconsider this strategy. We propose two major changes, one on the level of design principles, and one on the level of the phasing of the learning process/ instructional functions.

On the level of design principles, more attention has to be paid to a proper problem analysis at a conceptual level in the beginning of the teaching-learning process. All treatment steps can be conceptualised as input-output systems, as depicted in Figure 1. It should be clear to students that the modelling of turbidity removal is *only* an exemplar for input-output systems in general. The conceptualised representation of the modelling problem needs to be recalled in learning phase IV to induce reflection. In this respect, we see two routes:

1. Let students draw up a plan of action for other input-output systems, or
2. Let students compare the modelling approach they followed with other approaches, such as the more solid mechanistic approach.

As for the first route, during enactment in class it became apparent that students were not motivated to outline a plan of action for a future research project, likely because students know that such a plan will not be carried out by themselves. Hence, the second route might be more promising. Process models for input-output systems can roughly be divided into mechanistic and empirical (or 'black box') models. Mechanistic models strive to understand and mathematically describe the mechanisms behind the processes occurring in a given system. A mathematical model is a systematic attempt to translate conceptual understanding of a real-world system into mathematical terms. Empirical (or 'black box') models are simpler and often obtained by fitting mathematical equations to a set of experimental data. This approach is used when the process under examination is very complex and/or not well understood. In addition, empirical models are much easier to develop than mechanistic models in terms of time and money. If you are only interested in the way the system reacts to external changes, empirical models are as useful as mechanistic models. Thus, we propose a new strategy component for the design principle *content* *modelling*: students compare different modelling approaches and point out some pros and cons of their own approach.

On the level of phasing of the learning process/instructional functions, reflection should be induced earlier in the teaching-learning process. At present, reflection is induced in the learning phase V (the final teaching-learning activities).

Strategy components

A **Visualise and conceptualise for students the example problem on which they are going to work**:
- demonstrate treatment step coagulation/flocculation
- **conceptualise the modelling problem as an input-output system**

B Supply students with a worked-out analogous modelling problem as leading example:
- factsheet 'modelling trichloromethane removal by activated carbon filtration'

C Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand:
- perform experiments
- construct scatter plots
- analyse and typify correlations
- perform single and multiple regression

D Let students apply the constructed model in a real-world setting:
- **calculate the dose of coagulant needed to produce clear water**

E Let students compare different modelling approaches:
- **compare the black-box modelling approach with the mechanistic approach**

… expected to result in …

… because of …

Pedagogic effects

A Students formulate the purpose of the modelling and activate their prior procedural knowledge base (*b*)

B Students activate and enrich their prior conceptual and procedural knowledge base:
- mention epistemic values 'goodness of fit', 'reliability' and 'validity' (***e***)
- draw up a modelling procedure (***f***)

C Students show understanding of (***h***):
- accuracy of measurements
- global trends and correlations
- lines of best fit through scatter plots
- single and multiple regression models
- epistemic values 'goodness of fit', 'reliability' and 'validity'

D Students recall and evaluate (*i*):
- **purpose of the regression model**
- **model outcomes in terms of goodness of fit, reliability and validity**

E Students reflect on the epistemology of models and modelling (*j*)

Arguments

A Previous applications of the curriculum unit have proved that **visualisation of the modelling problem evokes students' notions concerning a modelling procedure. By conceptualising the modelling problem, students grasp the broader applicability of the modelling procedure to be learned.**

B It is found that supplying students with an advanced organiser informs students' views on the activities to conduct and (type of) knowledge to learn/apply. Previous applications of the curriculum unit have revealed that a worked-out analogous modelling problem, originating from the authentic practice at hand, serves as a suitable organiser. It provides students with a view on epistemic values to take into account and the end product they are to deliver.

C It is found that emergent modelling, e.g. gradually formalising empirical data in mathematical models, is a suitable way to guide students through levels of abstraction. Previous enactments of the curriculum unit have revealed that multiple regression should be preceded by single regression to reduce complexity and foster students' understanding.

D Previous applications of the curriculum unit have shown that it is necessary to guide students back to the purpose of the modelling. The epistemic values of purpose, goodness of fit, reliability and validity become meaningful to students when evaluating the model outcomes in a real-world setting.

E Previous applications of the curriculum unit have proved that comparing the empirical (black-box) modelling approach with the mechanistic one induces reflection on the pros and cons. Students become aware that multiple modelling approaches exist with different epistemologies. Moreover, students make explicit an empirical (black-box) modelling approach for input-output systems in general.

Figure 9. Altered conceptualised scheme of the design principle 'content modelling'. The capital letters connect strategy components with expected pedagogic effects and underlying arguments. Alterations of the previous filling-in (see Figure 3) are depicted in bold. The italic letters in 'Pedagogic effects' refer to the instructional functions in Figure 11.

In classroom practice, however, this valuable activity is often left out, because of shortage in time, students not being motivated, a teacher not seeing the benefits, etc. In addition, the specific outcome(s) of reflection are often not well articulated by the designer, thus hindering enactment of reflection in class. Therefore, we propose to plan the reflection before the explicating phase. This means that the instructional functions of learning phases IV and V are switched and slightly altered. The focus of learning phase IV will become evaluation and reflection, while the major function of learning phase V is to make explicit the findings. Summarising all the implications, we come to an altered filling-in of the design principle of *content modelling*, as depicted in Figure 9.

Design principle 'chain of activities'

The data showed that students, in general, experienced the sequence of teaching-learning activities as meaningful. The modelling procedure indeed complies to a large extent with students' commonsense about modelling procedure. However, as noted above, the instructional function of learning phase IV was not fulfilled in sufficient extent. No explicit motivation to describe the findings in a factsheet was noticed. In retrospect, we argue that this might be overcome by explicitly announcing the end product in the original assignment, in combination with regular class meetings in which the assignment is recalled. Summarising all the implications, we come to a slightly altered filling-in of the design principle of *chain of activities*, as depicted in Figure 10.

Strategy components

i Give students a clear assignment concerning the example problem they are to work on and **direct their attention to the end product they are to deliver**

ii Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration:
- select relevant process variables
- conduct experiments under controlled circumstances
- analyse data by correlation & regression

iii **Plan regular meetings with students to look ahead on future activities**:
- recall the assignment and record progress

… *expected to results in…*

… *because of* …

Pedagogic effects

i Students have a motive to learn/apply knowledge to solve the example problem at hand (***g***). **Students adopt the factsheet as means to report the results and findings** (***k***)

ii Students are aware about *why what to do* at every point in the teaching-learning process. Students see the point of every teaching-learning activity in the sequence leading to an outcome (***h***)

iii **Students constantly have the purpose in mind and record 'how far we have come' and 'what still needs to be done'** (***h***)

Arguments

i Previous applications of the curriculum unit showed that prolonged engagement is established by providing students with a clear assignment.

ii It is found that the experts' modelling procedure complies with students' notions regarding solving the example problem. Earlier applications of the curriculum unit showed that in order to construct an ongoing sequence of teaching-learning activities each modelling stage needs to be evaluated from students' perspective.

iii Previous applications of the curriculum unit revealed that regular meetings keep students 'on track'. Students record the tasks already accomplished and future tasks, while keeping the purpose of the modelling in mind.

Figure 10. Altered conceptualised scheme of the design principle 'chain of activities'. The roman numerals connect strategy components with expected pedagogic effects and underlying arguments. Alterations of the previous filling-in (see Figure 4) are depicted in bold. The italic letters in 'Pedagogic effects' refer to the instructional functions in Figure 11.

Altered design framework

The results acquired give rise to alterations in the design framework underlying the curriculum unit. The alterations concern mainly the design principle of *content modelling* and the instructional functions of learning phases IV and V. Figure 11 depicts the altered design framework. For the sake of clarity, we highlight only the strategy components of the design principles.

Design Framework			
Learning phases / Instructional functions	*Design principles*		
	Context	*Chain of activities*	*Content modelling*
I: Orientate on the practice ***a)*** Connect to the prior conceptual knowledge base ***b)*** Connect to the prior procedural knowledge base ***c)*** Evoke motivation to study the problems posed in the practice ***d)*** Evoke a motive to zoom in on an example problem	**Strategy component 1:** Provide students with a broad orientation base **Strategy component 2:** Give students a rich, whole task		**Strategy component A:** Visualise **and conceptualise** for students the example problem on which they are going work
II: Zoom in on an example problem ***e)*** Make explicit and build on the prior conceptual knowledge base ***f)*** Make explicit and build on the prior procedural knowledge base ***g)*** Evoke a motive to solve the example problem		**Strategy component i:** Give students a clear assignment concerning the example problem they are to work on **direct their attention to the end product they are to deliver**	**Strategy component B:** Supply students with a worked-out analogous modelling problem as leading example
III: Solve the example problem ***h)*** Proceed through the sequence of activities and learn/apply knowledge until a satisfactory solution for the example problem can be presented	**Strategy component 3:** Select the essential situated knowledge and supply it to students by means of articles and/or manuals **Strategy component 4:** Organise students to ensure that they keep track of situated knowledge	**Strategy component ii:** Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration **Strategy component iii: Plan regular meetings with students to look ahead to future activities**	**Strategy component C:** Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand
IV: Evaluate and reflect on the findings ***i)*** **Evaluate the learned conceptual and procedural knowledge** ***j)*** **Reflect on the procedural knowledge**			**Strategy component D: Let students apply the constructed model in a real-world setting** **Strategy component E: Let students compare different modelling approaches**
V: Express the findings ***k)*** **Make explicit the learned conceptual and procedural knowledge**	**Strategy component 5:** Select an end product, matching the example problem, to assess students' performance		

Figure 11. Altered design framework, a synthesis of design principles, learning phases and instructional functions, providing heuristics for structuring teaching-learning processes using authentic modelling practices as contexts for learning. Alterations of the previous filling-in (see Figure 5) are depicted in bold.

Conclusion and discussion

This study has sought to describe a knowledge base for the use of authentic practices as contexts for learning in upper secondary chemistry education, such that students learn about models and modelling. More specifically, it provides insight into the strategies and rationales underlying the design of a teaching-learning process. In general, the results suggest that authentic practices are valuable sources of inspiration for use in chemistry education. However, the findings also reveal that the adaptation of an authentic practice is a challenging task. The focus, content and sequence of teaching-learning activities needs to be adjusted and justified from students' perspective. In the following, we note some reflections and points of interest not mentioned so far. We end this section by mentioning some limitations of this study and offer an outlook to future research.

Reflections on the design framework

In the current study we focussed on the functioning of the structure of the teaching-learning process, and used the findings to evaluate the design framework. In general, the designed structure of the teaching-learning process functioned well. However, inducing motives for reflection among students on the applied modelling approach and procedure turned out to be difficult. Therefore, we suggested revisions concerning (1) the instructional functions regarding evaluation and reflection in learning phase IV and (2) the design principle *content modelling*. The adjusted design framework is depicted in Figure 11. Future research is needed to test the proposed adjustments.

The design framework offers a valuable contribution to a knowledge base about designing context-based curricula. At present, we lack instructive design theories to inform practitioners and other educational designers. We agree with the 'design research collective' that there is a need for sharable theories that help to communicate relevant implications to educational designers (Cobb et al., 2003). Educational designers often face uncertainty about 'what to do' or when to apply a strategy, or both. The way in which the knowledge base related to educational design can be described and exported to others is still under debate. In the current study we used a design framework, a synthesis of learning phases, instructional functions and design principles. The proposed method enables the systematic evaluation of learning phases and accompanying design principles at the detailed level of the classroom. In our opinion, this enables gradual progression in understanding and explaining of the effects of teaching-learning processes in class. We also recommend that other methods are described and evaluated, in order to arrive at standards to improve mutual communication and understanding within the research community.

Limitations of the design framework

The usability of the design framework for structuring other teaching-learning processes is subject to some restrictions:

- It is only valid for using an authentic practice as the context for learning. The authentic practice to be adapted should be carefully selected.
- It holds only for the domain of models and modelling. Further research is needed to evaluate the applicability across other chemistry (science) domains.
- It suits pre-academic chemistry education; students in grades 10 and 11 (aged 16–17 years), high school chemistry (upper secondary level).
- For its application, the teachers should be well involved in the domain-specific pedagogy of authentic practice based curriculum units. Teachers need to be competent to apply the strategy components in the classroom with sufficient quality.

In addition, the design framework has only been tested in detail in two schools, with 36 students in total. More practical experiences are needed to confirm the results.

Reflections on using authentic practices as contexts for learning

In this study we investigated the use of authentic chemistry modelling practices as contexts for learning such that students develop a coherent understanding of the purpose and functioning of models and modelling in science. In the final teaching-learning activities students showed themselves to be able to evaluate the constructed regression models on the advanced features of goodness of fit and reliability. Moreover, students showed awareness of the empirical foundation of the developed model, and gained a sense of statistical thinking, taken as struggling with variations in everything that is measured about phenomena, processes or objects. The data thus strengthens the hypothesis that the current teaching-learning approach benefits students' learning of models and modelling.

Traditionally, school science emphasises (unintentionally) to students a straightforward route to discovering new things, leaving out the difficulties and failures inherent in conducting research. We believe that students should experience for themselves how science depends (heavily) on valuations of the researcher and includes making choices and struggling with numerous questions and uncertainties. The current approach enables students to gain some insight into socio-scientific values related to authentic practices, for instance, the awareness that not all contaminants can be removed completely, thus leading to balancing public health risks, and that at some point the economics related to treatment processes become important. So, apart from acquiring understanding of models and modelling as such, this approach offers other valuable potentials to science education.

Outlook and future work

In the current study we concentrated on the overall functioning of the design framework, with emphasis on the three design principles. Next, we will focus on the functioning of the adjusted design principle 'content modelling' to elaborate the specific learning outcomes related to models and modelling (Prins, Bulte, & Pilot, Submitted-b). Many studies have been conducted on students' understanding of models and modelling. In general they call for greater emphasis on the role and purpose of models in science, and the way models are constructed, similar to the way models are employed in an authentic setting. The results obtained in this study so far have confirmed these outcomes. However, the challenge lies in designing teaching-learning trajectories with sufficient quality, thus urging for more design based research to find ways to reach these ambitious goals.

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Appendix A. Frame of reference

The frame of reference describes the expected students' notions per strategy component. The strategy components are operationalised in teaching-learning activities, which are used as data sources. The students' notions are concretised completions of the intended pedagogic effects per strategy component.

Design principle 'context'

Strategy component	*Data Sources - teaching-learning activity (TLA)*	*Students' notions (e.g. concepts to learn, activities to conduct, display specific attitudes/affective aspects)*
1 Provide students with a broad orientation base: - occasional exceeding of legal set quality norms of drinking water - adapted version of the authentic project plan concerning 'Modelling drinking water treatment'	TLA 1, 2, 3	Students become aware of: - Notion of process variables influencing the removal efficiency - Identification of turbidity as one of the occasionally exceeded quality parameters imposed by law - Think of measurements to prevent occasional outruns: determine the influence of process variables - Develop a mathematical model to describe the influence of the process variables
2 Give students a specific role and task: - role play as junior employees of the 'Institute for Public Health and the Environment' - model the removal of turbidity by coagulation/flocculation	Written questionnaire Field notes	Students become engaged in the practice: - interested for studying treatment processes - motivated to 'zoom in' on an example problem posed in the practice
3 Select the essential situated knowledge and supply it to students by means of articles and/or manuals: - article 'Coagulation/flocculation treatment' - article 'Mechanisms of coagulation' - manual 'Correlation & regression'	TLA 6, 12, 15, 16	Students understand: - Negative charged particles (colloids and fine silk) causing turbidity - Coagulation mechanisms - The hypothetical influence of process variables (dose coagulant, starting turbidity, temperature, acidity and total salt concentration) on the end turbidity: - The practical operation of coagulation/flocculation treatment - Scatter plots of end turbidity vs process variable - Types of correlation: negative, positive, non. - Single and multiple regression models: linear, power, exponential, logarithmic
4 Visualise for students the example problem on which they are going to work: - demonstrate treatment step coagulation/ flocculation	TLA 6	Students become owners of the modelling problem - Clear view on the problem
5 Organise students to ensure that they keep track of situated knowledge: - construct a list of concepts	TLA 4, 8, 14, 17	Students select key concepts: - Coagulation, flocculation, sedimentation - Process variables - Turbidity - Colloids, coagulant - Correlation, regression - Mathematical models: linear, power, exponential, logarithmic - Goodness of fit indicated by R^2
6 Select an end product, matching the example problem, to assess students' performance: - write a factsheet 'Modelling turbidity removal'	TLA 19	Students see the point of the exercise and are motivated to share and communicate all results and findings to the community

Design principle 'content modelling'

Strategy component	*Data Sources (Teaching-learning activity (TLA))*	*Students' notions (e.g. concepts to learn, activities to conduct, display specific attitudes/affective aspects)*
A Supply students with a worked-out analogous modelling problem as leading example: - factsheet 'modelling trichloromethane removal by activated carbon filtration'	TLA 5	Students are brought to: - Formulate a modelling procedure for the example problem - Identification of epistemic values to evaluate the developed models - See the end product they are to deliver
B Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand: - perform experiments - construct scatter plots - analyse and typify correlations - perform single and multiple regression	TLA 12, 13, 15, 16	Students perform modelling activities: - Conduct experiments according to prescripts (see the point of collecting much data for each process variable) - Draw scatter plots and delete suspicious measurements - Select the process variables with a significant correlation (positive or negative) with the end turbidity - Conduct single regression (fit linear, power, exponential and logarithmic models on the data) - Conduct multiple regression (fit additive and multiplicative models on the data)
C Let students advise on a modelling procedure to apply to a similar problem: - advise on future research on modelling the treatment step coagulation/ flocculation	TLA 20	Students draw up a generic modelling procedure and describe each stage based on own experiences: - Identify process variables - Empirically determine influence - Apply statistical techniques (correlation & regression) to quantify correlations

Design principle 'chain of activities'

Strategy component	*Data Sources (Teaching-learning activity (TLA))*	*Students' notions (e.g. concepts to learn, activities to conduct, display specific attitudes/affective aspects)*
i Give students a clear assignment concerning the example problem to work on and formulate tasks that coincide with the main stages in the teaching-learning process	TLA 4	Students - Have a clear view on what to do in the lessons to come - Recognise the tasks as specific stages in the modelling procedure
ii Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration: - select relevant process variables - conduct experiments under controlled circumstances - analyse data by correlation & regression	Written questionnaire	Students - Constantly know *why what* to do next - See the point of extending knowledge in intended direction
iii Plan work meetings with students after each main stage in the teaching-learning process to look ahead to future activities: - recall the assignment and record progress	Written questionnaire	Students constantly: - Have the purpose of the modelling in mind - Feel they are addressed as junior employees with an assignment
iv Let students evaluate to what extent the example problem has been solved: - summarise all findings and evaluate the constructed regression model	TLA 18	Students reflect on: - The purpose of the modelling and the applied procedure - Epistemic values of goodness of fit, reliability, and validity.

7

Evaluation of a Design Principle for Fostering Students' Epistemological View on Models and Modelling using Authentic Practices as Contexts for Learning in Chemistry Education[1]

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1 Prins, G. T., Bulte, A. M. W., & Pilot, A. (Submitted). Evaluation of a Design Principle for Fostering Students' Epistemological View on Models and Modelling using Authentic Practices as Contexts for Learning in Chemistry Education.

CHAPTER 1
Introduction and Research Overview

Research question 1
Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?

CHAPTER 2
Selection of Authentic Modelling Practices as Contexts for Chemistry Education

CHAPTER 3
Students' Involvement in Authentic Modelling Practices as Contexts in Chemistry Education

Modelling human exposure and uptake of chemicals

Modelling drinking water treatment

Research question 2
What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?

CHAPTER 5
Elaboration of a Design Framework for Adapting Authentic Practices into Contexts for Learning Models and Modelling in Chemistry Education

CHAPTER 4
Removal of Water Turbidity

CHAPTER 6
Evaluation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education

CHAPTER 7
Evaluation of a Design Principle for Fostering Students' Epistemological View on Models and Modelling using Authentic Practices as Contexts for Learning in Chemistry Education

Research question 3
What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?

CHAPTER 8
Valuation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education

CHAPTER 9
Lessons Learned and Reflection

Chapter 7 describes the teaching-learning process with the reformulated design principle 'content modelling', including the adjusted instructional functions regarding evaluation and reflection. In this chapter we present the specific learning gain of students concerning the epistemology of models and modelling. After the lessons, students showed themselves to be able to reflect on the epistemic values of goodness of fit and reliability, and to a lower extent on that of validity. The findings of this second research cycle, as well as the first cycle (cf. Chapter 6), suggest there is a need to make explicit and discuss with students the modelling approach to apply. Although the redesigned teaching-learning process led to improved learning results, it still proved difficult to induce meaningful evaluation and reflection.

The central research question addressed is:
To what extent does the current completion of the design principle of 'content modelling' lead to students acquiring the intended insight into the epistemology of models and modelling?

Abstract

Science education should foster students' epistemological view on models and modelling consistent with formal epistemology in science and technology practices. This paper reports the application of a curriculum unit in the classroom using an authentic chemical practice, 'Modelling drinking water treatment', as the context for learning. An authentic practice is defined as professionals working on an issue guided by common motives and purposes, according to a similar type of procedure and applying relevant knowledge. The epistemology on models and modelling in the practice was analysed and anchored in the curriculum unit. The knowledge involved was captured in a design principle 'content modelling'. A design principle provides heuristic guidelines to reach the intended pedagogic effects in the classroom. Throughout the field tests, research data was collected by means of classroom observations, interviews, audio-taped discussions, completed worksheets and written questionnaires. Students were able to evaluate the advanced model features of goodness of fit and reliability, and, to a lesser extent, validity. However, reflection on the modelling approach applied can be improved. The findings were used to reconsider the current completion of the design principle 'content modelling'. This study contributes to the acquisition of a knowledge base concerning the use of authentic practices as contexts for learning in chemistry education.

Introduction

One of the central goals of science education is to promote model-based reasoning in students (Clement, 2000). Students should understand that models are primarily a representation of ideas about phenomena and can be rejected, replaced or modified in order to fit new (empirical) data. In this process students encounter advanced model features, like purpose, reliability and validity, and become acquainted with different modelling approaches and procedures.

Before further discussing the benefits and challenges of model-based reasoning, we define our use of the terms model and the process of modelling in this study. We broadly define a scientific model as a set of representations, rules, and reasoning structures that allow one to generate predictions and explanations regarding an idea, object, event, process or system (Gilbert and Boulter, 2000; Schwarz and White, 2005). Scientific models can range from scale models, iconic and symbolic models depicting chemical formulae and chemical equations, mathematical models representing conceptual relationships of physical properties and processes (e.g. $PV = nRT$), and computer simulations, to theoretical models, describing well-grounded theoretical entities (e.g. kinetic theory model of gas volume, temperature and pressure). We use the term modelling for the process used in much of modern science that involves (a) embodying key aspects of theory and data into a model, (b) evaluating that model using epistemic values such as reliability and validity and (c) revising that model to accommodate new theoretical ideas or empirical findings (Schwarz and White, 2005). In this paper we concentrate on models and modelling in the chemistry domain.

Many modelling tasks given to students in school do not give rise to deeper understanding related to models and modelling (Erduran and Duschl, 2004). As reported in the literature, many students have difficulties grasping the essence of models and modelling (Grosslight, Unger, Jay, & Smith, 1991). Our central argument in this paper is that the epistemology of many school modelling tasks is antithetical to the epistemology of scientific modelling. This explanation has important implications for the design of modelling tasks conducted in schools. New modelling tasks will be needed that come closer to the epistemology of scientific modelling. It has been claimed that this might be realised if students are engaged in modelling processes similar as those used in research or technology settings in which real science and technology takes place (Edelson, 1998; Sadler, 2007). In this paper we refer to such settings as authentic modelling practices.

Authentic modelling practices are characterised by a community of workers working according to shared purposes, common motives and standardised procedures using relevant knowledge, tools and attitudes (Bulte, Westbroek, Van Rens, & Pilot, 2004; Prins, Bulte, Van Driel, & Pilot, 2008). Authentic modelling practices can be adapted into contexts for learning. If this is done so that students become meaningfully engaged, the assumption is that students come to construct, test and evaluate models guided by similar motives and convictions as in the authentic practice. In addition, students come to give meaning to models and modelling in a way similar to the authentic practice in which the models are employed. This vision of learning of models and modelling is underpinned by the activity theory in education (Engestroem, 1987; Leont'ev, 1978).

In a previous study we adapted the authentic practice 'Modelling drinking water treatment' into a context for learning and applied the resulting curriculum unit in classroom (Prins, Bulte, & Pilot, Submitted-a, Submitted-b). In the present study, we evaluate and reflect on the learning outcomes related to models and modelling. We aim to elaborate the potential of the approach outlined above and reflect on strategies applied in the teaching-learning process to focus students on the epistemology of models and modelling.

Theoretical framework

In this section we first summarise some major epistemological views regarding models and modelling. Secondly, we characterise and position the applied modelling approach in the authentic practice 'Modelling drinking water treatment'. Thirdly, we outline the major characteristics of the context for learning, including a description of strategies applied in the teaching-learning process to focus students on the epistemology of models and modelling.

Epistemology of models and modelling

Models are regarded as essential to the production, dissemination, and acceptance of scientific knowledge (Gilbert, 2004). Although modelling is considered an integral part of scientific literacy, the epistemological status of a model depends on one's ideas relating to what science and scientific activity are (Sensevy, Tiberghien, Santini, Laubé, & Griggs, 2008). The epistemologist Giere (1988) suggest a 'naturalistic' explanation of science based on how science is actually done in laboratories, offices, and so on (in contrast to a 'philosophical' explanation explicating a logical foundation of science). Giere treats scientific theories as a structured family of models, and distinguishes a perspective of discovery, in which new theories and models are created and elaborated, and a perspective of justification, where theories and models are tested against empirical evidence. In the latter, two interests are identified, namely 'evidence-based' and 'value-loaded'. The evidence-based interest values theories and models on the basis of evidence. In contrast, the value-loaded interest leads scientists to prefer one theory or model over another independently of considerations of evidence. One should keep in mind that the evidence-based and value-loaded interests are both valuable and do not exclude each other. In numerous occasions in science the evidence for preferring one theory or model over another purely on epistemic grounds is scant or poor, in which case value-loaded interests decide the issue. In this respect, value-loaded interests play a dual role. They structure theory and model choices within the perspective of justification under conditions of epistemic uncertainty, and they structure practice in the perspective of discovery. Value-loaded interests generate a kind of dynamics of scientific practice. Scientists do not just choose theories and models, they work on and with them. The above view on science and scientific activity is reflected in modelling as characterised by the epistemologist Hacking (1983/2005). The major points are:

- Theories are not easy to define.
- Observations are not necessarily theory driven. There have been important observations in the history of science which have included no theoretical assumptions.
- Theory and experiments cannot be directly articulated. There is an 'enormously wide ranging intermediate activity best called model-building'.
- The activity of model-building consists of two processes; one starting from theory, which makes the theory more concrete or visible, and one from experiment, which makes this experiment more abstract.

Science education involves more than learning facts, concepts, theories, models and laws, it also involves developing appreciation for the usefulness of the epistemological ideas and assumptions of the discipline (Enfield, Smith, & Grueber, 2007). Students should come to understand that our present scientific and technological knowledge is a consequence of successful conjecture between data and theory, observation and theory, and fact and theory. In addition, students should experience that theories and models are large-scale intellectual constructions that constitute the scientists' understanding and guide the day-to-day activities of scientists. Such emphasis would help students to understand why scientists do experiments, why there can be legitimate controversies in science, and even why learning science is difficult (Carey and Smith, 1993).

Learning about the epistemology of models and modelling requires particular contexts for learning. Sociocultural theories explain how such changes can occur as a result of engagement in authentic practices (Vygotsky, 1981). Sandoval (2005) argues that individuals can rely on multiple epistemologies to interact in different social contexts. From this view, learners must interact with others in a series of practices around real-world phenomena and processes, eliciting students' ideas, challenging those ideas and introducing alternative ideas. Therefore, the hypothesis is that curriculum materials that use authentic practices as contexts for learning will engage students to learn and use the epistemic notions consistent with the formal epistemology of the particular practice at hand. In the current study the authentic practice 'Modelling drinking water treatment' is used as a context for learning. Below we give an overview of the current practice, with emphasis on the epistemology regarding models and modelling (Prins et al., 2008).

Epistemology of models and modelling in the authentic practice 'Modelling drinking water treatment'

The treatment of drinking water, and the modelling thereof, is an ongoing matter of concern in many countries, since the quality of drinking water is an important area within the field of public health. Different kinds of contaminants, such as organic compounds and micro-organisms, need to be removed to produce safe drinking water. Several treatment methods are available for this purpose, such as sand filtration and activated carbon filtration. With growing pressures on water treatment, there is now a greater need to optimise water works, whether to increase throughput, reduce operational costs, or minimise capital expenditure (Rietveld and Dudley, 2006).
Although drinking water treatment has a long history, the mathematical analysis of treatment processes is still young. Within this practice, many models are data driven, for example, that for coagulation/flocculation treatment. Other treatment processes, such as disinfection, filtration and activated carbon filtration, have been widely studied and the models have a sound basis. Roughly, two modelling approaches can be distinguished in the current practice, namely mechanistic and empirical (or 'black box'). Mechanistic models strive to understand and mathematically describe the mechanics underlying the processes occurring in a given system. Empirical models are simpler and are often obtained by fitting mathematical equations to a set of experimental data. In general, the mechanistic modelling approach starts from theoretical ideas about the process at hand, while the empirical modelling approach starts from experiment (although mechanistic and empirical models contain certain elements of both). Mechanistic modelling falls within the 'evidence-based' perspective of justification. The starting point of modelling is theory about the process. Empirical modelling, on the contrary, is more 'value loaded' and starts from an experimental point of view. Both the 'evidence-based' and 'value-loaded' interests are present in the practice of drinking water treatment, as well as modelling starting from theory or experiment.

Even though a mechanistic model is preferred, a empirical model is in many cases inevitable, especially when dealing with very complex processes or if the theoretical knowledge is simply lacking. In addition, empirical models are cheap and easily constructed compared with mechanistic models, and are equally powerful in describing process behaviour in response to external alterations, e.g., changes in process variables. Both modelling approaches are conceptualised in Figure 1. In a empirical model there is limited information from inside included in the model. One tries to establish a relation between input and output, based on outside information alone.

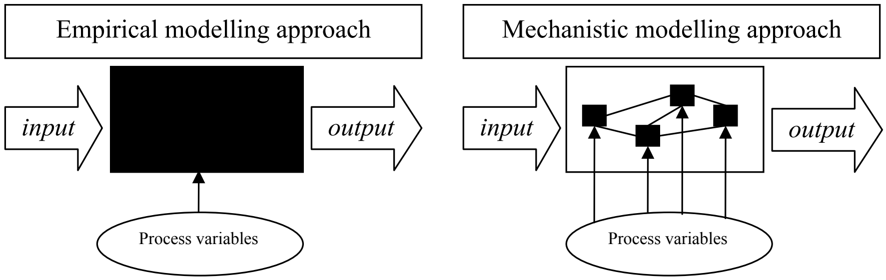

Figure 1. Conceptualised scheme of an empirical and mechanistic modelling approach.

In a mechanistic model information from inside is included, and consists of an argued assemblage of variables, including fit parameters to calibrate the model on empirical data.

Authentic practice 'Modelling drinking water treatment' as a context for learning

The authentic practice 'Modelling drinking water treatment' comprised the modelling of multiple treatment processes, numerous substances and quality parameters. For use as a context for learning, we decided to focus, or 'zoom in', on one particular treatment step and quality parameter, namely the removal of turbidity by coagulation/flocculation (Prins, Bulte, Van Driel, & Pilot, 2009). The main reason for focussing on turbidity removal by coagulation & flocculation is the availability of small-scale laboratory experiments suitable for the school environment (Prins, Wigmans, Bollen, Bulte, & Pilot, Submitted). In this section we describe the major characteristics of the context for learning. Turbidity is caused by suspended matter, such as clay particles and colloids. The coagulation/flocculation treatment is affected by a variety of process variables, such as type and dose of coagulants and flocculants, starting turbidity, acidity (*pH*), salt concentration, mixing effects and temperature. In the authentic practice, a black-box modelling approach is applied to find correlations between end turbidity and process variables and to formalise these in mathematical models. In the context for learning, all the above process variables are identified, but only three process variables are experimentally investigated, namely dose coagulant, starting turbidity and temperature. The removal efficiency can be formalised by the formula $Tubidity_{out} = f(turbidity_{in}, dose\_coagulant, Temperature)$. Figure 2 depicts a conceptualised scheme of the empirical modelling approach, as applied in the context for learning. Turbidity$_{in}$ denotes the incoming turbidity, while turbidity$_{out}$ denotes the residual turbidity.

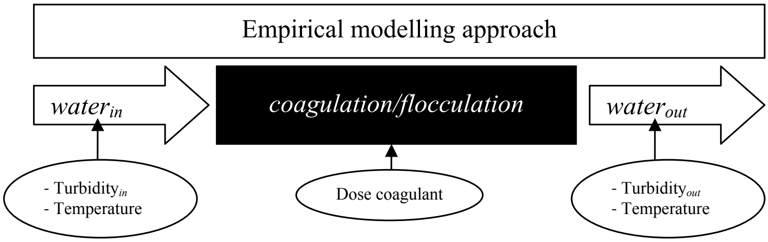

Figure 2. Conceptualised scheme of the empirical modelling approach of turbidity removal by coagulation/flocculation.

The empirical modelling approach consists of three major stages (Prins, Bulte et al., Submitted-a):

1. Identify major process variables, based on chemistry underlying coagulation/flocculation mechanisms;
2. Conduct experiments under controlled conditions:
   - Measure the end turbidity ($turbidity_{out}$) as function of the process variables; dose coagulant, starting turbidity ($turbidity_{in}$) and temperature. In each series, only one process variable is changed while the other two are held constant;
   - Present the experimental data in scatter plots;
3. Perform regression:
   - Select those process variables with significant correlation;
   - Conduct single regression: fit linear and non-linear (power) regression models on the data;
   - Conduct multiple regression: fit additive and multiplicative models on the data:
     - Multiple linear regression model (additive model, in which process variables are assumed not to interact with each other):
       $Turbidity_{out} = a + b_1 Turbidity_{in} + b_2 Dose\_coagulant + b_3 Temperature$
     - Multiple power regression model (multiplicative model, in which interaction between process variable is taken into account):
       $Turbidity_{out} = a(Turbidity_{in}^{b_1})(Dose\_coagulant^{b_2})(Temperature^{b_3})$.

The regression models are evaluated on the following epistemic values:

- *Purpose*: describe and formalise the relation between the $turbidity_{out}$ and process variables $turbidity_{in}$, dose_coagulant and temperature;
- *Goodness of fit*: indicated by the value of R^2. Theoretically, R^2 can reach the maximum value of 1, denoting a perfect fit. However, all values > 0.8 are qualified as a good fit. A notable aspect is that the goodness of fit becomes more significant the more measurements are available;
- *Reliability:* depending on the number and accuracy of the gathered experimental data, to be judged by the (team of) researcher(s);
- *Validity:* the tested range of the process variables, e.g. $X_1 < turbidity_{in}$ (NTU) $< X_2$, $Y_1 <$ dose coagulant (mg/L) $< Y_2$ and $Z_1 <$ temperature (°C) $< Z_2$.

In conclusion, the applied black-box modelling procedure for turbidity removal by coagulation/flocculation can be characterised as 'value-loaded' (complex process, use an additive or multiplicative regression model) within the perspective of justification (models are fitted on empirical data), starting from an experimental point of view (select significant process variables, make the data more abstract). Below, we turn to strategies to apply in the teaching-learning process to focus students on the epistemology regarding black-box modelling described above.

Strategies to focus students on the epistemology of models and modelling

We expect that students are aware of the existence of the mentioned epistemic values in a rudimentary sense. However, students lack the knowledge and experience to give completion to the epistemic values, and qualitatively describe and discuss them. The challenge is to design a teaching-learning process such that students' epistemological view on models and modelling will develop in the intended way. This poses numerous design issues regarding the details and sequence of the teaching-learning activities.

Design principles are defined as tools providing heuristic guidelines by means of strategy components for realising pedagogic effects in class (Van den Akker, Gravemeijer, McKenny, & Nieveen, 2006). Design principles link *strategy components*, e.g., what to do, how precisely, when in the sequence, with what tools and how enacted, *pedagogic effects*, e.g., students' epistemological views on models and modelling, and *arguments*, e.g., literature on educational research, empirical findings from previous applications and/or practical considerations. In the adaptation of the authentic practice into a context for learning we distinguished three design principles, labelled *context*, *content modelling* and *chain of activities* (Prins, Bulte et al., Submitted-a, Submitted-b). In the current study we focus specifically on the functioning of the design principle of 'content modelling'. The principle of 'content modelling' deals with focussing learners on the essential generic content regarding models and modelling. Figure 3 depicts the design principle 'content modelling'.

In this study we evaluate to what extent the strategy components lead to the intended pedagogic effects, e.g., students' epistemological view on models and modelling, and reflect on the underpinning arguments.

Strategy components

A Visualise and conceptualise for students the example problem on which they are going to work:
- demonstrate treatment step coagulation/flocculation
- conceptualise the modelling problem as an input-output system

B Supply students with a worked-out analogous modelling problem as leading example:
- factsheet 'modelling trichloromethane removal by activated carbon filtration'

C Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand:
- perform experiments
- construct scatter plots
- analyse and typify correlations
- perform single and multiple regression

D Let students apply the constructed model in a real-world setting:
- calculate the dose of coagulant needed to produce clear water

E Let students compare different modelling approaches:
- compare the black-box modelling approach with the mechanistic approach

… expected to result in …

… because of …

Pedagogic effects

A Students formulate the purpose of the modelling and activate their prior procedural knowledge base

B Students activate and enrich their prior conceptual and procedural knowledge base:
- mention epistemic values 'goodness of fit', 'reliability' and 'validity'
- draw up a modelling procedure

C Students show understanding of:
- accuracy of measurements
- global trends and correlations
- lines of best fit through scatter plots
- single and multiple regression models
- epistemic values 'goodness of fit', 'reliability' and 'validity'

D Students recall and evaluate:
- purpose of the regression model
- model outcomes in terms of goodness of fit, reliability and validity

E Students reflect on the epistemology of models and modelling

Arguments

A Previous applications of the curriculum unit have proved that visualisation of the modelling problem evokes students' notions concerning a modelling procedure. By conceptualising the modelling problem, students grasp the broader applicability of the modelling procedure to be learned.

B It is found that supplying students with an advanced organiser informs students' views on the activities to conduct and (type of) knowledge to learn/apply. Previous applications of the curriculum unit have revealed that a worked-out analogous modelling problem, originating from the authentic practice at hand, serves as a suitable organiser. It provides students with a view on epistemic values to take into account and the end product they are to deliver.

C It is found that emergent modelling, e.g. gradually formalising empirical data in mathematical models, is a suitable way to guide students through levels of abstraction. Previous enactments of the curriculum unit have revealed that multiple regression should be preceded by single regression to reduce complexity and foster students' understanding.

D Previous applications of the curriculum unit have shown that it is necessary to guide students back to the purpose of the modelling. The epistemic values of purpose, goodness of fit, reliability and validity become meaningful to students when evaluating the model outcomes in a real-world setting.

E Previous applications of the curriculum unit have proved that comparing the empirical (black-box) modelling approach with the mechanistic one induces reflection on the pros and cons. Students become aware that multiple modelling approaches exist with different epistemologies. Moreover, students make explicit an empirical (black-box) modelling approach for input-output systems in general.

Figure 3. Conceptualised scheme of the design principle of 'content modelling'. The capital letters connect strategy components with expected pedagogic effects and underlying arguments.

Scope and research question

This research study is positioned within the broader perspective of developing and investigating context-based curriculum units in science education. The aim of this study is to contribute to a knowledge base regarding the use of authentic chemical modelling practices as contexts for learning. For this we designed a curriculum unit which was put into practice in the classroom, with students in grade 10 and 11 (age 16–17 years), in upper secondary chemistry education, with emphasis on the functioning of the design principle of 'content modelling'. The central research question addressed here is:
To what extent does the current completion of the design principle of 'content modelling' lead students to acquire the intended insight into the epistemology of models and modelling?

Method

In this section we describe the designed curriculum unit and its application in the classroom, the participants, the data collection and analysis.

Design-based research
Our design-based research approach strongly resembles what Cobb, Confrey, DiSessa, Lehrer, and Schauble (2003) described as 'design experiments' conducted in the classroom. This approach implies the instructional design of a teaching-learning process, accompanied by a set of argued expectations of how the process is expected to take place and why it should operate according to these expectations (Lijnse, 1995). These expectations are based on literature as well as empirical findings in previous research cycles. The teaching-learning process is designed in close cooperation with teachers. The testing of the process takes place in a small-scale case study, with a classroom and its teacher as the unit as analysis (Cobb, Stephan, McClain, & Gravemeijer, 2001). The findings are used to evaluate the design principle, which might give reasons for a (partial) redesign to be tested in the next research cycle.

The curriculum unit

The curriculum unit consists of five separate learning phases, in which different instructional functions are to be achieved. In Table 1 the broad outline of the curriculum unit is described per learning phase. In Appendix A all the teaching-learning activities are described in detail.

Application in the classroom

The curriculum unit was put into practice at four different schools in the Netherlands in the period from January to June 2008. In two of the schools, the curriculum unit was tested in detail with respect to the functioning of the design principle 'content modelling', as case studies. Both of these schools can be characterised as rural schools with few students from ethnic minorities. In total 44 students participated, aged 16–17 years, and in grades 10 and 11. The curriculum unit compromised eight lessons of 50 minutes, excluding time for private study. The students worked in teams of four persons (11 teams in total). The teachers were well acquainted with the content and pedagogy of the curriculum unit, since they were involved in the design.

Data collection and analysis

Given the purpose of this study, the data required are essentially qualitative. The data collection and analysis is concentrated around teaching-learning activities (TLA) that are regarded as critical as it comes to learning epistemology of models and modelling. The analysis consisted of four stages.

In the first stage, preceding the actual data analysis, two researchers (first and second authors of this paper) developed and agreed upon a frame of reference as a coding scheme. This frame of reference consists of a set of expected students' notions per (cluster of) teaching-learning activities. The teaching-learning activities are the operational construct of the strategy components A to E (see Figure 3), while the students' notions are the concretised completions of the intended pedagogic effects per strategy component. In Appendix B the frame of reference is described in detail.

In the second stage, the data was analysed by both of the researchers independently, using this pre-formulated frame of reference.

In the third stage, all the codes were combined to reveal major trends and findings. Firstly, for each teaching-learning activity per student team, if at least 80% of the intended pedagogic effects were realised, the corresponding strategy component was deemed fully accomplished. If between 20 and 80%, the valuation was partial, and if between 0 and 20% it was deemed to have achieved a low level of accomplishment. Secondly, for each strategy component, the judgements of all the student teams were combined. A particular strategy component itself was deemed fully accomplished if it scored high in at least 80% of all student teams. A strategy component

Table 1. Broad outline of the content of the five learning phases in the curriculum unit. The placement of the strategy components of the design principle 'content modelling' are highlighted in bold.

Learning Phase	*Description of the learning phase*
I: **Orientate on the practice**	The first phase induces among students a motive for studying the problems posed in the practice at hand, and provides them with a sense of direction concerning where their study will lead them. Firstly, students orientate on the treatment of ground- and surface water for production of drinking water. Secondly, students take notice of occasional exceeding of (chemical) parameters, including the turbidity. Thirdly, the removal of turbidity by coagulation/flocculation is demonstrated by an experiment in class. Students formulate a purpose of modelling and a (rudimentary) modelling procedure for turbidity removal by coagulation/flocculation [**Strategy component A**]. Fourthly, students compare their formulated modelling procedure with the modelling procedure proposed by experts, by studying an adapted and shortened version of an authentic project plan 'Modelling drinking water treatment'.
II: **Zoom in on an example problem**	In the second phase the students enrich their own formulated modelling procedure. Students make explicit the sequence of modelling activities to conduct and the epistemic values to judge the quality of the constructed model(s), and they gain sight of the (type of) end product to deliver. This process is facilitated by studying a factsheet describing a worked-out analogous modelling problem, namely modelling the removal of trichloromethane by activated carbon filtration [**Strategy component B**]. Students extract the modelling procedure and identify the epistemic values of purpose, goodness of fit, reliability and validity.
III: **Solve the example problem**	In the third phase the students extend and apply their knowledge related to modelling turbidity removal by coagulation/flocculation. This extending and applying of knowledge is an iterative (intertwined) process. The main stages, as already identified in learning phase II, are: 1. Identify process variables affecting turbidity removal by coagulation & flocculation, e.g., dose of ferric chloride, starting turbidity, temperature, acidity, … 2. Conduct experiments under controlled conditions to determine the influence of three process variables, namely dose of ferric chloride, starting turbidity and temperature. Students work according to laboratory prescripts. 3. Conduct regression on the acquired empirical data. Students draw scatter plots, select those process variables with significant correlation, and fit linear and non-linear (power) regression models to the data. First a single regression, followed by a multiple regression. Students evaluate the constructed multiple regression model on epistemic values purpose, goodness of fit, reliability and validity [**Strategy component C**].
IV: **Evaluate & reflect on the findings**	In the fourth phase students summarise, evaluate and reflect on their findings. Students used the constructed multiple regression model to calculate the dose of ferric chloride needed to produce clear water in an industrial plant site [**Strategy component D**]. They judge the model outcomes in terms of reliability and validity. Next, students reflect on the applied modelling approach, as an exemplary case of black-box modelling. They compare the black-box approach with the mechanistic approach and formulate pros and cons [**Strategy component E**]. Finally, students give advice on future research concerning the modelling of turbidity removal by coagulation/flocculation.
V: **Express the findings**	In the fifth phase the students make explicit their findings in light of the particular modelling issue worked on. Students write a factsheet (as introduced in learning phase II), summarising the main results, including an outlook on further research from the students' perspective.

was deemed low, if 80% of all student teams judged it partly accomplished or less. In case of a score somewhere between these two extremes, the strategy component was deemed partly accomplished. Thirdly, a rater consistency check was conducted by calculating the intraclass correlation coefficient using a two-way mixed effects model (Shrout and Fleiss, 1979).

In the fourth stage, both researchers discussed all the judgments to identify underlying considerations, to unravel students' perspectives and to reflect on the strategy components applied. Finally, all the results were discussed by the complete research team.

The collected data sources are audio-taped conversations of student teams at work, written answers of student teams, interviews with student teams and field notes. Below, we briefly describe each data source and specific analysis procedure.

Audio-taped conversations

While working on teaching-learning activities (TLA) 18-19, the conversations of the student teams at work were audio-taped. Next, the conversations were transcribed *verbatim*, and coded by both researchers independently from an interpretative perspective (Smith, 1995) using the frame of reference.

Written answers

All written answers from the student teams on teaching-learning activities (TLA) 3, 5, 14-16, 18-19, and the factsheets, were coded by two researchers (first and second author) independently using the frame of reference.

Interviews

Each student team was interviewed during or shortly after having accomplished teaching-learning activity (TLA) 3. The interview was semi-structured with the aim being to reveal the students' perspectives on (a) the purpose of the modelling and (b) the modelling procedure to apply (common sense modelling approach). The length of the interview was approximately 10 minutes. The interviews were audio-taped and transcribed *verbatim*. Next, the interviews were coded by both researchers independently from an interpretative perspective (Smith, 1995) using the frame of reference.

Field notes

During the complete enactment of the curriculum unit on both schools field notes were made by the first author of this paper. The major purpose of the field notes was to check whether the strategy components, and corresponding teaching-learning activities, were enacted in class with sufficient quality.

Results

In this section we present the results for each strategy component. At the end, we combine and summarise the findings to answer the research question. The teaching-learning activities were enacted in the classroom as planned. The analysis showed a substantial consistency between the raters reflected in the intraclass correlation coefficient of 0.78.

Strategy component A: Visualise and conceptualise for students the example problem on which they are going to work:

- demonstrate treatment step coagulation/flocculation
- conceptualise the modelling problem as an input-output system

The results show that all teams do notice the process variables of dose coagulant and starting turbidity. Other process variables mentioned were stirring effects, temperature and type of coagulant. All teams recognised the variability of the input. As for the purpose of modelling, ten teams mention the dose coagulant in order to produce clear water. To achieve this, in general, two perspectives are brought to the fore. Six teams propose to concentrate on the relation between the end turbidity and the dose coagulant. On the contrary, five teams suggest focussing explicitly on the process, typified by statements such as '*elucidate what happens on a molecular level*'.

Team 7's written answer on teaching-learning activity 3 was:

'Which substances cause the turbidity? What exactly happens? What causes the particles to grow during the stirring phase?'

Ten teams formulated a modelling procedure in response to the plenary demonstration. The majority of the teams (10) focussed on conducting experiments to investigate the variability of external factors, as exemplified below:

Team 4 describes their procedure as follows:

'… try different amounts [dose coagulant], and each time test the residual turbidity and coagulant. If you notice that too much turbidity remains, or too much coagulant, then you can determine the situation in which both are the lowest possible. But, since it is variable, you need to test it each time.'

Examples of other mentioned procedural steps are '*study which substances reside in turbidity*' and 'find out the best coagulant that leads to coagulation'. In Table 2 the results are summarised, including some general remarks on the functioning of strategy component A.

Table 2. Overview of the realisation (full, partial, low) on each strategy component and major considerations.

Strategy component	# student teams			Major considerations	
	Full	Partial	Low	Successful	Opportunities and/or possible improvements
A: Visualise and conceptualise the example problem	9	2	-	Students showed notion of: - variability through external factors - process variables - the purpose of modelling and a rudimentary modelling procedure	- Emphasise the appropriate modelling approach
B: Supply students with a worked-out analogous problem	7	4	-	Students formulated a modelling procedure	- Explicit focus on epistemic values of goodness of fit, reliability and validity
C: Involve students in the nature, characteristics and wording of the models at hand	4	6	1	Students did show understanding of: - correlations between quantities - epistemic values of goodness of fit and reliability	- Notion of significance of correlation - Construct a continuous line of teaching-learning activities from single to multiple regression - Emphasise the epistemic value of validity
D: Let students apply the constructed model in a real-world setting	6	3	2	Students were aware of: - considerations regarding predictive value of model - the number and accuracy of the empirical measurements	- Notion students that the model needs extensive testing in industrial environment
E: Let students compare different modelling approaches	6	4	1	Students evaluated: - applied empirical modelling approach	- Make explicit learned 'meta knowledge' regarding black-box modelling. - Reflect on the applied modelling approach and make explicit broader applicability

Strategy component B: Supply students with a worked-out analogous modelling problem as a leading example:
- factsheet 'modelling removal of trichloromethane by activated carbon filtration'

The strategy to bring in a worked-out analogous modelling problem aims to make explicit the meta-modelling knowledge. Ten teams considerably enriched their rudimentary modelling procedure, as formulated in teaching-learning activity 3. These teams also demonstrate the ability to apply the meta-modelling knowledge for modelling turbidity removal.

Team 9 describes the modelling procedure as follows (for reasons of length, only the main procedural steps, shortened and summarised, are presented):

- *Explain the working of the treatment step:*
    - *Schematic representation of treatment step*
    - *List of process variables*
- *Process variables:*
    - *Overview of qualitative influence of each process variable*
    - *List of process variables to be researched | kept constant*
- *Empirical data:*
    - *Plot all gathered data in diagrams*
    - *Draw conclusions from diagrams*
- *Correlation & regression:*
    - *Analyse the diagrams for correlation*
    - *In case of correlation -> conduct regression*
    - *Determine goodness of fit (value R^2)*
- *Evaluate & reflect*
    - *Evaluate the mathematical model on reliability*
    - *Recall the purpose of the modelling*
    - *Advise on future research.*

The epistemic values of goodness of fit, reliability and/or validity, however, were only notified by four teams. In Table 2 the results are summarised, including some general remarks on the functioning of strategy component B.

Strategy component C: Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand:

- perform experiments;
- construct scatter plots;
- analyse and typify correlations;
- perform single and multiple regression.

Strategy component C embodies some key aspects regarding modelling. First of all, student teams analyse scatter plots to characterise the type of correlations. Secondly, students fit regression models on the data, both linear and power. Thirdly, students evaluate the regression models on aspects goodness of fit, reliability and validity.

The results show that nine teams were able to draw correct conclusions regarding the correlations based on the scatter plots. The drawing of the scatter plots gave the student teams more insight into the quality of their measurements. The teams evaluated each single data point (whether or not falling within the trend) and deleted doubtful measurements. The process variables of dose coagulant and starting turbidity correlated clearly with end turbidity. However, the temperature was less obvious. Six teams concluded that the correlation of the temperature was not significant, and thus could be excluded from further analysis, as typified in Figure 4.

'... this scatter plot shows that there is little correlation between temperature and the end turbidity. This can be concluded from the low correlation. The process variable temperature has hardly any/no influence on the end turbidity ....'

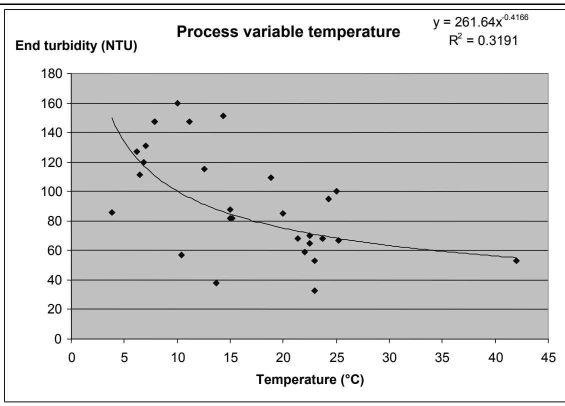

Figure 4. The analysis of student team 1 regarding the type of correlation based on the scatter plot of temperature against end turbidity.

The majority of the teams (10) did understand the arguments either to leave out or take into account the temperature. For example, here is Team 7 discussing with the teacher the construction of multiple regression model:

S4: … And if we combine two [process variables], you leave one [process variable] constant, ... and if you combine three [process variables], then you should hold two [process variables] constant [in each series of experiments]. … So, if we combine three [process variables], then you get the constant values of the other two, and [the model] becomes even less accurate.
Teacher: It [the model] will become less accurate, yes. But, what determines whether or not you take into account the temperature?
S2: How much influence it has.
Teacher: Right!
S3: And how much it differs with [the temperature of] the water taken in [by the drinking water treatment plant].

All teams were able to determine the best line (linear or power) through the scatter plots, including the mathematical formula. While beyond the scope of the exercise, six teams also fitted exponential (and even logarithmic) regression models. These teams extensively used the epistemic value of goodness of fit as an evaluative criterion. This fact brought to the fore a fundamental limitation of the black-box modelling approach: the absence of theoretical arguments to navigate to a particular regression model. We will come to this point later on.

In total nine teams succeeded in constructing a multiple regression model. The remaining two teams failed in multiple regression. In valuating the regression models, seven teams used goodness of fit as the decisive criterion. Only four teams explicitly formulated the validity of the constructed regression models. In Table 2 the results are summarised, including some general remarks on the functioning of strategy component C.

Strategy component D: Let students apply the constructed model in a real-world setting:
- calculate the dose of coagulant needed to produce clear water.

Six teams succeeded in calculating the dose coagulant and reflected upon the predictive value of the outcomes. However, the findings reveal that in total ten teams argued about the predictive value of their constructed model. Arguments brought to the fore vary from ‘process variables not taken into account’ to ‘model based on inaccurate measurements’.

Team 5 qualifies the model outcome as follows:

This seems to us a not likely outcome to add 20.6 g/L coagulant [to produce water with 1 NTU]. Our model is also not valid in this situation: the pH and temperature are different. This means that our model should be adapted.

Four teams judge their model outcomes as unpredictable, but suggest comparing the outcome with real-world data, as exemplified by the statement below:

Team 10 reflect on the model outcomes as follows:

To see whether this [outcome] is real, it should be tested for reliability by conducting this experiment in the real world [not laboratory setting] multiple times. If the amount of added coagulant proves to be around 132 mg/L, then the model outcomes are trustworthy. This, of course, should be tested multiple times under varying conditions …

The majority of the teams (10) conclude that more (accurate) measurements are needed and that more process variables should be researched to 'make the model fit for every situation'. Four teams argue explicitly for testing the model in a real industrial plant environment, showing that these students are aware of the present state of the model. In Table 2 the results are summarised, including some considerations on the functioning of strategy component D.

Strategy component E: Let students compare different modelling approaches:
- compare the black-box modelling approach with the mechanistic approach

The findings reveal that ten teams identified the black-box modelling approach and evaluated the approach on epistemic grounds, as shown by statements below:

The 'black box' approach is quick, easy and also effective as it comes to describing process behaviour. (Team 3)
The 'black box' is just a big experiment, you test process variables, apply regression and construct a formula. A 'mechanistic' approach is much more theoretical regarding which process variables and why. (Team 7)
We did not know exactly what happens during the process. (Team 2)

If high (> 0.8) [value R^2], then alright according to the 'black box' method, but theoretically much remains unclear. (Team 8)

All teams underline the need for future research, using the epistemic values of validity and goodness of fit, as well as the quality of the measurements, as primary arguments. Four teams explicitly suggest following a more mechanistic approach, as they felt uncomfortable with the empirical modelling approach.

Team 1 suggest future research:

S3: Is there reason for a follow up? You could …
S4: extensive …
S3: …develop a mechanistic model for an exact description of the working and behaviour of the process.
S2: cause …
S3: well, … with use of a mechanistic model you can give an exact description.

More or less a follow up of teaching-learning activity 18, all teams again articulate the need to improve the quality of the measurements. Team 4 proposed implementing some kind of JAR test, in which all experiments are done in exactly the same manner.

As for typifying the general problem regarding input-output systems, the answers vary from '*account for variable input, not just one variable*', '*apply black box or mechanistic approach*' to '*variability of external values*'. On average, the teams emphasise '*variability*' as a major problem. Four teams formulated a general procedure for modelling input-output systems, although regression as an essential step was mentioned only once. However, the exact learning gain on meta level remains unclear. It is questionable whether the learning gain is largely absent, or that it is simply not measured. In Table 2 the results are summarised, including some considerations on the functioning of strategy component E.

Summary of main findings on the strategy components

The results for the strategy components A to E are summarised in Table 2. For each strategy component, we also present the major considerations (successful aspects, as well as opportunities and/or possible improvements). As becomes clear, strategy components A (visualise and conceptualise the example problem) and B (supply students with a worked-out analogous problem) function to a sufficient extent. However, strategy component C (involve students in the nature, characteristics and wording of the models at hand) needs redesign. A main aspect to consider is how to construct a continuous line of teaching-learning sequences from single to multiple regression, such that students arrive at the intended multiple regression model(s). Strategy components D (let students apply the constructed model in a real-world setting) and E (let students compare different modelling approaches), finally, do function as expected and give rise to the intended pedagogic effects, but their functioning can still be improved.

Conclusion and discussion

The aim of this study was to elaborate knowledge regarding the use of authentic chemical modelling practices as contexts for learning. The knowledge involved was captured in the design principle of 'content modelling' with five strategy components. The principle of 'content modelling' deals with focussing learners on the generic content regarding models and modelling. The results show that four out of five strategy components (A, B, D, E) function sufficiently. Strategy component C, however, requires reconsideration. In this final section we reflect on the functioning of each strategy component, as well as the broader applicability of this design principle for adapting other authentic modelling practices into curriculum units. In addition, we formulate implications for future research.

Reflections on the functioning of the strategy components

Based on the findings on the pedagogical effects, it can be concluded that strategy component A (visualise and conceptualise the example problem) functions as expected, especially for identifying the process variables, and formulation of the purpose of the modelling as well as a rudimentary modelling procedure. The results show that nearly half of the teams suggest a empirical approach, and the others suggest a mechanistic approach. To further underline the pros and cons of the modelling approach to apply, we add a new strategy component: point out and discuss in class the appropriate modelling approach. A goal of strategy components A (visualise and conceptualise the example problem) and E (let students compare different modelling approaches) was to conceptualise the coagulation/flocculation treatment step as an example case of an input-output system. This was introduced in strategy component A, and recalled in strategy component E. It was intended that the students would grasp the broader applicability of the empirical modelling approach for complex input-output systems. However, none of the teams took notice of the broader applicability. We are a bit cautious to draw explicit conclusions about this, because the broader applicability can be typified as (a sort of) meta-knowledge, which was hardly made explicit by students (see results on strategy component E). However, the findings suggest that conceptualisation *alone* does not automatically led students to see the broader applicability. Mentioning other input-output systems that would be recognisable from students' perspective, for which an empirical modelling approach is feasible, might support such understanding.

It can be concluded that strategy component B (supply students with a worked-out analogous problem) works sufficiently for evoking and expressing a modelling procedure. It enriches students' prior modelling knowledge and informs them about modelling activities to conduct. However, the majority of the teams did not note the epistemic values. Such orientation early in the curriculum unit is regarded as essential, because these values are recalled later on in the curriculum unit to evaluate the constructed regression models. We propose to extend the strategy component with measures that will direct students to the epistemic values.

Strategy component C (involve students in the nature, characteristics and wording of the models at hand), however, needs reconsideration. The results show that the proposed gradual formalisation of the observed trends is effective, but demands a careful outlining at the fine granularity of teaching-learning activities. Two major aspects came to the fore:

- The significance of the correlation, e.g., in the present case, the temperature;
- Construction of a continuous line of teaching-learning activities from single to multiple regression.

It seems advisable to emphasise the significance of the correlation in the teaching-learning process, in terms of (1) amount of measurements and (2) value of the correlation coefficient. Students need understanding on this matter to be able to judge whether a process variable should be taken into account or not. In the authentic practice, a multiple regression is applied in a straightforward way. However, in the current teaching-learning process the line of reasoning runs via single regression, because students are unfamiliar with regression. It was expected that multiple regression is (too) complex for students to learn straight away. The single regression was thus built in as an intermediate stage. From a scientific point of view, this intermediate step is questionable. At this point we see two options:

1. Skip single regression and directly conduct a multiple regression in class. Students immediately fit additive and multiplicative models to the data, using computer program MS Excel; or
2. *Assume* a linear (or power) correlation between dose coagulant and/or starting turbidity with end turbidity. Explain the assumed correlation as much as possible from a chemical point of

view, based on the way the particles interact. Next, conduct single regression, followed by multiple regression, in which additive and multiplicative models are fitted.

Further research is needed to elaborate the pedagogic effects of both options.

Strategy component D (let students apply the constructed model in a real-world setting) proved successful in inducing a motive among students to evaluate their model outcomes explicitly. The majority of the teams came up with relevant considerations, especially regarding the number and accuracy of the measurements. This might be an indication that students understand that the quality of the measurements is extremely important in a black-box modelling approach. However, the actual calculation of the dose coagulant using the constructed model needs redesign. In addition, the notion that the model has been constructed in a laboratory setting, and thus needs extensive testing in an industrial environment preceding real usage, can be fostered.

The strategy component E (let students compare different modelling approaches) proved successful in evaluating the applied modelling approach. Students encountered that doing science is not a straightforward process, but implies fundamental choices with pros and cons. We propose to further strengthen the strategy component with an explicit focus on estimations made, assumptions and neglected variables. In our opinion, through discussing and comparing different modelling approaches earlier in the teaching-learning process, students' views on the epistemology of the applied modelling approach might be fostered.

Summarising all the implications, we come to a slightly altered and generalised filling-in of the design principle 'content modelling', as depicted in Figure 5. The results give rise to the incorporation of an extra strategy component, namely to discuss and to point out the appropriate modelling approach early in the teaching-learning process.

Reflections on fostering students' epistemological views of models and modelling

We started this paper with the statement that the epistemology of many school modelling tasks is antithetical to the epistemology of scientific modelling. Traditionally, school science (unintentionally) presents students with a straightforward route to the development of new models, leaving out the difficulties and failures inherent in conducting research. We argue that engaging students in authentic practice-based modelling processes might offer a way out. The results obtained in the present study support the arguments and encourage further research on the design challenges. Science curricula, emphasising learning about the nature, purpose and construction of models, has the potential to enable students to develop accurate and productive epistemologies of science (Schwarz and White, 2005). However, as reported in the literature, simply engaging students in developing models is not enough to achieve epistemological sophistication (Carey and Smith, 1993). One needs to add a "meta modelling layer", which enables students to develop not only scientific models but also explicit theories about the nature

Strategy components

A Visualise and conceptualise for students the example problem on which they are going to work:
- demonstrate treatment step coagulation/flocculation
- conceptualise the modelling problem as an input-output system

B Supply students with a worked-out analogous modelling problem as leading example:
- factsheet 'modelling removal of trichloromethane by activated carbon filtration'

C Discuss with students different modelling approaches and point out an appropriate one for the example problem at hand

D Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand:
- perform experiments
- construct scatter plots
- analyse and typify correlations
- perform single and multiple regression

E Let students apply the constructed model in a real-world setting:
- calculate the dose of coagulant needed to produce clear water

F Let students compare different modelling approaches **and reflect on the assumptions and estimations made, and the possible effect of neglected variables**:
- compare the black-box modelling approach with the mechanistic approach

… *expected to result in* …

… *because of* …

Pedagogic effects

A Students activate their prior conceptual knowledge base and their procedural knowledge base

B Students make explicit and build on their prior conceptual knowledge base and their procedural knowledge base:
- mention epistemic values goodness of fit, reliability and validity
- draw up a modelling procedure

C,D Students proceed through the sequence of activities and learn/apply detailed knowledge until a satisfactory solution for the example problem can be presented:
- accuracy of measurements
- global trends and correlations
- lines of best-fit through scatter plots
- single and multiple regression models
- epistemic values goodness of fit, reliability and validity

E Students evaluate the learned conceptual and procedural knowledge:
- purpose of the regression model
- model outcomes in terms of goodness of fit, reliability and validity

F Students reflect on the epistemology of models and modelling

Arguments

A Previous applications of the curriculum unit have proved that visualisation of the modelling problem evokes students' notions concerning a modelling procedure. By conceptualising the modelling problem, students grasp the broader applicability of the modelling procedure to be learned.

B It is found that supplying students with an advanced organiser informs their views on activities to conduct and (type of) knowledge to learn/apply. Application of previous versions of the curriculum unit has revealed that a worked out analogous modelling problem serves as a suitable organiser. It provides students with a view of the epistemic values to take into account and the end product to deliver.

C Previous applications of the curriculum unit have proved that discussing different modelling approaches for the problem at hand fosters reflection on the applied approach in learning phase IV. Students become aware that multiple modelling approaches exist.

D It is found that emergent modelling, e.g., gradually formalising empirical data in mathematical models, is a suitable way to guide students through levels of abstraction.

E Previous applications of the curriculum unit have shown that it is needed to guide students back to the 'purpose of the modelling'. The epistemic values of purpose, goodness of fit, reliability and validity become meaningful to students when evaluating the model outcomes in a real-world setting.

F Previous applications of the curriculum unit have shown that comparing modelling approaches induces reflection on the pros and cons. Students become aware that multiple modelling approaches exist with different epistemologies. Moreover, students make explicit a black-box modelling approach for input-output systems in general.

Figure 5. Conceptualised scheme of a design principle 'content modelling'. The capital letters connect strategy components with expected pedagogic effects and underlying arguments. Alterations to the original filling-in (see Figure 3) are shown in bold.

of models themselves. In our opinion, this can be realised by engaging students in different authentic modelling practices, in which different epistemological views are employed, such as constructing mechanistic and black-box models. By doing so, we expect that students will gain a richer, more varied perspective on science. In addition, it enables students to gain some insight into socio-scientific values related to authentic practices. However, as might become clear from this study, there are still multiple (major) design challenges in using authentic practices as contexts for learning. The promising results can only be achieved by high quality in the design and enactment of the teaching-learning process.

Limitations

The conclusions of this study are subject to at least three limitations. Firstly, it should be noted that this particular authentic practice was selected after a thorough evaluation (Prins et al., 2008). It is important to select authentic modelling practices which, in principle, are feasible for upper secondary chemistry education.

Secondly, the design principle 'content modelling' applies to (1) using an authentic practice as the context for learning, (2) the domain of models and modelling, and (3) students in grades 10 and 11 (aged 16–17 years), high school chemistry (upper secondary level). The present filling-in of the principle emerged from the adaptation and enactment of only one authentic practice. The application of this design principle to other authentic modelling practices, either within chemistry or other science domains, needs to be examined. Thirdly, the teachers involved were all well informed about the pedagogy of the curriculum unit. Other teachers willing to enact the curriculum unit and to apply this design principle should be confident with the domain specific pedagogy.

Implications for future research

Further development of design principles, or equivalent ways for capturing knowledge on educational designs, is important, because it bridges (abstract) theories on learning with the design of concrete teaching-learning activities in class. There is a need for such explicit knowledge, since in many curriculum innovations teachers are designated as the developers of teaching-learning processes. In the next stage of this project we will focus on the broader applicability of the design principle of 'content modelling'. The fact that model-based teaching and learning is widely regarded as central in science education makes it worthwhile to develop further a knowledge base about the use of authentic modelling practices as contexts for learning.

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Appendix A. Overview of the curriculum unit in terms of content and sequence of teaching-learning activities

In this appendix the curriculum unit is described in terms of content and sequence of teaching-learning activities per learning phase.

Phase I: Orientate on the practice

Content related questions	Sequence of teaching-learning activities (TLA) including desired learning outcomes
	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. In addition, for each treatment step students summarise the process variables that effect the removal efficiency. • Students realise the societal importance of good quality drinking water (public health). Students gain insight into the dynamics of the treatment process.
What causes turbidity? What is coagulation/ flocculation?	**TLA 2: Exceeding of chemical parameters**. Students receive a list of (occasionally) exceeded chemical parameters for drinking water (source: government document). Students notice the outrun of the quality parameter turbidity. Turbidity is removed by the treatment step of coagulation/flocculation. • Students realise that the removal of turbidity by coagulation/flocculation is one of the issues dealt with in the treatment of water.
The dosage of ferric chloride needs to be adjusted to the starting turbidity to produce clear water.	**TLA 3: Zoom in on turbidity removal by coagulation/flocculation**. The teacher conducts a laboratory experiment in classroom showing the clearance of turbid water by coagulation/flocculation. Next, the teacher conceptualises the problem as an exemplary case of an input-output system. Students outline a modelling procedure to find a relation between starting turbidity, dose coagulant and end turbidity. • Students make explicit their notions regarding the purpose of the modelling and the modelling procedure. Students grasp the broader applicability of the modelling procedure to be learned.
How is this done in real practice?	**TLA 4: Orientate on the modelling approach proposed by experts.** Students study an adapted and shortened version of an authentic project plan concerning 'Modelling drinking water treatment'. They compare their own formulated modelling procedure (TLA 3) with the modelling approach proposed by experts. • Students make a list of similarities and differences in both modelling approaches. Students gain a sense of direction, in terms of modelling activities to conduct.

Phase II: Zoom in on an example problem

Content related questions	Sequence of teaching-learning activities (TLA) including desired learning outcomes
What constitutes major steps and what knowledge is involved in modelling the removal of turbidity by coagulation/ flocculation?	**TLA 5: Draw up a modelling procedure for removal of turbidity by coagulation/flocculation**. Students receive a factsheet summarising the approach and outcomes of an analogous modelling problem: removal of trichloromethane by activated coal filtration. This analogous problem serves as a leading example. Students enrich their formulated modelling procedure, and notice epistemic values to evaluate the resulting model. • Students formulate a modelling procedure: 1 Find out more about coagulation and flocculation 2 Identify process variables (next to dose of ferric chloride and starting turbidity) 3 Experimentally investigate the influence of variables 4 Develop a mathematical formula for predicting end turbidity 5 Evaluate the model • Students copy the basic structure of the factsheet.

Phase III: Solve the example problem

Content related questions	Sequence of teaching-learning activities (TLA) including desired learning outcomes
How does coagulation/ flocculation work?	**TLA 6: Study treatment step coagulation/flocculation**. Students study an article about treatment step of coagulation/flocculation. This article describes the way the treatment is conducted. It also illuminates the difficulties in removing the small clay particles and colloids causing turbidity. • Students make a summary. They realise that they need to identify all process variables that effect coagulation/flocculation.
Which process variables affect the removal of turbidity by coagulation/ flocculation?	**TLA 7: Identify process variables that affect coagulation/flocculation.** Students identify process variables and hypothesise about their possible influence. Students use the acquired knowledge in TLA 3 (demonstration) and TLA 6 (article on coagulation/flocculation). • Students identify multiple process variables that influence the end turbidity, such as dose coagulant, starting turbidity, temperature and mixing effects.
	TLA 8: Extend the list of identified process variables. The teacher gives a short lecture about the chemistry underpinning coagulation processes. Next, students study an article from which they learn about coagulation mechanisms and extend their list of process variables. • Students add process variables acidity (*pH*) and total salt concentration. Students realise that the influence of the process variables needs to be examined experimentally.
	TLA 9: Bring up to date list of concepts and factsheet. Students bring up to date their factsheet (TLA 5) and their list of content related concepts. • Students realise that it is important to update their newly acquired knowledge and findings regularly.
How large is the influence of each process variable?	**TLA 10: Investigate the influence of process variables empirically.** The teacher divides the work such that three process variables are studied experimentally: dose coagulant ($FeCl_3$), starting turbidity and temperature. Students receive laboratory prescripts for the experiments. • Students understand that everybody needs to conduct the experiments in a similar way in order to combine the results later on.
	TLA 11: Draw scatter plots. Students plot scatter diagrams showing the experimental results of end turbidity versus (1) dose coagulant, (2) starting turbidity and (3) temperature. Students interpret the results and think back and forth between the hypothesised influence (TLA 7 & 8) and observations.
How accurate are the measurements?	**TLA 12: Reflect on obtained results.** Students evaluate the obtained experimental results. • Students find out that some experimental results are suspect, due to poor performance or being deviant from the observed tendency, and reflect on possible explanations.
	TLA 13: Bring up to date list of concepts and factsheet. Students bring up to date their factsheet (TLA 5) and their list of content related concepts. • Students realise that it is important to update their newly acquired knowledge and findings regularly.

Which process variables significantly influence the turbidity?	**TLA 14: Correlation between end turbidity and process variables**. Students present their scatter diagram summarising their results. The teacher invokes discussion about the observed correlations. Students select the process variables with a significant effect on turbidity removal (leaving starting turbidity and dose coagulant). Students study a manual dealing with correlation (and regression). • Students realise that the experimental results need to be analysed further in order to quantify this influence.
How to quantify the influence of the process variables?	**TLA 15: Single regression of end turbidity on dose coagulant and starting turbidity**. The teacher gives a short lecture about regression. Next, students perform single regression on end turbidity versus (1) dose coagulant and (2) starting turbidity. Students fit linear and non-linear (power) regression models and reflect on their 'goodness of fit'. Students work according to a manual dealing with correlation and regression, and use MS Excel software. • Students realise that one model is needed to account for different influences on the same process simultaneously.
How to couple the models to one formula?	**TLA 16: Multiple regression**. Students attend a short lecture about multiple regression. Next, students fit multiple linear and non-linear (power) regression models to the data, according to planned procedure using MS Excel. Students evaluate the resulting regression model on aspects 'goodness of fit' and 'validity'.
	TLA 17: Bring up to date list of concepts and factsheet. Students bring up to date their factsheet (TLA 5) and their list of content related concepts. • Students realise that it is important to update their newly acquired knowledge and findings regularly.

Phase IV: Evaluate and reflect on the findings.

Content related questions	Sequence of teaching-learning activities (TLA) including desired learning outcomes
In what way can the model contribute to turbidity removal by coagulation & flocculation?	**TLA 18: Apply developed multiple regression model**. Students apply the multiple regression model (TLA 16) to calculate the dosage of coagulant needed to produce clear water in a production side given a certain raw water quality. Students evaluate the outcomes on the aspects 'purpose', 'reliability' and 'validity'. • Students realise that their recommendations should be underpinned by reporting the main findings.
What are the strengths and weaknesses of the applied 'black- box' modelling approach?	**TLA 19: Reflect on the applied 'black-box' modelling approach**. The conceptualised input-output system (TLA 3) is recalled. Students compare the applied black-box modelling approach with the mechanistic approach and think of pros and cons. In addition, students think over future research on turbidity removal by coagulation/flocculation based on their own experiences and extended knowledge. • Students realise that this type of modelling is an exemplary example of process modelling, and thus is worthwhile to make explicit.

Phase V: Express the findings

Content related questions	Sequence of teaching-learning activities (TLAs) including desired learning outcomes
	TLA 20: Write a factsheet 'Modelling turbidity removal by coagulation/ flocculation'. Students write a factsheet summarising the applied modelling procedure, main findings, conclusions and advice for future work. This factsheet is assessed by the teacher. • Students make their learned knowledge explicit.

Appendix B. Frame of reference

The frame of reference describes the expected students' notions per strategy component. The strategy components are operationalised in teaching-learning activities, which are used as data sources. The students' notions are concretised completions of the intended pedagogic effects per strategy component.

Strategy component	*Data sources (Learning phase | Teaching-learning activity - TLA)*	*Students' notions (e.g. concepts to learn, activities to conduct, display specific attitudes/affective aspects)*
A Visualise and conceptualise for students the example problem on which they are going to work: - demonstrate treatment step coagulation/flocculation - conceptualise the modelling problem as an input-output system	I | TLA 3	- Identify process variables (1) dose coagulant, (2) starting turbidity and (3) stirring regime - Think of measurements to take to prevent occasional outruns of the norm - Formulate a rudimentary modelling procedure for input-output systems
B Supply students with a worked-out analogous modelling problem as leading example: - factsheet 'modelling removal of trichloromethane by activated carbon filtration'	II | TLA 5	- Formulate a modelling procedure for the example problem 1. Study coagulation/flocculation 2. Identify process variables and describe influence 3. Conduct experiments 4. Present data in scatter plots 5. Develop mathematical model to quantify influence 6. Evaluate and reflect on the constructed model 7. Write a factsheet - Identify epistemic values (goodness of fit, reliability, validity) to evaluate the developed models - View on the end product to deliver
C Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand: - perform experiments - construct scatter plots - analyse and typify correlations - perform single and multiple regression	III | TLA 14 – 16 Factsheet	- Conduct experiments according to prescripts (see the point of collecting much data for each process variable) - Draw scatter plots and delete suspicious measurements - Select the process variables with a significant correlation (positive or negative) with the end turbidity - Conduct single regression (fit linear and power models on the data) - Conduct multiple regression (fit additive and multiplicative models on the data) - Evaluate the constructed models on the goodness of fit

D Let students apply the constructed model in a real-world setting: - calculate the dose of coagulant needed to produce clear water		- Evaluate the calculated dose coagulant - Evaluate the predictive value of the constructed model on the reliability (number and accuracy of the measurements) and validity (tested range, industrial vs. laboratory setting)
E Let students compare different modelling approaches: - compare the black-box modelling approach with the mechanistic approach	IV | TLA 18 – 19 Factsheet	- Identify the black-box modelling approach and reflect on pro and cons: • Quick and cheap • Suitable to describe process behaviour • No solid mechanistic foundation - Evaluate the constructed model and formulate future research - Formulate a generic modelling procedure for input-output systems

8

Valuation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education[1]

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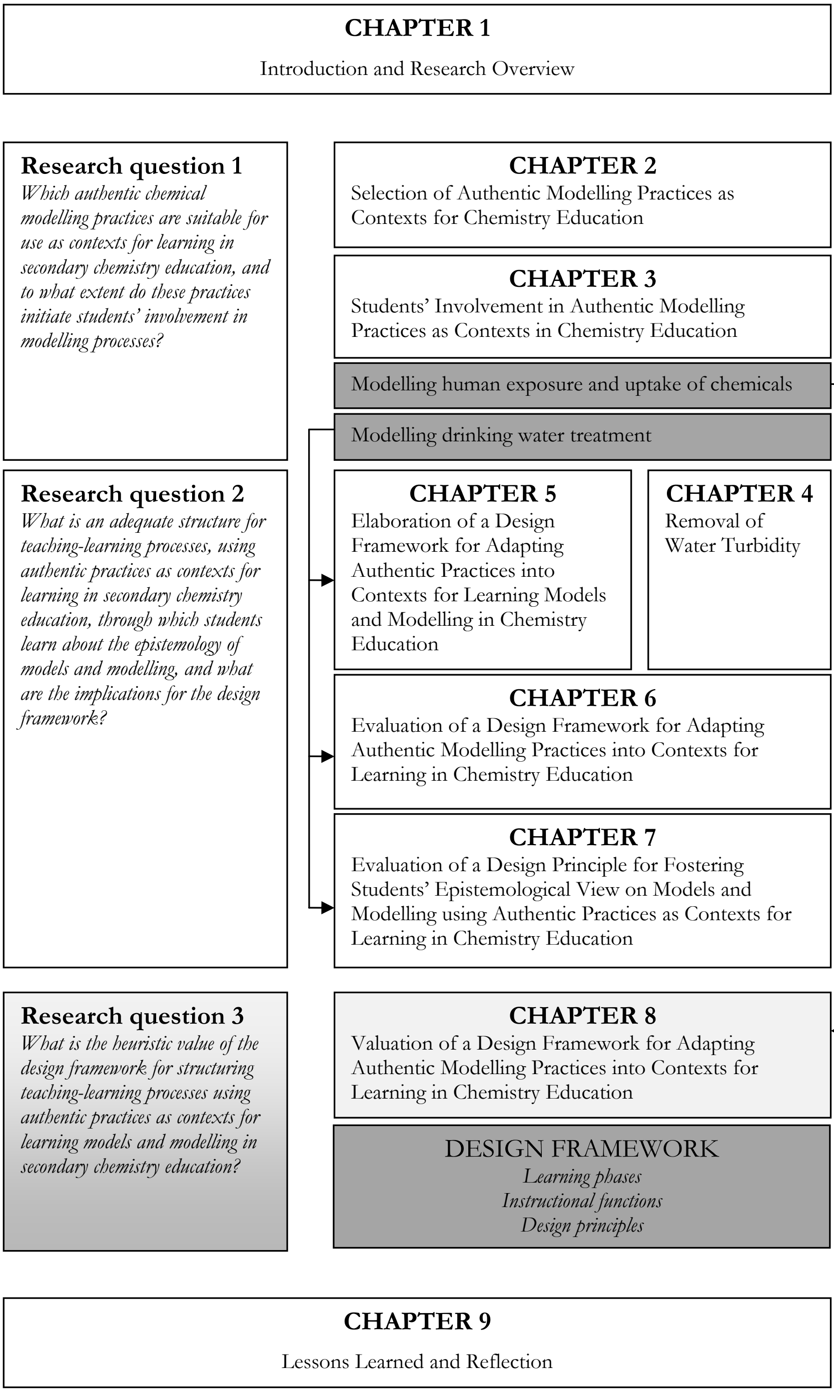
CHAPTER 1
Introduction and Research Overview
Research question 1
Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?
CHAPTER 2
Selection of Authentic Modelling Practices as Contexts for Chemistry Education
CHAPTER 3
Students' Involvement in Authentic Modelling Practices as Contexts in Chemistry Education
Modelling human exposure and uptake of chemicals
Modelling drinking water treatment
Research question 2
What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?
CHAPTER 5
Elaboration of a Design Framework for Adapting Authentic Practices into Contexts for Learning Models and Modelling in Chemistry Education
CHAPTER 4
Removal of Water Turbidity
CHAPTER 6
Evaluation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education
CHAPTER 7
Evaluation of a Design Principle for Fostering Students' Epistemological View on Models and Modelling using Authentic Practices as Contexts for Learning in Chemistry Education
Research question 3
What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?
CHAPTER 8
Valuation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education
DESIGN FRAMEWORK
Learning phases
Instructional functions
Design principles
CHAPTER 9
Lessons Learned and Reflection

In Chapter 8 the heuristic value of the design framework is evaluated. The design framework is applied for adapting the authentic practice of ‘modelling human exposure and uptake of chemicals from consumer products’ into a context for learning for upper secondary chemistry education. This practice was selected as suitable in previous studies (cf. Chapters 2 and 3). The adaptation was undertaken by six experienced chemistry teachers, who were well informed about the design framework. The heuristic value was determined on three dimensions: completeness, instructiveness and appreciation. The analysis of the process of adaptation and the teaching materials produced show that the design framework provides useful guidelines for structuring teaching-learning processes. Specific points to account for are the need to evoke a motive among students to model an example problem themselves and the specific outcomes of the evaluation and reflection phase.

The central research question addressed is:
What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?

Abstract

For adapting authentic practices into contexts for learning, there is need for a explicit knowledge base. In this study, we use a design framework, a synthesis of three design principles, learning phases and instructional functions, to adapt authentic modelling practices into contexts for learning for pre-academic chemistry education. An authentic practice is characterised by shared purposes, common motives and standardised procedures using relevant issue knowledge, tools and attitudes. The design framework provides heuristic guidelines for structuring teaching-learning processes. The design principle 'context' deals with involving learners in a focal event embedded in its cultural setting. This implies the setting, the behavioural environment, the specific language and the extra-situational background knowledge, such that students become engaged in a modelling activity. The design principle 'content modelling' deals with focussing learners on the essential generic content regarding models and modelling. The design principle 'chain of activities' deals with constructing a sequence of teaching-learning activities such that learners constantly know 'why what to do' at every step in the process. The adaptation was conducted by a design team consisting of six experienced chemistry teachers and one researcher. The heuristics provided by the design framework are valued on the dimensions of completeness, instructiveness and appreciation. The results show that the design framework is complete and highly appreciated. However, the instructiveness can further be improved by incorporating explicit guidelines for reflection, as well as for evoking students' motives to become engaged in an example problem. Future research should focus on the broader applicability of the proposed design framework. Further development of such design frameworks is important, since in many curriculum innovations teachers are designated as developers of teaching-learning processes.

Introduction

Research on educational design has drawn attention in the past decade, particularly in the field of (science) education (Van den Akker, Gravemeijer, McKenny, & Nieveen, 2006). This interest has grown from the recognition that general philosophical orientations on learning and instruction, like constructivism or the sociocultural tradition, often fail to provide detailed guidance in *designing* teaching-learning processes at a concrete level in the classroom. This might especially hold for fields characterised by a dominant, rather inert body of knowledge, like science or mathematics. During educational design processes, there is a variety of decisions to be made regarding the specific content, the type of classroom activity, the respective roles of teacher and students, the teaching resources, the various possibilities of class organisation etc. To address these questions, the 'design-based research collective' suggests that proper design-based research should lead to 'sharable theories' that help to communicate relevant implications to educational designers (Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003).

These 'sharable theories' should consist of guidelines, rules, heuristics and theoretical aspects at different levels of abstraction, thus linking general philosophical orientations with the actual teaching and learning in the classroom. In addition, such 'sharable theories' should offer opportunities to be investigated empirically in order to improve, refine or refute the 'sharable theory'. At present, we lack such empirically testable 'sharable theories'. Moreover, within the research community there is hardly consensus about the nature of such 'sharable theories'. In the remaining part of this paper we use the term 'design framework' to denote a 'sharable theory' that informs educational designers about the design of teaching-learning processes using authentic modelling practices as contexts for learning.

In previous research studies we used activity theory in education as the general philosophical orientation from which to start (Prins, Bulte, Van Driel, & Pilot, 2008). Consequently, we use authentic chemical practices as contexts for learning. Authentic practices are characterised by shared purposes, common motives and standardised procedures using relevant issue knowledge, tools and attitudes (Prins et al., 2008). We systematically adapted the practice 'Modelling of drinking water treatment' into a context for learning models and modelling. We concentrated on making explicit learning aims, formulated learning phases, elaborated design principles and finally constructed a design framework (Prins, Bulte, & Pilot, Submitted-a). The curriculum unit was put into practice in classrooms, and the empirical findings were interpreted in relation to the design framework (Prins, Bulte, & Pilot, Submitted-b). The design framework was initially based on theoretical arguments, and the teachers' and researchers' own practical considerations and valuations, and in latter stages it was enriched by empirical findings (Prins et al., Submitted-b; Prins, Bulte, & Pilot, Submitted-c). In this study, we use the design framework to adapt another authentic practice, namely 'Modelling human exposure and uptake of chemicals from consumer products'. The aim of this paper is to investigate the heuristic value of the design framework for adapting authentic modelling practices into contexts for learning.

Theoretical framework

In this section we first focus on the area of interest: learning about models and modelling in pre-academic chemistry education. Next, we describe activity theory in education as a general philosophical orientation. This section ends by describing the design framework as it emerged from our previous research, with emphasis on the design principles, learning phases and accompanying instructional functions.

Learning models and modelling

In science education, the terms model and modelling are used quite ambiguously (Harrison and Treagust, 2000). In this paper we concentrate on learning models and modelling within the domain of chemistry. We use the term model to describe some structured representation, including symbolic elements, of the essential characteristics of an idea, object, event, process or system (Gilbert and Boulter, 2000). Examples of models used in science and technology are iconic and symbolic models to depict chemical formulae and chemical equations, mathematical models to represent conceptual relationships of physical properties and processes (e.g. $PV = nRT$), and theoretical models to describe well-grounded theoretical entities (e.g. kinetic theory model of gas volume, temperature and pressure). We define the act of modelling as the construction, evaluation and revision of a model in response to a particular task (Van der Valk, Van Driel, & De Vos, 2007).

The exploratory study of Grosslight, Unger, Jay, and Smith (1991) revealed that students generally do not clearly distinguish between the ideas and/or purposes underlying models, and have trouble with advanced model features like validity and reliability. In addition, students lack insight into the process of modelling, that is, the construction, testing and evaluation of models (Erduran and Duschl, 2004).

To overcome these learning problems related to models and modelling, it has been suggested that students should be involved in modelling processes. By doing so, students come to learn the characteristics of models (Erduran and Duschl, 2004; Gobert and Pallant, 2004). Our approach is to adapt authentic chemical modelling practices into contexts for learning (Bulte, Westbroek, Van Rens, & Pilot, 2004). The use of authentic practices in education stems from and relates to the situational nature of cognition (Brown, Collins, & Duguid, 1989), and activity theory in education (Leont'ev, 1978), rooted in the sociocultural tradition (Vygotsky, 1978). Both philosophical orientations are briefly portrayed.

Philosophical orientations

In response to Dewey's (1964) recommendations, authenticity has become an objective for innovation in science education. A number of research studies has shown that students often fail to apply the knowledge taught in school in real-world settings. Brown, Collins and Duguid (1989) argue that knowledge is situated, being in part a product of the activity, practice and culture in which it is developed. This view of knowledge affects our understanding of learning: 'Authentic activity … is important for learners, because it is the only way they gain access to the standpoint that enables practitioners to act meaningfully and purposefully' (Brown et al., 1989, p. 36).

Learning environments that reflect a real-world setting are expected to encourage learners to see more opportunities to apply the new learning. A well known pedagogic approach commonly associated with the situated nature of knowledge is cognitive apprenticeship. Cognitive apprenticeship supports learning by enabling students to acquire, develop and use cognitive tools in authentic situated activity. Furthermore, cognitive apprenticeship aims to enculturate students into authentic practices through activity and social interaction. In cognitive apprenticeship the notion of learning is viewed as an emerging property of the whole person's legitimate peripheral participation in communities of practice (Lave, 1996).

Activity theory, rooted in the sociocultural tradition, describes society in terms of connected social practices as manifestations of activity (Leont'ev, 1978; Vygotsky, 1978). The abstract concept of activity has been described in detail by Engestroem (1987). In its simplest form, an activity is defined as the engagement of a subject in pursuit of a certain goal or objective. The *subject* refers to the individual or group whose agency is chosen as the point of view in the analysis. The *object* refers to the 'raw material' or 'problem space' at which activity is directed and which is moulded and transformed into *outcomes*. Activity theory regards the 'activity' as the primary 'unit of knowledge'. Human activity is driven by an object-related motive and carried out within a community. The activity consists of (a chain of) actions, which in turn are realized through operations. Activity is mediated by instruments created by humans, such as tools and language and social relations.

The associated pedagogic approach is that a learner enters into a cognitive apprenticeship with the teacher who interprets the practice (Gilbert, 2006). From the socially accepted attributes of a given practice the teacher's task is to identify the attributes which are recognised and mastered by students, and the attributes which lie in the 'zone of proximal development' of the students

(Confrey, 1995). The recognised and mastered attributes form the starting point of the learning process. These attributes can be used to introduce the social practice and facilitate students' involvement. The attributes identified within the 'zone of proximal development' embody the notion of learning.

Design framework for adapting authentic practices into contexts for learning

For the phases in the teaching-learning process and the instructional functions, we use an 'instructional version of an authentic practice'. This phasing emerged from research on the feasibility and effects of an 'authentic practice based curriculum unit' in the classroom (Bulte, Westbroek, De Jong, & Pilot, 2006), inspired by previous research on meaningful teaching-learning strategies (Kortland, 2001; Westbroek, 2005).

The learning phases are synthesised with design principles (Van den Akker, 1999). Inspired by McKenny, Nieveen and Van den Akker (2006), we define design principles as theoretically and empirically grounded constructs linking *strategy components* (e.g., what to do, how precisely to do it, when in the sequence, with what tools and how enacted), *pedagogic effects* (e.g. students' epistemological views on models and modelling), and *arguments* (e.g. literature on educational research, empirical findings from previous applications and/or practical considerations). The three design principles we have formulated are labelled: context, content modelling and chain of activities. These design principles are briefly described.

Design principle 'context'

The design principle of *context* deals with involving learners in a focal event embedded in its cultural setting (Gilbert, 2006). This implies that the setting, the behavioural environment, the specific language and the extra-situational background knowledge are such that students become engaged in a modelling activity. We need to account for significant differences between experts, who in general are well-informed in the field in which they are employed, and learners, who lack basic affinity and essential background information. In addition, the school environment is completely different from the environments in which experts work, both in aims and cultural role and function in society. In short: what is authentic for experts is not equally authentic for learners. Thus, one of the first stages in adapting an authentic modelling practice is a careful analysis of the attributes which are already known and mastered by students, and the attributes which are within the 'zone of proximal development' of students. Using this information, students need to be introduced to the practice such that object-related motives for modelling will arise. Figure 1 depicts the strategy components leading to the intended pedagogic effects and underlying arguments, as elaborated and tested in previous research (Prins et al., Submitted-b).

Strategy components

1 Provide students with an orientation base: supply broad overview of the subject dealt with as well as the authentic practice at hand
2 Give students a rich, whole task
3 Select essential situated knowledge and supply it to students by means of articles and/or manuals
4 Organise students to ensure that they keep track of situated knowledge
5 Select an end product, matching the example problem, to assess students' performance

… expected to result in …

… because of …

Pedagogic effects

1 Students activate their prior conceptual knowledge base (***a***) and display motivation to study the problems posed in the practice (***c***)
2 Students are willing and show ownership to work on an exemplary problem (***d***)
3 Students proceed through the sequence of activities and learn/apply knowledge until a satisfactory solution for the exemplary problem can be presented (***h***)
4,5 Students make explicit the learned conceptual and procedural knowledge (***k***)

Arguments

1 Previous applications of an authentic practice based curriculum unit have shown that (1) students need a broad overview of the subject dealt with in order to position the exemplary problem they are going to work on, (2) emphasising the societal relevance evokes students' broad interest and (3) it is important to provide students with a view on the *what* (construct a model), *how* (modelling) and *why* (content-related motive).
2 Previous applications of an authentic practice based curriculum unit have revealed that providing students with a whole rich task fosters students' motivation, willingness and sense of ownership.
3 Previous applications of an authentic practice based curriculum unit have shown that it is important to select and supply to students the essential situated knowledge to avoid cognitive overload. Furthermore, the knowledge needs to be split up in proportional pieces and communicated to students 'just in time'. The use of articles and/or manuals fosters students' sense of authenticity and corresponds with the common method of information search by experts.
4 Previous applications of an authentic practice based curriculum unit have proved that explicitly recording the situated conceptual knowledge encountered fosters students' understanding of key concepts.
5 Previous enactments of an authentic practice based curriculum unit have shown that it is important to select a suitable assessment tool fitting the example problem and the students' tasks.

Figure 1. Conceptualised scheme of the design principle 'context'. The numbers connect strategy components with expected pedagogic effects and underlying arguments. The italic letters in 'Pedagogic effects' refer to the instructional functions in Figure 4.

Design principle 'content modelling'

The design principle of *content modelling* deals with focussing learners on the essential generic content regarding models and modelling. Using authentic chemical modelling practices as contexts for learning, it is tempting to regard the experts' issue knowledge as intended learning outcomes for students. However, while some of what the experts do is very specific for their work and is best taught by 'on-the-job' training, there is also likely to be a core of generic content which is common to all modelling practices within the chemistry domain (Gott, Duggan, & Johnson, 1999). This generic content includes the applied modelling procedure and the epistemic notions such as purpose, validity, reliability and goodness of fit. Figure 2 depicts the strategy components leading to the intended pedagogic effects and underlying arguments, as elaborated and tested in previous research (Prins et al., Submitted-c).

Design principle 'chain of activities'

The design principle of *chain of activities* deals with constructing a sequence of teaching-learning activities such that learners constantly know *why what* to do at every step in the process. In general, experts know *why what* to do at every stage in the chain of modelling activities. Experts have clear content-related motives to go from one activity to the next, inspired by relevant background information on the modelling issue.

Strategy components

- A Visualise and conceptualise for students the example modelling problem on which they are going to work
- B Supply students with a worked-out analogous modelling problem as leading example
- C Discuss with students different modelling approaches and point out an appropriate one for the example problem at hand
- D Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand
- E Let students apply the constructed model in a real-world setting
- F Let students compare different modelling approaches and reflect on the assumptions and estimations made, and the possible effect of neglected variables

… *expected to result in* …

… *because of* …

Pedagogic effects

- A Students activate their prior conceptual knowledge base (***a***) and their procedural knowledge base (***b***)
- B Students make explicit and build on their prior conceptual knowledge base (***e***) and their procedural knowledge base (***f***)
- C,D Students proceed through the sequence of activities and learn/apply detailed knowledge until a satisfactory solution for the exemplary problem can be presented (***h***)
- E Students evaluate the learned conceptual and procedural knowledge (***i***)
- F Students reflect on the epistemology of models and modelling (***j***)

Arguments

- A Previous applications of an authentic practice based curriculum unit have proved that visualisation of the modelling problem evokes students' notions concerning a modelling procedure. By conceptualising the modelling problem, students grasp the broader applicability of the modelling procedure to be learned.
- B It is found that supplying students with an advanced organiser informs students' views on activities to conduct and (type of) knowledge to learn/apply. Previous applications of an authentic practice based curriculum unit have revealed that a worked-out analogous modelling problem serves as a suitable organiser. It provides students with a view on epistemic values to take into account and the end product to deliver.
- C Previous applications of an authentic practice based curriculum unit have proved that discussing different modelling approaches for the problem at hand fosters reflection on the applied approach in learning phase IV. Students become aware that multiple modelling approaches exist.
- D It is found that emergent modelling, e.g., gradually formalising empirical data in mathematical models, is a suitable way to guide students through levels of abstraction.
- E Previous enactments of an authentic practice based curriculum unit have shown that it is needed to guide students back to the 'purpose of the modelling'. The epistemic values of purpose, goodness of fit, reliability and validity become meaningful to students when evaluating the model outcomes in a real-world setting.
- F Previous enactments of an authentic practice based curriculum unit have proved that comparing modelling approaches induces reflection on the pros and cons. Students become aware that multiple modelling approaches exist with different epistemologies.

Figure 2. Conceptualised scheme of the design principle 'content modelling'. The capital letters connect strategy components with expected pedagogic effects and underlying arguments. The italic letters in 'Pedagogic effects' refer to the instructional functions in Figure 4.

The challenge is to construct a sequence of teaching-learning activities such that students can also see *why what* to do at every stage (Lijnse and Klaassen, 2004). The experts' chain of activities provides a basic outline for the sequence of teaching-learning activities. Next, each activity needs to be evaluated from students' perspective according to the problem-posing approach (Klaassen, 1995), so that every teaching-learning activity builds on the previous one and prepares the next one. Figure 3 depicts the strategy components leading to the intended pedagogic effects and underlying arguments, as elaborated and tested in previous research (Prins et al., Submitted-b).

Strategy components

i Give students a clear assignment concerning the example problem they are to work on and direct their attention to the end product they are to deliver
ii Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration
iii Plan regular meetings with students to look ahead to future activities

… *expected to results in…*

… *because of* …

Pedagogic effects

i Students have a motive to learn/apply knowledge to solve the example problem at hand (***g***). Students have a view on the way results and findings are to be reported (***k***)
ii Students are aware about *why what to do* at every point in the teaching-learning process. Students see the point of every teaching-learning activity in the sequence leading to an outcome (***h***)
iii Students constantly have the purpose in mind and record 'how far we have come' and 'what still needs to be done' (***h***)

Arguments

i Previous applications of an authentic practice based curriculum unit showed that prolonged engagement is established by providing students with a clear assignment.
ii It is found that the experts' modelling procedure complies with students' notions regarding solving the example problem. Previous applications of an authentic practice based curriculum unit showed that in order to construct an ongoing sequence of teaching-learning activities each modelling stage needs to be evaluated from students' perspective.
iii Previous applications of an authentic practice based curriculum unit revealed that regular meetings keep students 'on track'. Students record the tasks already accomplished and future tasks, while keeping the purpose of the modelling in mind. Students experience how each modelling stage builds on the previous one and prepares the next one.

Figure 3. Conceptualised scheme of a design principle chain of activities. The roman numerals connect strategy components with expected pedagogic effects and underlying arguments. The italic letters in 'Pedagogic effects' refer to the instructional functions in Figure 4.

The design framework consists of a synthesis of the three design principles, learning phases and instructional functions, as depicted in Figure 4. The design framework gives a compendious overview of placement of the strategy components in the teaching-learning process. The design principles cover multiple learning phases. The pedagogic effects in the design principles build on the instructional functions. Although the design principles are formulated as separate entities, they overlap at some points.

Scope and research questions

This project is part of a larger research programme on the use of authentic practices as contexts for learning in pre-academic chemistry education. In the previous studies, two authentic practices were selected as feasible: 'Modelling drinking water treatment' and 'Modelling human exposure and uptake of chemicals from consumer products' (Prins et al., 2008; Prins, Bulte, Van Driel, & Pilot, 2009). Next, we adapted the practice 'Modelling drinking water treatment' into a context for learning and designed a curriculum unit that was applied in classrooms (Prins et al., Submitted-a, Submitted-b, Submitted-c). The adaptation was conducted in close cooperation with six experienced chemistry teachers. All six teachers put the unit into practice in their own classrooms.

The complete design process consisted of two research cycles. During the research cycles we identified and summarised all acquired experiences and conceptualised the findings in a design framework. The present study builds on the emerging design framework.

In this study, the practice 'Modelling human exposure and uptake of chemicals from consumer products' is adapted into a context for learning. The major aim is to gain insight into the heuristic value provided by the design framework. The heuristic value is captured on three dimensions: completeness, instructiveness and appreciation (Mettes and Pilot, 1980, p. 188, 268). The design framework is applied by a design team consisting of the same six experienced chemistry teachers and one researcher (first author of this paper). The central research question addressed here is: *What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?*

Design Framework			
Learning phases / Instructional functions	*Design principles*		
	Context	*Chain of activities*	*Content*
I: Orientate on the practice ***a)*** Connect to the prior conceptual knowledge base ***b)*** Connect to the prior procedural knowledge base ***c)*** Evoke motivation to study the problems posed in the practice ***d)*** Evoke a motive to zoom in on an example problem	**Strategy component 1:** Provide students with an orientation base: supply broad overview of the subject dealt with as well as the authentic practice at hand **Strategy component 2:** Give students a rich, whole task		**Strategy component A:** Visualise and conceptualise for students the example problem they are going to work on
II: Zoom in on an example problem ***e)*** Make explicit and build on the prior conceptual knowledge base ***f)*** Make explicit and build on the prior procedural knowledge base ***g)*** Evoke a motive to solve the example problem		**Strategy component i:** Give students a clear assignment concerning the example problem they are to work on and direct their attention to the end product they are to deliver	**Strategy component B:** Supply students with a worked-out analogous modelling problem as leading example
III: Solve the example problem ***h)*** Proceed through the sequence of activities and learn/apply knowledge until a satisfactory solution for the example problem can be presented	**Strategy component 3:** Select the essential situated knowledge and supply it to students by means of articles and/or manuals **Strategy component 4:** Organise students to ensure that they keep track of situated knowledge	**Strategy component ii:** Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration **Strategy component iii:** Plan regular meetings with students to look ahead to future activities	**Strategy component C:** Discuss with students different modelling approaches and point out an appropriate one for the example problem at hand **Strategy component D:** Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand
IV: Evaluate and reflect on the findings ***i)*** Evaluate the learned conceptual and procedural knowledge ***j)*** Reflect on the procedural knowledge			**Strategy component E:** Let students apply the constructed model in a real-world setting **Strategy component F:** Let students compare different modelling approaches and reflect on the assumptions and estimations made, and the possible effect of neglected variables
V: express the findings ***k)*** Make explicit the learned conceptual and procedural knowledge	**Strategy component 5:** Select an end product, matching the example problem, to assess students' performance		

Figure 4. A design framework, a synthesis of design principles, learning phases and instructional functions, providing a heuristic guidelines for structuring teaching-learning processes using authentic modelling practices as contexts for learning.

Method

This section presents the participants and a description of the authentic practice 'Modelling human exposure and uptake of chemicals from consumer products' and of the collection and analysis of data. This study concerns phenomenological research in which the design framework is the phenomenon under examination (Creswell, 2007). Given the purpose of the study, the data collected are essentially qualitative.

Participants

The design team consisted of six experienced chemistry teachers and one researcher (first author of this paper). All members of the design team participated in the previous research projects in which the authentic practice 'Modelling drinking water treatment' was adapted into a context for learning. Each one of the teachers had over 10 years' experience in secondary chemistry education, from grade 8 to grade 12. The design team came together in the period from January 2008 to July 2008. Three meetings of three hours each were organised, in which the authentic practice at hand was elaborated and the design framework was used to adapt the practice into a context for learning.

Authentic practice 'Modelling human exposure and uptake of chemicals from consumer products'

In this section we broadly describe the authentic practice 'Modelling human exposure and uptake of chemicals from consumer products'. This practice has been studied in detail in our previous study (Prins et al., 2008).

Motives for modelling human exposure and uptake

There is a wide diversity of consumer products, ranging from shoe polish to detergents and pesticides, that may contain hazardous chemicals. Consumers use all kinds of products for their personal convenience on a daily basis. In the Netherlands, the manufacturers themselves are responsible for the safety of their products, for which they use different systems. A commonly used method is expert judgement. However, when a product is encountered with questionable health risks, a quantitative judgement about the actual human health risks is also needed. For such assessment, one needs to calculate the total uptake of potentially hazardous chemicals from consumer products, based on detailed information on the composition of the product itself and on the contact route. In response to this need, the National Institute of Public Health and the Environment developed the 'Consumer Exposure' (CONSEXPO) tool (Van Veen, 2001) with the aim of developing mathematical models to describe exposure and uptake of chemicals from consumer products, and to assist in conducting a quantitative risk assessment.

Situated and modelling knowledge involved

As may be clear from the above description, the CONSEXPO tool comprises a wide diversity of consumer products, exposure and contact routes, and mathematical models. Prior to adapting this practice into a context for learning, we decided to reduce the complexity (Prins et al., 2009). We focus merely on the uptake of chemicals from consumer products from the contact route 'by mouth'. For the contact route 'by mouth' several physical models are available, like single ingestion $E = \frac{w_f q}{DV_{product}}$ and leaching from product $E(t) = E_0 \exp^{-\left(\frac{RA}{E_0 V}t\right)}$.

In these models E is the amount of the compound taken up. Both models contain empirical parameters, like the initial leaching rate (R), parameters specific for the product at hand, such as the initial amount of compound (E_0), weight fraction (w_f), surface (A) and volume (V), and parameters related to type of use, like amount of product (q), dilution (D) and duration (t). The main modelling activities and situated knowledge are shown in Figure 5.

Data collection and analysis

At the first meeting, the participants elaborated the design framework as it emerged from the previous research studies concerning the adaption and application in classrooms of the authentic practice based curriculum unit 'Modelling drinking water treatment'. The main purpose of the first meeting was to become acquainted with the design framework. The elaboration was focussed on the five learning phases and the accompanying design principles of context, content modelling and chain of activities. Furthermore, the design team studied the authentic motives and purposes, the modelling procedure and the situated knowledge of the authentic practice 'Modelling human exposure and uptake of chemicals from consumer products'.

Preceding the second meeting, all teachers individually adapted the authentic practice 'Modelling human exposure and uptake of chemicals from consumer products' into a context for learning using the design framework. In the second meeting the six teachers were grouped into three pairs. Each pair discussed the designed contexts for learning with a focus on similarities and differences. Next, each pair constructed one context for learning based on their own designs, and presented their findings to the other participants. At the end of the second meeting, three combined contexts for learning were available. The discussions and plenary presentations were audio-taped.

Preceding the third meeting, the researcher (first author) analysed the three combined contexts for learning and merged them into one context for learning. This context for learning was brought back to the entire design team in the third meeting, where it was discussed and evaluated. The plenary discussion was audio-taped.

The collected data sources are audio-taped conversations of plenary sessions and teams at work, and the written contexts for learning, both individual (6) and combined (3). All audio-taped conversations were transcribed *verbatim*. Next, the data was analysed from an interpretative perspective (Smith, 1995).

The analysis consisted of three stages. In the first stage, the researcher (first author), categorised all the data according to:

1. learning phase: I–V.
2. design principle: context (1–5) – content modelling (A–F) – chain of activities (i–iii).

In the second stage, the empirical data was analysed by two researchers (first author and a critical associate) independently. Each learning phase and design principle was valued on three dimensions, namely completeness, instructiveness and appreciation, in terms of high, moderate or poor. A design principle itself was valued high, if at least 80% of the strategy components were valued high by the both researchers. A low value was given if 20% (or less) of the strategy components were judged low. If somewhere between these extremes, the design principle was deemed moderate. In the third stage, all findings and results were discussed by the complete research team (three authors of this paper) and the outcomes were described in a summary of the valuation.

Modelling procedure	Situated knowledge
Quantify human exposure and uptake of chemicals out of consumer products. Develop additional method next to existing expert judgement	General overview of potential harmful substances in consumer products Background knowledge on contact route/uptake/ modelling
Describe exposure routes of chemicals from consumer products to humans. ↓ Identification of hazardous chemical compounds per product ↓ Identification of exposure routes of chemical compounds from product	<u>Contact:</u> - Exposure - Uptake (inhale, skin, mouth) - Scenario's (duration, frequency) Categorisation of consumer products Mixtures/pure substances/solvents Concentration (weight fraction) Evaporation characteristics/Mass balances for evaporation Diffusion Chemical identification of substances Molecular structure of substances
Develop mathematical models describing exposure ↓ Quantification of relevant parameters by experiments ↕ Model calibration	<u>Statistics:</u> - Averages - Standard deviation - Distributions: ▪ mean ▪ uniform ▪ empirical Differential equations Systematic modelling approach
Validate model by calculating human uptake in several case scenarios and combine with expert judgement	<u>Dose-effect relations:</u> - Long-term average vs. acute - Worst case dose - Standard dose
Evaluation of model ↓ Reflection on starting questions or problems	Dealing with uncertainties Risk assessment

Figure 5. The modelling procedure and situated knowledge in the authentic practice 'Modelling human exposure and uptake of chemicals from consumer products'. Arrows indicate the direction of the modelling process.

Results

For the sake of clarity, we present the major decisional points and exemplary statements arising from the three meetings. The findings are categorised per design principles and learning phases. The resulting context for learning is described in Appendix A.

Findings on the design principles

Below, we present the findings for the three design principles of context, content modelling and chain of activities. In Table 1 the valuations and considerations regarding the heuristics provided by the design principles are summarised.

Table 1. The heuristic value of the design principles 'context', 'content modelling' and 'chain of activities', and learning phases & instructional functions, judged along the dimensions of completeness, instructiveness and appreciation.

Design principles, learning phases & instructional functions	**Dimensions and valuations**			**Major considerations**
	Completeness	*Instructiveness*	*Appreciation*	
Design principle: context	High	Moderate	High	- Point of attention: evoke a content-related motive among students for modelling an example problem themselves
Design principle: content modelling	Moderate	Moderate	High	- Applied by all teams: use an analogous problem as advanced organiser - Under discussion: construct or provide the employed models to students
Design principle: chain of activities	High	Moderate	High	- The experts' modelling procedure is a valuable design tool for outlining a sequence of teaching-learning activities
Learning phases & instructional functions	High	Moderate	High	- The design of the orientation phase, in order to achieve proper students' involvement, bears much uncertainty - Point of attention: induce a motive among students to evaluate and reflect on the findings. - Supply strategy components for evaluation and reflection

Design principle context

Team 1 started with a short analysis on the expected students' views of the practice. Although the practice is regarded as potentially interesting for students, they concluded that 'it will be difficult to get the students in the proper line' and 'students are not automatically owners of the problems posed'. It was thus felt necessary to illustrate the problems posed by focussing on chemicals released from consumer products which students use regularly themselves, like earrings, necklaces, cosmetics etc. Team 1 suggested starting with an orientation on the production process of consumer products. The main arguments for such an introduction were:

- to make students aware that chemicals which are put into consumer products might also come out during use;
- to point out to students that some chemicals are necessary to give consumer products desirable properties;
- to rule out the 'easy' solution which students may come up with: 'just don't use the potential hazardous chemicals in consumer products' or 'use harmless alternatives'.

Team 1 emphasised the need to point out to students the general concern among the public, by means of newspaper items about the release of hazardous chemicals. In this stage, they suggested introducing the Dutch government institute, Voedsel & Waren Autoriteit (VWA), as being responsible for risk assessment and public communication regarding products with questionable health risks.

> *Teacher 1: … I continued, because the task of VWA is stated clearly on their website. The employees working [there] have three major tasks: supervision, risk assessment of new and/or suspected products and communication about health risks. Regardless of the exact type of products, you would like students to perform a risk assessment followed by a communication …*

After discussion, team 1 decided to pick the release of dyes from the tops of water bottles, which are used daily by students, as an example problem. Next, students should formulate a modelling procedure for determining the total uptake of dyes from the tops of water bottles, facilitated by, for instance, the website of the VWA. However, the team stressed the importance of a careful planned route for the knowledge acquisition, to avoid students being drowned in details.

> *Teacher 2: In the previous case* [the adaptation of the practice 'Modelling drinking water treatment'] *students focussed on understanding the analogue problem. As a teacher you must guide students to focus on essential knowledge only.*

Finally, the team proposed to (1) discuss the formulated modelling procedures, (2) make an inventory of empirical data to be collected and (3) point out the type of end product to be delivered by students.

Team 2 started with an analysis of the attributes from the practice which are 'not mastered' by students. The team concluded that the students most probably were unaware about exposure and uptake routes, legally-imposed norms and legislation and dose-effect relations. To introduce the practice, the team decided to focus students on the potentially hazardous chemicals in non-food products by means of (1) newspaper items, (2) internet search and (3) label analysis of some consumer products.

Teacher 3: … for instance, by means of newspaper items, the problems will become clear to students, it frames the type of problems [non-food products] and students also get a view of the actors involved.

Team 2 considered it important that the introduction should open ways to bring in relevant chemical knowledge:

Teacher 4: Chemical knowledge … substances added to give products certain desirable properties … doing so, you [the teacher] can raise the theories concerning polymers or phthalates.

Teacher 4: … for instance, let students analyse the composition of various products by studying the label.

It was also expected that students would be unfamiliar with the government institutes controlling and/or authorising the health safety of non-food products. By researching and comparing the products with questionable health risks, it was also expected that students would come to know that the answer to the question, 'Who is responsible of the health safety of the products?', is not always clear. As for the situated knowledge, team 2 decided to let students construct a list of concepts as they went along during the teaching-learning process. At the end, students should make their findings explicit by means of a report. In this report students should also point out the generic modelling procedure for problems of a similar type.

Team 3 decided to start with an orientation on the various exposure routes, and to represent the routes schematically. The team proposed to focus also on desirable uptake of chemicals. For instance, one issue is to administer a desirable amount of medicines in humans aged less than 3 years through the 'natural' uptake route by mouth.

Teacher 5: … on a conceptual level the problem is similar, and it emphasises the positive aspects …

Team 3 considered it necessary to expose students to the different actors involved, such as the manufacturers, experts, civil servants and researchers. To give students a view of the expected end product, team 3 discussed the opportunities to bring in as teaching material an allowance report dealing with another administration route. For the next stage, team 3 concentrated on outlining the relevant situated knowledge:

- orientate on the model employed (What is the meaning of each parameter involved? How do we measure each parameter?)
- study the laboratory work (read through prescripts, consult literature, analyse data)
- study and formulate a contact scenario, summarising estimations about the type, frequency and duration of use
- calculate the uptake with use of the model and contact scenario.

After having conducted all the work, students were expected to be able to evaluate their findings. They should answer the questions: 'Is the drug release above desired level?' and 'Is the release of potentially harmful substances below the legally set norms?', and finally, 'Is our new allowance method successful?'. This should motivate students to make explicit their conclusions (write allowance report), reflect on the procedure (limitations and uncertainties) and formulate future research.

In Table 1 the valuations and considerations regarding the design principle 'context' are summarised.

Design principle content modelling

Team 1 planned a demonstration in class to visualise the leaching out of chemicals, to inform students about the *what how* to do in the lessons to come. Team 1 decided to use an analogous problem to give students an idea about the type of activities to conduct. For this, an already written risk assessment for an other type of consumer product with a different contact route was proposed.

> *Teacher 1: … students become acquainted with the end product as well as the chain of activities to conduct…*

It was expected that such a strategy would (further) awake and strengthen students intuitive notions regarding the modelling activities. A major point of discussion was the timing to bring in the models to be employed, and the background knowledge regarding contact routes and scenarios.

Teacher 1: … the list of available models [for each contact route] scares students. The models are not readable. We should focus students on the essential procedural steps and knowledge first. The appropriate models should be presented later [in the teaching-learning process] …

Teacher 2: The studying of the theory … if you select the analogue problem such that the consumer product is quite similar [to tops of bottles], than you can use the same concepts again [in the teaching-learning process].

Teacher 1: Students have no knowledge about contact route and scenarios. But, you can use the authentic document [listing all the various scenarios, routes and models]. Students should be able to pick the most likely contact route [for tops of bottles].

Team 2 selected the leaching of phthalates as an example problem, to be visualised in class by the leaching of dyes. The leaching of dyes was thus considered as a 'model' for the leaching of phthalates. The deficiencies of this approach should be made explicit at the end of the teaching-learning process.

Teacher 4: Dyes as model for phthalates … it is not clear for me … is it about phthalates or dyes?

Teacher 3: … dyes as model for phthalates … the shortcomings of this model should be discussed at the end [of the teaching-learning process].

Next, team 2 considered it important to let students experience for themselves the release of phthalates, and to demonstrate to students the leaching of dyes.

Teacher 4: Let students smell different bottles of water: the released phthalates give each sample a different odour.

Teacher 4: … here we plan a practical demonstration in class … it will evoke among students intuitive notions regarding the problems and induce the question 'how to handle the problem?'. Lots of brainstorming, but students should come up with the idea to measure somehow the 'concentration of dyes' …

To evoke a modelling procedure among students, team 2 suggested orientating students on an analogous example dealing with another type of consumer product, such as toothpaste. The analogous example should be presented such that students would easily indentify the major steps in the procedure. By doing so, it was expected that students would be able to draw a modelling procedure for their own task: '*Preferably, students themselves should discover how to cope with our* *problem and which knowledge to learn*'. Team 2 discussed the benefits and disadvantages of (1) simply supply the employed models, or (2) deduce or construct a model themselves. Several arguments were brought to the fore:

> *Teacher 3: in the practice they [experts] just use the appropriate model. They know which one to use.*

> *Teacher 4: These models seem to originate from theories about condensed matter … do we want students to learn how these models are realised, or do they have to learn the authentic modelling procedure? That is my question. You do not pick a model from some predefined list.*

> *Teacher 3: In my case they [students] do! Students should ask themselves 'Which model is appropriate for use in this case?'. Afterwards, you [teacher] can clear up the model and discuss the origins in class. At the end [of the teaching-learning process] students evaluate the model employed: What are the limitations? … and maybe compare with the experts' approach: What are the differences with our approach?*

As for the experiment to conduct, a similar discussion was raised: 'Let students work according to a "straitjacket" prescript that works in line with the appropriate model (deduced from the authentic practice)' versus 'Let students design their own experiment and afterwards construct a model themselves'. The team left both options open and was unable to decide. After having collected all the (empirical) data, the team proposed to evaluate in class:

- the quality of the gathered results for a risk assessment
- the limitations of the employed model
- the followed modelling procedure.

Team 3 planned in a stage in which students orientate themselves on the procedure to follow for their example problem. For this they suggested using a worked-out analogous problem: a report summarising the findings concerning the release of phthalates out of personal decoration. It was emphasised that the modelling approach in both the example problem and the analogous problem should be the same on a conceptual level.

> *Teacher 6: … please keep in mind that the format of the report is completely different. Students are to deliver an allowance report for a new administration route, while they study research about the release of phthalates. The procedures then should be the same. I don't know whether this is the case …*

In Table 1 the valuations and considerations regarding the design principle 'content modelling' are summarised.

Design principle chain of activities

Team 1 used the general procedure followed by experts as the backbone of the sequence of students' activities.

> *Teacher 1: … you can see that they [experts] analyse the release [of chemicals] followed by the actual harmfulness of the chemicals, the exposure and finally the actual risk assessment and conclusions. And this is eventually also what we expect students to do…*

Team 1 examined the modelling procedure with special emphasis on the role and position of the experimental part in the sequence from the students' perspective.

> *Teacher 2: … the need for modelling should become clear to students … the experiment should be well positioned in the risk assessment procedure …*

The need for modelling should arise among students from the recognition that you cannot actually measure the uptake 'directly in humans'. This notion was considered crucial, because '*otherwise they just do the tasks we give them without understanding why*'. From this, a chain of motives, from the students' perspective, was proposed, as exemplified by the statement below:

> *Teacher 2: … the order should be (1) clarify need for modelling, (2) focus on contact routes, (3) study available models describing contact routes and (4) conduct experiments to collect empirical data.*

Team 2 also proposed that students should focus explicitly on the authentic procedure followed by experts, specifically those employed by the Dutch government institute Voedsel & Waren Autoriteit (VWA), dealing with quantifying the potential health risks of chemicals released from consumer products. The working procedure of experts was analysed thoroughly. It was concluded that the experts' modelling procedure forms the frame for outlining the sequence of activities, although not all steps would be obvious to students.

> *Teacher 4: … the method of the professionals … that is the main frame, also for me to understand [what exactly is going on] … not all is obvious [for students] … for instance … the contact routes and employed models … we need to design extra teaching-learning activities to pay attention to this.*

Team 3 proposed to the give students the task of writing an allowance report for a new administration route.

> *Teacher 5: … let's position students in the role of a manufacturer who would like to introduce a new administration route on the market. Preceding such introduction, the new administration route should be augmented, empirically tested and justified. The specifications should be known …*

Students were to be given a straightforward assignment to 'develop and investigate a new administration route for medicines for humans aged less than 3 years'. The procedure to follow (as outlined in Figure 4) was considered rather straightforward and in line with students' commonsense notions. However, the team identified several stages in the procedure in which students' motives should be carefully examined.

> *Teacher 6: … very important that students know that in the experiment they only measure the release rate … and subsequently use this information to calculate different scenarios … the theory on diffusion etc. should be introduced to students when they are 'ready' for it and it fits in the course.*

In Table 1 the valuations and considerations regarding the design principle 'chain of activities' are summarised.

Findings on the learning phases

Below, we present the findings for each of the five learning phases. In Table 1 the valuations and considerations concerning the learning phases and instructional functions are summarised.

Learning phase I: Orientation on the practice

The design team unanimously decided to start the curriculum unit with a broad orientation on 'uptake of chemicals out of consumer products by humans'. Next, an explicit focus on the actors involved was proposed. In this stage students should concentrate on questions such as, 'Who is responsible?', 'Who does what?' and 'What are the various stages in risk assessment?'. Following this introduction, it was proposed to conceptualise risk assessment in terms of 'chemicals in a product' taken up through some 'contact route' by a 'specific consumer'. It was expected that such representation (in a picture) would organise and activate students' prior knowledge base by asking 'What do we need to know for each category in order to calculate the total uptake?':

> *Teacher 1: … the three categories [framed] into some kind of picture could function as a 'roadmap' for students. Where am I now? To which category does this information belong? … You can recall this roadmap whenever needed in the teaching-learning process.*

At the end of learning phase I, an example problem should be presented: the release of dyes from a range of synthetic consumer products. It was considered important to illustrate the release of dyes through a practical demonstration in class in order to give students a sense of direction.

Learning phase II: Zoom in on the example problem

The design team emphasised an explicit attention to a modelling approach. Students should see the point of modelling themselves. For this, it was suggested to discuss in class the 'difficulties of measuring total uptake in humans and possible measurements to take'. Three main learning objectives of learning phase II were identified:

1. express and build on students' intuitive procedural knowledge in terms of a sequence of activities to conduct
2. give students a view of the (type of) knowledge to learn
3. describe the end product students should deliver.

To reach these objectives, the strategy of studying a worked-out analogous problem (a risk assessment) was unanimously adopted. In addition, it was proposed to recall the basic structure of the end product regularly to 'keep students on track'. A point of discussion was the necessity of letting students draw up a plan of action for their example problem. A number of arguments, both pros and cons, are exemplified below:

> *Teacher 3: … to expect from students a complete plan of action … in the*
>
> *remaining part of the curriculum unit we present a fixed sequence of activities and use prescripts for the experiments. That does not match well … possibly even discourages students.*
>
> *Teacher 2: But you would like students to really think over the way to handle the problem, based on the experts' approach.*
>
> *Teacher 5: At the end of the curriculum unit it is intended that students reflect on the modelling procedure. That is only possible if students have had the possibility to implement own ideas and follow their own thoughts.*

It was decided that the worked-out analogous problem, based on experts' work, should explicitly focus on the main points of the procedure. As a consequence, in the latter learning phases the emphasis would be on evaluation of the procedure followed.

Learning phase III: Solve the example problem

In the third learning phase, it was decided to organise the teaching-learning activities according to 'chemicals in a product', 'specific contact routes' and 'type of consumer', as introduced in phase I. For each category specific information needs to be collected, partly based on the models employed. This rough outlining is in line with the modelling procedure as depicted in Figure 5. For each category a specific teaching-learning activity was proposed. So, at the time students start to collect empirical data, they should know *which why* and *how* to acquire data.

> *Teacher 1: For each category empirical data should be collected, either by experiment or literature or otherwise. Afterwards you can combine all the data and calculate the total uptake. Regularly use the roadmap [introduced in phase I] as reference framework.*

It was suggested to deliver to students an adapted version of an authentic manual summarising contact routes, appropriate models and specific consumer information. The need to point out to students the nature of the appropriate model and the meaning of each parameter involved was emphasised. In addition, the specific situated knowledge regarding the laboratory work, such as spectroscopy, should be communicated at the time needed. Learning phase III ends by calculating the total uptake by consumers.

Learning phase IV: Evaluate and reflect on the findings

The design team was of the opinion that the practice at hand would bring up many considerations among students. Among these are: the exactness of the empirical data collected, the accuracy of the estimations, the validity of the total uptake calculated, the modelling procedure followed etc. It was suggested that students should be systematically guided towards each point of consideration. A separate activity was proposed in which students would compare the calculated total uptake with the legally-imposed norm. This was expected to evoke the need to make explicit the findings and write a 'risk assessment'. Finally, it was proposed to recall the multiple problems, as introduced in phase I, and optionally let students think over the way to handle another problem, such as the release of phthalates.

> *Teacher 3: We did concentrate ourselves on the release of dyes, at the end you might consider to introduce a more serious problem: the release of phthalates … students by now should realise that if dyes leach, other substance will also!*

> *Teacher 1: Can you apply the learned knowledge to other substances? What should be altered, what can stay the same?*

Learning phase V: Make explicit learning gain

The design team suggested that phase V should start with an explicit recall of the end product to be delivered. In addition, it was proposed that students should draw up an advice for future research.

Conclusions and discussion

In the present study we used a design framework to adapt the authentic practice 'Modelling human exposure and uptake of chemicals from consumer products' into a context for learning. We focussed on the heuristic value provided by the design framework. The heuristic value is captured in three dimension: completeness, instructiveness and appreciation. In this section we first summarise and reflect on the major findings. The numbers, capitals and captions refer to the strategy components of design principle 'context' (see Figure 1), 'content modelling' (see Figure 2) and 'chain of activities (see Figure 3), respectively. Secondly, we evaluate the broader usability of the design framework and formulate research.

For learning phase I, all teams intensively used the strategy components 1 (supply broad orientation) and 2 (give students a rich, whole task). In addition, the component A (visualise and conceptualise the example problem for students) was used intensively. However, in general, the results show that the filling-in of learning phase I bears much uncertainty. This uncertainty is reflected in the differences in the focus, content and activities in each context for learning. Apparently, designing the orientation phase poses many questions, probably due to the many pedagogic effects to fulfil. A proper design of the orientation phase is important, because it greatly influences students' expectations and motivations. It should be directive, that is evoke a motive for modelling an example problem, but at the same time offer opportunities for students to bring in their own ideas and thoughts, in other words, activate their prior knowledge base.

For learning phase II it was noteworthy that all teams also paid attention to selecting a suitable example problem for students to work on, as well as an end product matching the example problem (strategy component i). The studying of an analogous problem, with the aim of identifying the type of knowledge to learn and activities to conduct, was adopted by all the teams and was highly appreciated (strategy component B). In retrospect, all the strategy components within learning phase II provide useful guidelines.

For learning phase III, the use of adapted authentic documents to communicate situated knowledge was appreciated (strategy component 3). However, there was much discussion about which situated knowledge students actually need to cope with the example problem. The strategy component 'keep track of situated knowledge' (strategy component 4) was applied by only one team. It appeared that the experts' modelling procedure (strategy component ii) is a valuable tool for outlining a sequence of teaching-learning activities. All teams paid attention to the stages in the procedure which were expected to be 'not logical' or 'difficult' from students' perspectives. However, the design framework provided no clear guidelines for:

- inducing a content-related motive for modelling an example problem *by students themselves*
- organising an evaluation and reflection on the modelling approach and procedure *by students themselves*

As for the strategy component iii ('regular class meetings'), all teams underlined the importance of recording the progress. A important point of attention concerned 'constructing versus providing' the models employed by students. Discussion on this matter was initiated by applying the strategy components C ('discuss different modelling approaches') and D ('construct a series of teaching-learning activities informing students about the nature and wording of the models'). Although the design team did not come to a consensus, both strategy components brought into focus different pathways possible.

The instructional functions of learning phase IV, however, posed many questions to the design team. Although all participants thought of ways to apply the model in a real-world setting (strategy component E) and to summarise the pros and cons of the applied modelling procedure (strategy component F), the specific outcome(s) of the evaluation and reflection stage was a major point of discussion.

As for learning phase V, finally, the instructional functions and strategy components were instructive and were appreciated by the design team. All the teams stressed the importance of selecting an end-product matching the example problem (strategy component 5).

The findings show that the design framework provided useful heuristic guidelines for the adaptation of authentic modelling practices into contexts for learning. One of the benefits of applying this design framework is that the designers first focus on the structure of a teaching-learning process, that is, think of the content and sequence of teaching-learning activities, before going into details. The design framework was highly appreciated by all participants. The overall completeness was deemed high, although the design principle 'content modelling' needs reconsideration. The guidelines for involving students in the nature, characteristics and wording of the models need improvement. However, the instructiveness can be enhanced. There is need for explicit guidelines for the design of reflection activities, as well as arguments for supplying or constructing the models employed to students and routes to evoke students' motives to become engaged in an example problem. In addition, the design of learning phase I bears much uncertainty, as well as the design of a meaningful sequence of teaching-learning activities from students' perspective.

Limitations

The results obtained in this study are subject to certain limitations. Firstly, it should be noted that this particular authentic practice was selected after a thorough evaluation. Secondly, this design framework has been formulated based on the adaptation of one authentic practice. Generalisation of this design framework, as well as the usability for other authentic practices, either within the chemistry or science domains, needs to be studied. Thirdly, the teachers involved were all well informed about the design framework. Other teachers, willing to apply the presented design framework, should be confident with the proposed general pedagogic orientation and invest time to become acquainted with the line of reasoning incorporated.

Future research

We plan to develop a complete teaching-learning process, based on the designed structure, and apply the teaching-learning process in the classroom. The empirical data will be used to value the heuristic guidelines provided by the design framework. Furthermore, we plan to gain more insight into the broader applicability of the formulated design framework, by using it as a tool in outlining other teaching-learning sequences using authentic practices as the context for learning. Eventually, we expect our research work to contribute to the development of a knowledge base to inform educational designers about using authentic practices as contexts for learning.

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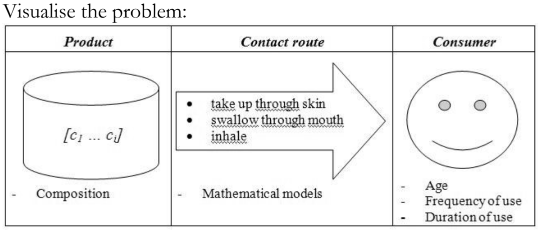
Appendix A: The designed structure of a teaching-learning process using the authentic practice 'Modelling human exposure and uptake of chemicals from consumer products' as context for learning

Phase	***Teaching-learning activity***	***Considerations***
Orientate on the practice	**1. Uptake of chemicals from consumer products.** Examples: - phthalates in water from synthetic bottles - dyes from synthetic materials - preservatives in plastics - nickel in jewellery - cosmetics Student activities: ○ Search for suspected consumer products ○ Make overview of production process of suspected consumer products ○ Find news items reporting on potentially harmful products	○ Pick examples that align with the 'world as experienced' by students. ○ Emphasise that certain chemical additives are needed to give the products desirable properties. ○ Additives give products desirable properties. ○ Legally set norms for chemicals, such as accepted daily intake (ADI).
	2. 'Zoom in' on actors involved Government institutes, manufacturers, consumers, etc. Student activities: ○ Describe the tasks and responsibilities of each actor concerning public health in relation to consumer products. ○ Describe the general stages in risk assessment and evaluate their pros and cons: • Expert judgement • Spot check of products • Quantitative research on occasion	○ General overview of actors involved in risk assessment. ○ Students should become aware that not all (single) product(s) can be tested.
	3. Conceptual analysis Visualise the problem:  Student activities: ○ Think about what you need to know from the *product, contact route and consumer* in order to conduct a risk assessment	○ Activate students' own pre-existing knowledge base. ○ Emphasise that on conceptual level the problems are similar, regardless the type of problem, contact route and consumer. ○ Use picture as 'roadmap' during teaching-learning process. ○ Recall in latter phases to induce evaluation and reflection.

	4. Present exemplary problem Conduct risk assessment concerning exposure and uptake of dyes from synthetic products. Contact route: swallow through mouth. Student activities: o Search for legally set norms (ADI) of the dyes. o Think about the modelling procedure to apply.	o Demonstrate the leaching of dyes in class.
Zoom in on an example problem	**5. Study a worked-out analogous problem** Bring in an authentic risk assessment, adapted for use in education. The risk assessment concerns another type of chemicals/products and contact routes (not swallow through mouth). Student activities: o Study the (adapted) risk assessment with aim to identify: - Type of knowledge to learn - Sequence of modelling activities to conduct - End product to deliver o Start by writing risk assessment for own example problem (take over the basic structure)	o Build on students' pre-existing knowledge base o Students' gain clear sight of sequence of modelling activities to conduct. o Students learn to select the main points, also of value for their own example problem, and leave out the details. o In authentic practices
Solve the example problem	**6. Consumer product** Students make a list of information needed on each consumer product: - Composition, especially dyes - Contact surface - Volume - Weight Student activities: o Scan labels of consumer products o Search composition on internet/ask manufacturer.	o Corresponds with the first step in modelling procedure in authentic practice.
	7. Contact route Students make a list of information needed on the contact route 'swallow through mouth': - Mathematical formula - Parameters to measure Student activities: o Select proper mathematical formula from pre-formulated list o Think over the meaning of each parameter and how to measure o Study the theoretical foundation of the mathematical formula o Practice application of the model by means of assignments.	o Corresponds with second step in modelling procedure in authentic practice. o Introduce the mathematical formula by means of an adapted authentic document summarising all available models per contact route.

	8. Consumer Students make a list of information needed on the consumer: - Age - Frequency of use - Duration of use Student activities: o Describe the use of the product by a (average) consumer.	o Corresponds with third step in modelling procedure in authentic practice.
	9. Collect empirical data By means of laboratory work (prescripts) and literature: - Measure initial release rate R. - Measure other parameters involved Student activities: o Study theory underlying the experimental methods o Study the laboratory prescripts o Conduct laboratory work, analyse the data and evaluate the results	o Corresponds with third step in modelling procedure in authentic practice. o Supply additional information about laboratory methods. o Explicitly evaluate the results and discuss limitations and assumptions.
	10. Total uptake Combine all (empirical) data and calculate the total uptake. - Distinguish average use and intensive use (worst case). Student activities: o Calculate the total uptake of the dye for two types of use for different consumers.	o Corresponds with the fifth step in modelling procedure in authentic practice. o Discuss the results in class.
Evaluate and reflect on the findings	**11. Evaluate the results** Evaluate the calculated total uptake on the aspects: - accuracy - reliability - validity - limitations - assumptions Student activities: o Evaluate the quality of the results.	o Students gain sight of the advanced features of employed models.
	12. Compare with legally set norms Draw conclusion about the possible health risks by comparing the calculated total uptake with the legally set norms (ADI). Student activities: o Evaluate two scenarios: average use and intensive use (worst case).	o Corresponds with the sixth step in modelling procedure in authentic practice.
	13. Evaluate modelling procedure Evaluate each step in the modelling procedure followed: - Successful steps - Possible improvements Student activities: o Recommendation for future research o Compare with the experts' approach o Propose an approach for other chemicals/contact routes/consumers based on your own experiences.	o Students realise that the applied modelling procedure is applicable to other (related) problems. o Students make explicit the main points in the modelling procedure.

Express the findings	**14. Write report** Students make explicit their learning gain by writing a risk assessment concerning the uptake of dyes from synthetic consumer products. Student activities: o Write risk assessment according to format o Advice for future research.	o Explicitly recall the basic format for writing a risk assessment.

9

Lessons Learned and Reflection

CHAPTER 1
Introduction and Research Overview

Research question 1
Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?

CHAPTER 2
Selection of Authentic Modelling Practices as Contexts for Chemistry Education

CHAPTER 3
Students' Involvement in Authentic Modelling Practices as Contexts in Chemistry Education

Modelling human exposure and uptake of chemicals

Modelling drinking water treatment

Research question 2
What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?

CHAPTER 5
Elaboration of a Design Framework for Adapting Authentic Practices into Contexts for Learning Models and Modelling in Chemistry Education

CHAPTER 4
Removal of Water Turbidity

CHAPTER 6
Evaluation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education

CHAPTER 7
Evaluation of a Design Principle for Fostering Students' Epistemological View on Models and Modelling using Authentic Practices as Contexts for Learning in Chemistry Education

Research question 3
What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?

CHAPTER 8
Valuation of a Design Framework for Adapting Authentic Modelling Practices into Contexts for Learning in Chemistry Education

DESIGN FRAMEWORK
Learning phases
Instructional functions
Design principles

CHAPTER 9
Lessons Learned and Reflection

Introduction

The purpose of this study is to contribute to a knowledge base for designing teaching-learning processes in chemistry education using authentic modelling practices as contexts for learning, such that students reach an adequate understanding of models and modelling. The knowledge regarding the educational design is captured in a design framework, a synthesis of design principles, learning phases and accompanying instructional functions.

The idea of using authentic practices as contexts for learning in science education has been proposed in chemistry education in the Netherlands by Van Aalsvoort (2000), Bulte, Klaassen, Westbroek, Stolk, Prins and Genseberger (2005) and Westbroek (2005). An authentic practice is defined as a homogeneous community of people working on real-world problems and/or societal issues characterised by three features, namely (1) shared content-related motives and purposes (to take on a certain issue), (2) a characteristic procedure (sequence of activities leading to an outcome) and (3) displaying relevant issue knowledge (Prins, Bulte, Van Driel, & Pilot, 2008). The studies have revealed that the idea is effective in principle, but draws heavily on the quality of the actual educational design. Authentic practices should serve as 'advance organizers that integrate motivational and cognitive functions' (Westbroek, Klaassen, Bulte, & Pilot, 2009). This study builds on this idea, and is related to several other studies elaborating the use of authentic practices as contexts for learning (Engelbarts, 2009; Meijer, Bulte, & Pilot, 2009; Westra, 2008).

In this final chapter the major results will be summarised and the contribution to theory-based design with respect to learning models and modelling in chemistry and science education will be discussed. We start with the three research questions posed in Chapter 1:

1. *Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?*
2. *What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?*
3. *What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?*

In answer to the first research question, we describe the characteristics of the selected authentic practice. In addition, we portray the designed context for learning, and report students' involvement. Regarding the second research question, we describe the emerging knowledge base concerning the use of authentic practices as contexts for learning. The knowledge base takes the form of (1) a design framework and (2) a structure of the teaching-learning process. The latter is exemplified by a detailed description of the designed teaching-learning process based on the selected authentic practice 'Modelling drinking water treatment'. Next, in answer to the third question, a study and reflection upon the broader applicability of the design framework will be presented. Finally, the outcomes of these studies will be generalised at two levels:

1. The learning of models and modelling in science education;
2. The use of authentic practices as contexts for learning in science education.

We position the outcomes within the present body of knowledge concerning learning models and modelling and reflect upon them in terms of potential benefits, points requiring attention, and pit falls to be taken into account.

Selected authentic practices and students' involvement

Research question 1 is: *Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?*

The use of authentic practices as contexts for learning offers some valuable starting points, such as content-related motives as to *why* to study a certain topic, according to *what* sequence of activities (procedure) and accompanying scientific knowledge. However, it cannot be expected that students are able to conceptualise the goals and direction to follow with the same width and depth as the professionals employed in an authentic practice (Westbroek et al., 2009). Therefore, at least two considerations come to the fore:

1. The selection of the authentic practice to be adapted into a context for learning needs to be justified from educational points of view and students' perspectives.
2. The selected authentic practice needs to be adapted in order to design a meaningful teaching-learning process from students' perspective.

The first research question focuses on the first consideration. Two practices were selected as suitable, based on two studies described in Chapters 2 and 3: (1) modelling human exposure and uptake of chemicals from consumer products, and (2) modelling drinking water treatment. The latter practice was adapted into a context for learning and tested in the classroom (cf. Chapters 4, 5, 6 and 7). Below the major characteristics of the authentic practice 'Modelling drinking water treatment' are described.

The authentic practice 'Modelling drinking water treatment' (cf. Chapter 2)
The authentic practice of modelling drinking water treatment is that of the chemical process engineers involved in modelling industrial process behaviour in order to improve efficiency and minimise costs of drinking water treatment. This authentic practice was regarded as suitable because: (1) there are clear motives for construction of the model, (2) the modelling procedure complies with students' prior procedural modelling knowledge, (3) the situated knowledge is consistent with the present Dutch science curriculum, and (4) it is feasible to conduct experimental work in the classroom as required for model construction, calibration and validation.

The objective of this authentic practice is to identify and to describe mathematically quantitative relations between the output of a certain treatment step and the relevant process variables. The latter comprises the input of biological, chemical and/or physical parameters and various process conditions. Such quantitative relations are desirable to account for the constantly varying quality of the incoming (raw) water to be treated, especially in case of surface water. In theory, such quantitative relations can be used to predict the quality of the drinking water after treatment as a function of the quality of the incoming (raw) water and the execution of the treatment process itself. These outcomes are compared with legal norms for drinking water, thus enabling alterations in the execution of the treatment process beforehand.

To develop such quantitative relations a characteristic modelling procedure is applied. In broad outline, three distinctive stages can be distinguished, each evoking the application of specific biological, chemical, physical and/or mathematical knowledge. The first stage involves the studying of the principles underlying the mechanisms of the treatment step in order to identify relevant process variables. This stage might include an orientation on process models already available and described in the literature. The second stage involves the gathering of experimental data under controlled conditions, both at the laboratory (pilot) scale and in real industrial plants. The third stage involves the development of a process model that describes the quantitative relations between input, output and relevant process variables. The modelling of the drinking water treatment is conceptualised in Figure 1. The block arrows indicate the flow of water with contaminants to be removed in treatment *step N*. $C_{iN,in}$ denotes the incoming amount of contaminant *i*, while $C_{iN,out}$ denotes the residual amount of contaminant *i* after *step N*. The removal efficiency in each step is affected by process variables, symbolised by pv_N.

In the authentic practice, basically two modelling approaches are applied, namely the empirical and the mechanistic approach. The mechanistic approach starts from a well defined theoretical knowledge base, whereas the empirical approach aims to describe process behaviour by fitting mathematical models to a set of experimental data. From a scientific (technological) point of view the mechanistic approach is preferred, since it strives to understand and describe mathematically

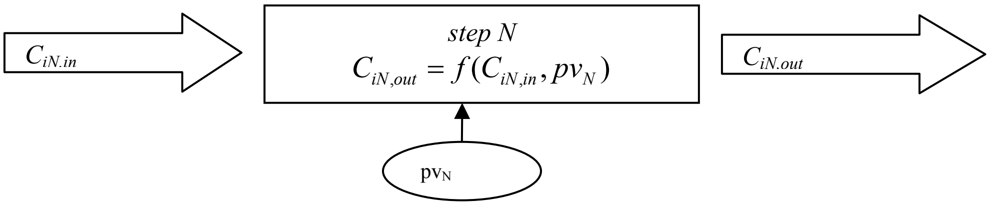


Figure 1. Conceptualised scheme of the modelling of the drinking water treatment process. The block arrows indicate the incoming water stream, containing contaminants ($C_{iN,\ in}$) to be removed, and the outflowing water stream, with a residual concentration of contaminants ($C_{iN,\ out}$). The quantitative relation between output, input and process variables can be formalised by a formula.

the mechanics underlying the processes occurring in a given system. However, in many cases the theoretical knowledge is lacking, thus favouring an empirical approach. Additional arguments might be the relative ease, speed and low cost of the empirical approach compared with the mechanistic approach.

Adaptation of the authentic practice 'modelling drinking water treatment' into a context for learning (cf. Chapter 3)

The modelling of the complete drinking water treatment process comprises numerous steps, parameters and process variables. Therefore, it was decided to 'zoom in' on the process of turbidity removal by coagulation/flocculation, based on valuations regarding students' (cognitive) abilities (e.g. chemistry and mathematical knowledge involved and students' prior knowledge base) and affective aspects (e.g. students' interests and sense of ownership). Turbidity is caused by small particles, such as colloids and fine silt. During coagulation/flocculation treatment these particles are removed by adding a coagulant, such as ferric chloride.

The efficiency of turbidity removal is affected by chemical process variables, such as the turbidity of the incoming water ($turbidity_{in}$), temperature (T), total salt concentration (c[salt]), acidity (*pH*) and the dose coagulant ferric chloride (V). In addition, several process conditions affect the efficiency of turbidity removal, such as the stirring method, frequency and duration. The dose coagulant (V) and process conditions can be directly manipulated. The coagulation/flocculation treatment is conceptualised as an input-output system, as depicted in Figure 2.

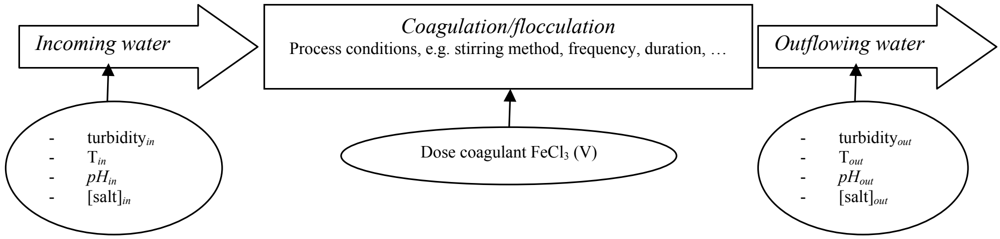


Figure 2. Conceptualised scheme of the coagulation/flocculation treatment process including relevant process variables. The block arrows indicate the flow of water.

Some process variables are easy distinguishable and understandable, such as turbidity$_{in}$, dose coagulant $FeCl_3$ (V) and temperature (T), while others can only be understood with detailed knowledge concerning coagulation mechanisms, such as acidity (pH) and total salt concentration ([salt]). The aim of modelling is to develop a mathematical model describing the relation between turbidity$_{out}$, turbidity$_{in}$ and other relevant chemical process variables, formalised as

$$turbidity_{out} = f(turbidity_{in}, V, T, pH, [salt]).$$

The model is evaluated on epistemic values, such as purpose, goodness of fit, reliability and validity. The applied modelling approach can be typified as empirical (or black box, data-driven). The modelling procedure consists of three distinct stages. In Table 1 the three stages are depicted with situated chemical and/or mathematical knowledge.

Students' involvement in the adapted authentic practice (cf. Chapter 3)

The valuations regarding students' (cognitive) abilities and affective aspects, were tested by mapping students' emerging engagement in terms of interests, ownership, familiarity and complexity. In addition, modelling procedures devised by students in response to the problem, as expressed by them, were evaluated. The results show that students' involvement was successfully initiated, evidenced by motivated students, willingness to continue and the completeness and quality of the realised modelling procedures. Students showed familiarity with basic techniques of water purification (e.g. filtration, activated carbon, sedimentation, oxidation) and had a rudimentary overview of the treatment of (surface and ground) water to produce drinking water. Students valued this theme because of the societal relevance of good quality drinking water. Concerning models and modelling, students showed awareness of the epistemic notions, e.g., purpose and reliability.

Table 1. Overview of the modelling procedure and accompanying situated knowledge in modelling turbidity removal by coagulation/flocculation.

Modelling procedure	Situated knowledge
Study the working of the treatment step	Coagulation/flocculation Process variables
Gather empirical data	Experiments under controlled conditions Correlation & regression
Develop a process model	Multiple regression

Teaching-learning process and design framework

Research question 2 is: *What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?*

The emerging design framework consists of three design principles, labelled 'context', 'content modelling' and 'chain of activities', learning phases and instructional functions (cf. Chapters 5, 6 and 7). Design principles (Van den Akker, 1999) consist of strategy components to be applied in the design of the teaching-learning process (it is up to the teacher to enact those strategies in the classroom with sufficient quality), pedagogic effects (specified educational activities and learning outcomes for students to achieve, to measure among students) and arguments (underpinning the strategy components and pedagogic effects, on theoretical and/or empirical grounds, practical considerations). The design principle of *context* deals with involving learners in a focal event embedded in its cultural setting (Gilbert, 2006). This implies the setting, the behavioural environment, the specific language and the extra-situational background knowledge, such that students become engaged in a modelling activity. The design principle *content modelling* deals with focussing learners on the essential generic content regarding models and modelling. The design principle *chain of activities* deals with constructing a sequence of teaching-learning activities such that learners constantly know *why what* to do at every step in the process (Lijnse, 1995). The teaching-learning process is designed according to the problem-posing approach (Klaassen, 1995). The core of the problem-posing approach is to bring students into such a position that they themselves come to see the point of extending their existing conceptual resources, experiential base and belief system in intended direction. The phases in the teaching-learning process and accompanying instructional functions are inspired by previous studies by Kortland (2001) and Westbroek (2005). Five learning phases are distinguished, labelled: 'orientate on the practice', 'zoom in on an example problem', 'solve the example problem', 'evaluate and reflect on the findings' and 'express the findings'.

The design framework, depicted in Figure 3, is based on the structure of the designed teaching-learning process using the authentic practice 'Modelling drinking water treatment' as context for learning. The structure is depicted in Figure 4.

Design Framework			
Learning phases / Instructional functions	Design principles		
	Context	Chain of activities	Content modelling
I: Orientate on the practice ***a)*** Connect to prior conceptual knowledge base ***b)*** Connect to prior procedural knowledge base ***c)*** Evoke motivation to study the problems posed in the practice ***d)*** Evoke a motive to zoom in on an example problem	**Strategy component 1:** Provide students with an orientation base: supply broad overview of the subject dealt with as well as the authentic practice at hand **Strategy component 2:** Give students a rich, whole task		**Strategy component A:** Visualise and conceptualise for students the example problem they are going to work on
II: Zoom in on an example problem ***e)*** Make explicit and build on the prior conceptual knowledge base ***f)*** Make explicit and build on the prior procedural knowledge base ***g)*** Evoke a motive to solve the example problem		**Strategy component i:** Give students a clear assignment concerning the example problem they are to work on and direct their attention to the end product they are to deliver	**Strategy component B:** Supply students with a worked-out analogous modelling problem as leading example
III: Solve the example problem ***h)*** Proceed through the sequence of activities and learn/apply knowledge until a satisfactory solution for the example problem can be presented	**Strategy component 3:** Select essential situated knowledge and supply it to students by means of articles and/or manuals **Strategy component 4:** Organise students to ensure that they keep track of situated knowledge	**Strategy component ii:** Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration **Strategy component iii:** Plan regular class meetings with students to look ahead on future activities	**Strategy component C:** Discuss with students different modelling approaches and point out an appropriate one for the example problem at hand **Strategy component D:** Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand
IV: Evaluate and reflect on the findings ***i)*** Evaluate the learned conceptual and procedural knowledge ***j)*** Reflect on the procedural knowledge			**Strategy component E:** Let students apply the constructed model in real-world setting **Strategy component F:** Let students compare different modelling approaches and reflect on the assumptions and estimations made, and the possible effect of neglected variables
V: Express the findings ***k)*** Make explicit the learned conceptual and procedural knowledge	**Strategy component 5:** Select an end product, matching the example problem, to assess students' performance		

Figure 3. A design framework providing heuristic guidelines for structuring teaching-learning processes using authentic modelling practices as contexts

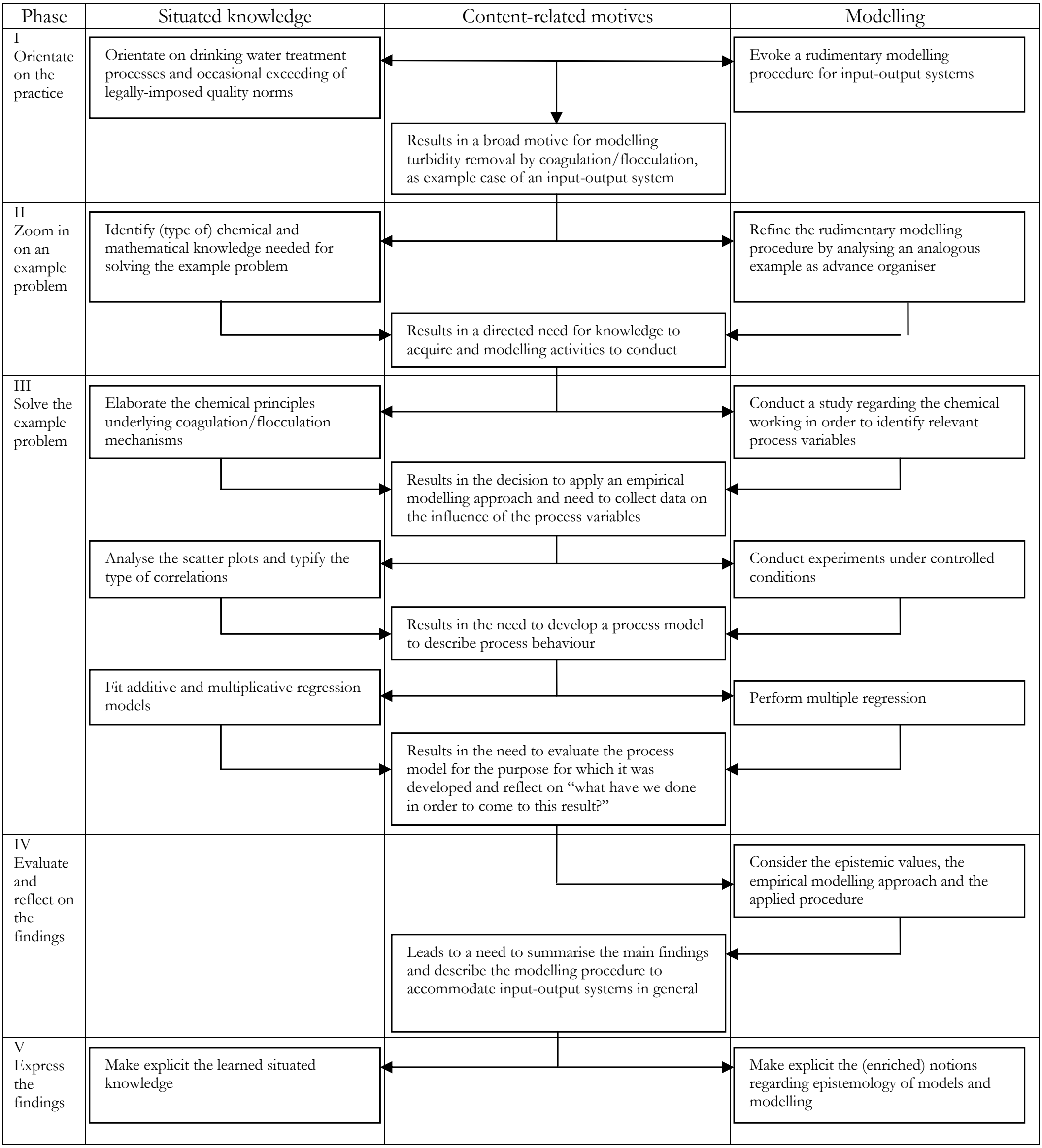


Figure 4. A structure of the teaching-learning process using the authentic practice ‘Modelling drinking water treatment’ as a context for learning. The blocks represent major stages in the teaching-learning process. The arrows indicate the flow of the process.

The designed structure of the teaching-learning process gives an overview of the motives-driven interrelated development of situated knowledge and modelling, specific for removal of turbidity by coagulation/flocculation treatment. Both outcomes (the design framework and the structure) embody a knowledge base that informs educational designers about adapting authentic modelling practices into contexts for learning. Such knowledge base is important, because there is need for 'sharable theories' that help to communicate relevant implications to educational designers. (Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003). At present, however, there is no clear consensus within the research community about the nature of such 'sharable theories', nor ways to describe knowledge concerning educational designs. Therefore, we advocate further research and debate to arrive at standards to foster mutual understanding and communication.

Description of the designed teaching-learning process (cf. Chapters 4, 5, 6 and 7).
In the next section we first describe the learning gain. Secondly, we portray the designed teaching-learning process in considerable detail.

Learning gain
After studying the curriculum unit, students have acquired an improved understanding of the epistemology of models and modelling. More specifically, students have a deeper insight into epistemic values, such as purpose, goodness of fit, reliability and validity. In addition, students are able to discuss the pros and cons of the empirical modelling approach. The second learning gain is that students know more about modelling input-output systems. This includes making explicit the major steps in the modelling procedure and describing them in considerable detail, using the coagulation/flocculation treatment as an example case. Students are able to explain the (chemical) working of coagulation/flocculation, including the relevant process variables, to describe the experimental method to investigate the influence and are able to outline the subsequent data analysis by regression. These two (generic) learning gains are worthwhile within chemistry education (or science education in a broader sense). Models are both major products as well as thinking tools employed across many disciplines in science and technology. In addition, within the field of science and technology many input-output systems, facing varying inputs, are encountered, such as ecosystems in biology (Westra, 2008).

Designed teaching-learning process
The sequence and content of the teaching-learning process are described below according to the five learning phases.

Phase I: Orientate on the practice

Phase I evokes among students a broad interest and motivation to study the practice of modelling drinking water treatment, such that students see the point of modelling a treatment step as an example. Students start to outline the treatment processes of both ground water and surface water (activate prior knowledge base). Students take notice of the varying quality of the (raw) ground water and surface water to account for during treatment. In order to emphasise that this poses real challenges for drinking water companies, students make a list of legally-imposed quality standards for drinking water that are occasionally exceeded, based on official government data concerning the quality of drinking water in the Netherlands in 2002. During this activity a broad interest in studying drinking water treatment is evoked among students, guided by questions such as: 'Why does occasional outrun of quality norms take place?' and 'What is done in practice to prevent such outruns?'.

Next, the removal of turbidity by coagulation/flocculation, one of the quality norms occasionally exceeded, is demonstrated in class. Students think of reasons for the occasional outrun of the turbidity and suggest (possible) measurements to prevent such outruns. This activity focuses students on the $turbidity_{in}$ and the dose of coagulant $FeCl_3$ (V) as major influencing process variables, and initiates the description of an intuitive modelling procedure to quantify this influence. The coagulation/flocculation treatment step is conceptualised as an exemplary case of an input-output system. Students analyse (and adjust) their expressed intuitive modelling procedure with respect to application for input-output systems in general.

In the last activity of phase I, students compare their intuitive modelling procedure with the modelling procedure proposed by experts. For this a shortened and adapted version of a real existing project plan, concerning the modelling of the drinking water treatment process originating from the authentic practice at hand, is used as teaching material. The adapted version gives a comprehensive summary of the main procedural steps and (type of) outcomes. While studying and analysing this adapted project plan, students become aware of the epistemic notions of purpose, goodness of fit, validity and reliability.

At the end of phase I students have a broad content-related motive to model turbidity removal by coagulation/flocculation themselves. This broad motive is strengthened by an understanding of the societal relevance of the exercise. Students are intrinsically motivated to solve this example modelling question, since they now have a broad outlook on the (type of) modelling activities to conduct and the (type of) knowledge to learn and apply (albeit in a rudimentary sense).

Phase II: Zoom in on an example problem

The broad content-related motive that was evoked in phase I is specified and directed in phase II. Following orientation, students are given the task of developing a process (mathematical) model of the relation between $turbidity_{out}$, $turbidity_{in}$ and other relevant process variables concerning coagulation/flocculation, and to report the major findings in a factsheet. To evoke a specific knowledge need and direct this in the intended direction, students receive a factsheet about modelling the removal of trichloromethane by activated carbon filtration. This factsheet serves as an advanced organiser (Ausubel, 1968) in two ways. Firstly, through studying an analogous modelling problem, students enrich their own intuitive modelling procedure, gain (more of) a view of the specific chemical and mathematical knowledge to learn, and again take notice of epistemic values, such as purpose, goodness of fit, reliability and validity. As a follow-up to their own intuitive modelling procedure, four questions arise:

1. How does coagulation/flocculation work and what are the relevant process variables effecting the $turbidity_{out}$?
2. What is the influence of all (separate) process variables on the $turbidity_{out}$ and how can the influence be quantified?
3. How to develop one process (mathematical) model combining all separate influences on the $turbidity_{out}$?
4. How to evaluate the process model?

Secondly, students become familiar with the basic structure of a factsheet as a means to report main results and findings. Students deliver a similar factsheet themselves at the end of phase V with data based on their own work. The factsheet is used as an assessment tool. In phase II students copy the basic structure of the factsheet and start filling out the factsheet with relevant knowledge as far as possible, based on what they now know about modelling turbidity removal by coagulation/flocculation. Since students will only be able to fill the factsheet partially, a directed knowledge need is evoked for the remaining part of the teaching-learning process.

Phase III: Solve the example problem

In phase III students extend and apply their knowledge of the modelling procedure (outlined in phases I and II) in order to develop a process (mathematical) model describing the relation between $turbidity_{out}$, $turbidity_{in}$ and other relevant process variables. The three major stages are described below.

Stage 1: Students conduct a literature study to gather information and learn about the (chemical) working of coagulation/flocculation, measuring turbidity and affecting process variables. The literature study includes an in-depth focus on the chemistry underlying coagulation/flocculation. The list of conceptual issues includes:

- negatively charged colloids;
- stable colloid systems in water through balancing opposing forces (e.g. repelling Coulomb and attractive VanderWaals forces), gravitational forces and Brownian motion;
- disturbing effect of coagulants, such as Fe^{3+}, causing colloids to gather, agglomerate and flocculate;
- mechanisms of coagulation, e.g., neutralisation, double layer compression and sweep floc.

This situated knowledge is required in order to construct a complete list of potentially relevant process variables. After students have a complete overview about the numerous variables included, the suitable modelling approach to apply (empirical or mechanistic) is discussed in class. At this point, students understand *why* to apply the empirical modelling approach (lack of theoretical knowledge about mechanisms) and *why* to focus on three variables (V, $turbidity_{in}$ and T) only (to reduce complexity, these three variables are likely not to interact with each other). Students hypothesise about the influence of the three process variables on $turbidity_{out}$, preceding the experimental investigation:

- An increasing dose coagulant Fe^{3+} (V) results in a decline of the $turbidity_{out}$; the $turbidity_{out}$ asymptotic approaches zero (power correlation);
- An increasing $turbidity_{in}$ results in a increase of the $turbidity_{out}$ (linear correlation);
- A raise of the temperature (T) could either result in a decline or increase of the $turbidity_{out}$. No argued type of correlation can be predicted.

Finally, students update their factsheet and start to construct a list of concepts based on the literature study. The list of concepts forms an integral part of the factsheet.

Stage 2: The teaching-learning process continues with laboratory work (cf. Chapter 4) to measure empirically the influence of the three process variables (V, $turbidity_{in}$ and T). Students work according to laboratory prescripts, present the data in scatter plots, and analyse the type of correlations. At this point it becomes clear that variables V and $turbidity_{in}$ show significant correlation with $turbidity_{out}$, and variable temperature shows no correlation within the tested range (approximately 5– 30 °C). The measured influence of variables V and $turbidity_{in}$ is compared with the expected influences. Next, a single regression is performed in which a power ($turbidity_{out}$ vs V) and a linear ($turbidity_{out}$ vs $turbidity_{in}$) regression model is fitted on the data. A manual correlation and regression is used as teaching material. A calculator and/or MS Excel software are used as computer tools. Students become acquainted with the content-specific filling-in of the epistemic notions of goodness of fit, reliability and validity. Finally, students extend their list of concepts and update their factsheet.

Stage 3: The third step in phase III involves students in constructing a process (mathematical) model describing the influences of both variables V and $turbidity_{in}$. Therefore students perform a multiple regression, again supported by a manual about correlation and regression and using MS Excel as a computer tool. Subsequently an additive (linear) regression model and a multiplicative (power) regression model are fitted on the data. Students evaluate both regression models on the epistemic values of goodness of fit, reliability and validity, respectively taken as:

- Goodness of fit: indicated by the value of R^2, in which a value > 0.8 denotes a good fit;
- Reliability: the amount and accuracy of the collected empirical data;
- Validity: the range of the tested variables V, T and $turbidity_{in}$, and the values of the variables held constant (e.g. pH, c[salt], process conditions).

Finally, students again extend their list of concepts and update their factsheet.

Phase IV: Evaluate and reflect on the findings

In phase IV students apply the developed process (mathematical) model to calculate the dose coagulant needed to produce clear water, given a certain incoming (raw) water quality. Students comment on the outcome(s). Students become aware of the fact that this process (mathematical) model has been developed in a laboratory environment. They understand that application of the model in, for example, an industrial setting, needs further examination. Doing so, students evaluate to what extent the developed process (mathematical) model has served the 'purpose' of the modelling activity.

Next, students explicitly reflect on the empirical modelling approach applied, formulate pros and cons to account for, and explicitly describe, the modelling procedure. Students come up with aspects such as the absence of a theoretical foundation, the critical value of good quality measurements and the (quickly) gained insight in process behaviour. This activity is initiated by recalling the conceptual input-output system as posed in phase I, thus inducing a motive to make explicit the findings at a meta level for (possible) application in similar situations, e.g., other treatment steps.

Phase V: Express the findings

In the final phase, students complete their factsheet summarising all their results and findings. They use as an example the factsheet that was introduced as an advanced organiser in phase

II. The learning gain regarding the epistemology of models and modelling, and the generic modelling procedure for input-output systems becomes explicit. The factsheets when completed and submitted are used to assess students' performance.

Heuristic value of the design framework

Research question 3 is: *What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?*

The heuristic value of the design framework has been evaluated by adapting the other selected authentic practice 'modelling human exposure and uptake of chemicals from consumer products' into a context for learning (cf. Chapters 2 and 3). The results of this study show that the design framework provides useful guidelines for structuring a teaching-learning process (cf. Chapter 8). The design framework is highly appreciated by the educational designers. In addition, the completeness was deemed high. However, the instructiveness needs improvement, mainly regarding (1) evoking students' motives for involvement in an example problem and (2) inducing meaningful reflection. Below, we reflect on both points of attention.

1. In spite of the (societal) importance and relevance of the selected authentic practices, which was underlined by students themselves, it is still hard to involve students in solving an example problem originating from that authentic practice. Apparently, the engagement of students draws heavily on their (intrinsic) motivation to learn. This puts an extra stress primarily on the outlining of learning phase I. The resulting recommendation is: make sure that students know *why*, *what* and *how* to do and learn in the remaining part of curriculum unit by means of visualisation of the example problem(s) and pointing out the generic content.
2. In an authentic practice the experts employed have clear content-related motives for reflection, because they know that similar problems will arise. For students this argument is not valid, thus there is a need for other (educational) strategies to induce reflection. In earlier designs, reflection was positioned as a final activity for students, on the grounds that 'students by then have a complete overview'. However, in classroom practice, the reflection stage was often simply skipped due to lack of time, students not being motivated (anymore) or not seeing the point of reflection. Later on, reflection was positioned in the last but one learning phase, phase IV. In addition, reflection was structured by means of specific questions and tasks for students. Although the results improved, we still need to find ways to induce meaningful reflection among students.

The validity of the design framework, for adapting other authentic practices into contexts for learning, is subject to the following conditions:

- High school chemistry (upper secondary education);
- Students grade 10-11 (aged 16–17 years);
- Domain: models and modelling;
- Authentic modelling practice as context for learning.

Authentic practices as contexts for teaching and learning of modelling

In this section we position the outcomes of the studies within the present body of knowledge regarding the teaching and learning of modelling in science education and reflect upon them.

Teaching and learning about models and modelling has drawn much attention in science education research in the past decades, due to the perceived importance of models and modelling in the disciplines of science and technology. Although the epistemological status of models is still under debate, in general they are viewed as intermediates between abstract theories and empirical data. From the literature it becomes clear that students and teachers experience many problems related to the teaching and learning of models and modelling. Many initiatives have been undertaken that address these learning problems, however according to Schwartz and White (2005, p. 168) the results are limited: '…teaching students about the nature of models and the process of modelling has proven to be difficult. Direct efforts at improving modelling knowledge have met with limited success'.

It is claimed that involving students in modelling fosters understanding in the nature of models and the models themselves. Without questioning the claim itself, Lijnse (2008) states that the real educational challenge lies in designing a teaching-learning process that guides students to the intended understandings for models and modelling, while accounting for students' perspectives, prior knowledge bases and (cognitive) abilities. Since many modelling approaches are available, the type of modelling as applied in the designed teaching-learning process, using the authentic practice 'Modelling drinking water treatment' as context for learning, is first typified. After that, we reflect on the benefits of involving students in adapted authentic modelling practices with respect to learning epistemology of models and modelling.

Modelling approach in the designed teaching-learning process

Giere (1988) describes two modelling approaches applied in science practices: (1) starting from existing theoretical notions about phenomena, processes and/or objects and (2) starting from the existing (visible) phenomena, processes and/or objects themselves. In the first approach an abstract theory is made more concrete, which can be typified as 'theory driven modelling'. The second approach starts from empirical data which are generalised. This might be classified as 'empirically driven modelling'.

In science education, a distinction is made between explorative and expressive modelling (Bliss and Ogborn, 1989). Explorative modelling aims at elaborating and testing given (scientific consensus) models. This corresponds largely to 'theory driven modelling'. The educational challenge here is to find ways to make students understand the theoretical underpinning of the particular model at hand such that they accept it and see the point of elaboration and testing of the model. Expressive modelling aims at students designing their own models for phenomena, processes and/or objects. This corresponds largely to the 'empirically driven modelling'. The challenge here is to outline the teaching-learning process such that students arrive at intended (scientific consensus) models, starting from students' pre-existing intuitive ideas and commonsense knowledge.

For science education, Lijnse (2008) describes four modelling activities:
1. common sense: students' intuitive thoughts and ideas of a phenomenon, process and/or object;
2. descriptive: scientific description of the phenomenon, process and/or object;
3. causal: causal explanation in terms of underlying mechanism(s);
4. dynamic modelling: causal explanation of (complex) systems in time.

The modelling activities should be regarded as complementary to each other. The modelling approaches and activities are synthesised as depicted in Table 2. The type of modelling in the designed teaching-learning process, using the authentic practice 'Modelling drinking water treatment' as context for learning, can be typified as 'empirically driven, expressive modelling'. The modelling activity is descriptive: a process is mathematically described. The modelling approach is indicated in Table 2.

Table 2. A classification of modelling approaches. The arrow indicates the start and endpoint of the type of modelling in the teaching-learning process using the authentic practice 'Modelling drinking water treatment' as context for learning.

Modelling approach	Modelling activities			
	Common sense	Descriptive	Causal	Dynamic
Empirically driven (expressive)	Increase of understanding →			
Theory driven (explorative)				

Having positioned and typified the modelling approach in the designed teaching-learning process, at least two questions come to the fore:

1. What are the benefits regarding students' understanding of the nature of models and the process of modelling?
2. What is the potential of using authentic modelling practices as contexts for learning to cover causal and dynamic modelling activities, as well as to involve students in theory driven (explorative) modelling approaches?

In the remaining part of this section these two questions will be answered in turn, based on the previous studies.

Question 1: What are the benefits regarding students' understanding of the nature of models and the process of modelling? (cf. Chapter 7)

The designed teaching-learning process aims at improving students' understanding of the nature of models and the process of modelling. As for the nature of models, the majority of the students in the case studies showed content-related insight into the epistemic values of purpose, goodness of fit and reliability. Students learned to formalise and describe the process behaviour in mathematical models. In this respect, the modelling process resembles what Gravemeijer (1999, p. 156) typified as emergent modelling: 'a process of gradual growth in which formal mathematics comes to the fore as a natural extension of the student's experiential reality'. The results acquired in this study concur with the proposition, as suggested in the literature, that students should be involved in a process of modelling in which their understanding contributes to the development of their models and the evaluation and testing of their models contributes to their evolving understanding (Penner, Lehrer, & Schauble, 1998). However, engagement of students in a modelling process *as such* does not (automatically) result in an improved understanding of models and modelling. Many educational design questions and issues need to be resolved in order to arrive at intended learning goals, as illustrated by the design research conducted in this study.

As for understanding the process of modelling, the results show a more diverse picture. The majority of the students put forward relevant notions regarding the empirically driven modelling approach, e.g., the absence of a sound theoretical foundation, the need for a good quality (number and accuracy) data set to describe the process behaviour, and the validity of the developed model. However, only a minority described the modelling procedure for (possible) application to modelling other input-output systems. It is questionable whether the students lacked insight into such broader applicable (meta-)modelling procedural knowledge, or whether the *motivation* to induce such reflection was inadequately implemented in the teaching-learning process. In short, the teaching-learning process we designed proved successful in inducing students to evaluate their learning outcomes related to models and modelling, but failed to induce meaningful reflection. Hereby I interpret reflection as the deduction and making explicit of the generic (meta-)knowledge for application in a new (similar) situation. In this respect, the reflection could be viewed as a precursor to transfer. Inducing meaningful reflection among students has proved to be difficult to achieve in the classroom (Callens and Ellen, 2009). In the present case, after having studied a 'single' unit on models and modelling, students experienced no need to reflect on the findings. One way to resolve the lack of reflection at a curriculum level, then, might be to implement multiple (modelling) units in sequence, each building on the previous one (Bulte et al., 2005; Lijnse and Boersma, 2004). Reflection exercises could be incorporated either between units, or at the beginning of each new unit.

In conclusion, despite the observed shortcomings in students' reflection, the use of authentic practices as contexts for learning offers a valuable source of inspiration for designing teaching-learning processes and, if properly adapted, does lead to the intended learning outcomes. This conclusion is subject to two major conditions which should be taken into account when interpreting and extrapolating the use of authentic practices as contexts for learning in chemistry (or science) curricula. First of all, in this study the point of departure was the authentic modelling practice itself. Our emphasis was to maintain coherency between motives, modelling activities and knowledge within the constraints of the classroom. Hence, we were not bound to the existing chemistry (science) curriculum and/or the models to be employed, nor to the division between (traditional) science domains and mathematics. Secondly, the results are based on the adaptation of (only) one well defined authentic practice established after a thorough and prolonged design process. The teachers were given time to become acquainted with the underlying pedagogy and practical feasibility in the classroom. More studies are needed to grasp the possible benefits and pitfalls of this approach.

Question 2: What is the potential of using authentic modelling practices as contexts for learning to cover causal and dynamic modelling activities, as well as to involve students in theory driven (explorative) modelling approaches?

This question first calls for an overview of authentic practices covering (theory driven) descriptive, causal and dynamic modelling levels. Assuming that suitable authentic practices are available for all approaches and activities, then secondly the benefits for learning models and modelling should be answered. As for the former, our society does offer a great deal of (partly overlapping) modelling practices. In this respect, there is no a-priori reason for a shortage of authentic practices as sources for educational use. The widespread availability of authentic practices in our society is reflected in research studies recently conducted within our institute, for example, the use of the practice of the experimental physicist for a unit on 'remote experiments' (Engelbarts, 2009) and the use of the Netherlands Institute of Ecology research practice for a unit on 'modelling ecosystem behaviour' (Westra, 2008). More distinctive, therefore, seems the latter question on the benefits for learning models and modelling. As outlined by Westbroek (2009), the course designer needs to adapt the authentic practice carefully in order to secure that the teaching-learning process remains purposeful from the students' perspective. Based on the outcomes of the previous studies (cf. Chapters 3, 5, 6 and 7), the existence of a well defined modelling procedure in the authentic practice is an essential criterion determining the overall suitability. To fulfil its function as an advanced organiser, students should be able to outline a (rudimentary) modelling procedure in line with (major stages in) the applied procedure. Thus, the primary question is whether or not a modelling procedure exists that will lead to a model with the intended quality. Especially for causal and dynamic modelling levels this seems questionable, since in these advanced levels more creativity, causal, complex and heuristic reasoning skills are involved, which cannot be 'captured' in a simple straightforward procedure. Students should then rely on some kind of modelling heuristic, such as described by Hesteness (2006). Such a heuristic may not be sufficiently 'directive' in the teaching-learning processes for many students in pre-academic education, unless they have already (a lot of) modelling experience, for example, in previous modules. Further design-based research is needed to exploit the potential educational benefits of adapting authentic practices covering (theory driven) causal and dynamic modelling levels.

Authentic practices as contexts in science education.

In this section we will reflect upon the use of authentic practices as contexts for learning in science education.

Providing students with a realistic and honest view of science in society has been a goal in many educational reform movements (Edelson, 1998). The use of authentic practices as contexts for learning can be seen as a way to serve this goal. However, to adapt an authentic practice such that it becomes authentic from students' perspective is no trivial task. In this section some general recommendations concerning 'authentic practice based curriculum units' are presented.

Designing learning environments that actually reflect real science practices potentially fosters students' motivation, involvement and ownership and enables them to acquire knowledge in meaningful contexts (Edelson, 1998). However, we need to account for very different populations of experts, teachers and students and differences in environments. As argued in Chapter 2, not all authentic practices are suitable for use in education. In retrospect, an authentic practice needs to comply with a number of prerequisites to be suitable for use in chemistry (science) education:

- The objectives in the adapted authentic practice should match the learning goals of pre-academic education;
- The example problem(s) should be shaped and conceptualised such that it (they) become(s) recognisable for students;
- An existing well defined procedure, in line with students' intuitive notions, should be available from which a sequence of teaching-learning activities can be derived;
- The chemistry (science) knowledge involved should be in line with students' (cognitive) abilities;
- Possible laboratory work, use of advanced computer tools, etc. should be practically feasible in the classroom.

An authentic practice offers the course designer a 'complete, rich setting' from which the useful attributes for educational purposes can be selected. In this respect Gilbert (2006) identifies four attributes:

a. A setting, a social, spatial, and temporal framework within which mental encounters with focal events are situated;
b. A behavioural environment of the encounters, the way that the task(s), related to the focal event, have to be addressed, to frame the talk that then takes place;
c. The use of specific language, as the talk associated with the focal event that takes place;
d. A relationship to extra-situational background knowledge.

When the four attributes in an authentic practice are elaborated such that it provides a coherent structural meaning for the students, it can be expected that the personal relevance for the students will be related to an understanding of why they are learning about science. The process of adaptation is characterised by shifts of emphasis, applying simplifications, selecting and presenting chemistry (science) knowledge and paying attention to students' motives, attitudes etc. The main objective in the process of adaptation is to maintain the coherency within the constraints of the classroom. In Figure 5 the design challenge is depicted in terms of major questions, considerations and points for attention.

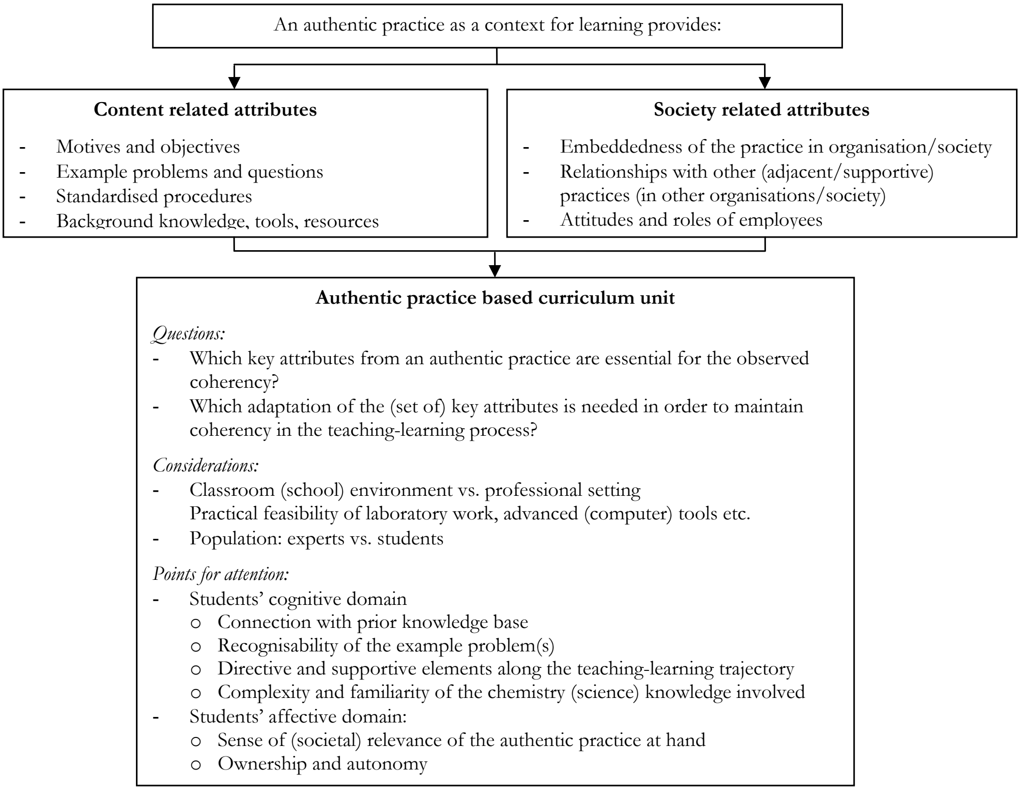


Figure 5. A schematic representation of the design challenges of adapting an authentic practice into a context for learning in terms of major questions, considerations and points requiring attention.

Concluding remarks and outlook

As with all research projects, as well as answers, new challenging questions and research areas are identified. In this final section I state briefly the main conclusions, indicate the relevance of this project in the perspective of the current Dutch chemistry curriculum reform, and suggest some new research areas emerging from this project.

This thesis began with an overview of persistent learning problems related to models and modelling in chemistry (science) education. The aim of this study was to explore the use of authentic modelling practices as contexts for learning as an approach to overcoming these problems. The results of these studies have provided more insight in the potential benefits of the approach. By involving students in adapted authentic practices they enriched their epistemological views on models and modelling. In comparison with the traditional use of models and modelling in chemistry education, students did become aware that multiple modelling approaches exist in science, each with their own pros and cons. They experienced the wording of the models, and gained improved understanding. Besides, this approach gave students a view about the functioning of science in society, a valuable aim to strive for in science education. I thus recommend incorporating such units in current chemistry and science curricula. In addition, these studies have provided an useful knowledge base for educational design, captured and described in (1) a design framework, a synthesis of teaching-learning phases, instructional functions and the design principles of *context*, *content* and *chain of activities*, and (2) a structure of a teaching-learning process. It has also become clear that adapting an authentic practice for educational purposes is no trivial task. Although the added value of the knowledge base for educational design as such is generally considered as relevant, up to now there is no clear consensus within the science education research community about how to make such knowledge explicit and how to communicate design knowledge. This thesis might contribute to the development of (some kind of) standard to foster mutual understanding and exchange of design knowledge.

Currently, the Dutch chemistry curriculum for pre-university education, VWO ('Voorbereidend Wetenschappelijk Onderwijs'), and higher pre-vocational education HAVO ('Hoger Algemeen Voortgezet Onderwijs') is being reformed according to the context-concept approach (Driessen and Meinema, 2003). The outcomes of this research project can be used as a leading example for designing curriculum units based on authentic practices, specifically on models and modelling. Such design using an authentic practice can help to frame contexts, activities and concepts. However, considering the application of this approach in the chemistry curriculum, at least two important aspects should be taken into accounted:

- Using authentic practices as contexts for learning leads to (1) the introduction of (new) chemistry content that is not present in the current curriculum, and (2) overlap and cross links with other (not chemistry) science and/or mathematics domains. Authentic practices tend to be multidisciplinary, covering areas that are not present in the current chemistry (science) curricula. For example, in the present study, coagulation mechanisms are introduced as new chemistry content, and correlation and regression was needed to analyse the empirical dataset.
- The chemistry (science) teachers should agree with and support the pedagogy underlying this approach, and should be given time for preparation to enact curriculum units of this type in class. The present study was conducted in close cooperation with six experienced teachers, in a period covering over two years. This resulted in high quality enactments by teachers who were able to find 'their own way in the curriculum unit' (Van Rens, Pilot, & Van der Schee, 2010; Vos, Taconis, Jochems, & Pilot, 2010).

Below, some new research areas are identified, also based the findings in this thesis. Studies in some of these areas have (recently) been started within our institute.

- Hitherto only a limited number of well described examples of using authentic practices as contexts for learning were available (Engelbarts, 2009; Meijer et al., 2009; Westbroek, 2005; Westra, 2008). More detailed descriptions and studies of examples are needed to refine the design framework and to gain insight in the range of the approach, in other domains than models and modelling.
- The approach of using authentic practices as contexts for learning leads to a new vision on establishing coherency between science and mathematics domains. In this thesis, a fruitful coherence between chemistry and mathematics naturally emerged. It is worthwhile to alter the perspective and take the activities and concepts that function within an authentic practice as the point of departure (Boer, Boersma, Goedhart, & Prins, 2009).
- The design of a series of authentic practice based teaching units offers opportunities for establishing coherency on curriculum level (Bulte et al., 2005; Lijnse and Boersma, 2004; Westbroek, 2005). Most likely, for such study to be successful, more authentic practice based curriculum units are needed. Such study could, potentially, also lead to an updated science curriculum (Van Berkel, 2005), in contrast to the current historically grown science curricula, and give rise to new design principles, such as transfer.
- New approaches to teaching and learning of science ask for new assessment tools. Research about the development of new assessment tools in alignment with course materials is needed (Gerkes, Bulte, Pilot, & Orpwood, 2009).
- Working on and with new curriculum materials is a powerful instrument for teachers' professional development. During such a process, teachers reflect on their own classroom practice and enrich their expertise (Dolfing, Bulte, Pilot, & Vermunt, 2009; Stolk, Bulte, De Jong, & Pilot, 2009; Stolk, De Jong, Bulte, & Pilot, 2009). More research on effective teacher professionalization trajectories is needed in order to implement new, innovative curriculum units in class. The design procedure involving close cooperation with teachers, as described in this thesis, might be used as a source of inspiration for other professionalization trajectories.

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Summary

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Summary

In science education, students should come to understand the nature and significance of models. This includes the motivation, strategies and argumentation underlying the development, evaluation and revision of models. This study explores the potential benefits of using authentic chemical modelling practices as contexts for learning. The approach is underpinned by the activity theory rooted in sociocultural theories on learning. An authentic modelling practice is characterised by professionals with common motives and purposes, working to a similar type of modelling procedure and applying relevant knowledge in the area they are working in. However, for using an authentic practice as a context for learning we need to account for significant differences between the student population and that of experts. This study strives to gain an improved understanding of the design of a teaching-learning process, using an authentic modelling practice as context for learning during which students:

- become meaningfully involved in a modelling process;
- gain understanding of the theoretical and empirical foundation of models;
- learn about epistemic notions, such as goodness of fit, reliability and validity.

At a more generalised level, this thesis aims to contribute to a knowledge base for designing teaching-learning processes in science education, such that students reach an adequate understanding of (the nature of) models and the process of modelling. The knowledge involved is captured in a design framework, consisting of learning phases, instructional functions and design principles. Three central research questions are addressed:

1. Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?
2. What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?
3. What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?

Each chapter in this thesis contributes to answering one of the central research questions.

Research question 1: Which authentic chemical modelling practices are suitable for use as contexts for learning in secondary chemistry education, and to what extent do these practices initiate students' involvement in modelling processes?

Chapter 2 focuses on the selection of suitable authentic chemical modelling practices for use as contexts for learning in secondary chemistry education. The review focused on the following criteria: students' interest and ownership; familiarity with the issue and perceived complexity; modelling procedure applied; knowledge involved and feasibility of the laboratory work in the classroom. Two practices were selected, namely: (1) modelling human exposure to and uptake of chemicals from consumer products, and (2) modelling drinking water treatment. Both practices met all formulated criteria to a large extent. The motives for model development appeared to emerge from clear, recognisable problems from the students' perspective. The characteristic modelling procedure corresponded to a large degree with students' expected commonsense procedural knowledge. Both practices offer opportunities to establish a solid connection with students' pre-existing knowledge base, for instance by focusing on a specific, well-chosen treatment step or chemical substances within consumer products. In addition, it is possible to carry out experimental work in the classroom for model calibration and validation.

Chapter 3 evaluated the extent of students' involvement in modelling processes using the two selected practices as contexts for learning. Learning tasks were designed in which students oriented themselves on the authentic practices and drew up plans of action for solving sample modelling problems situated within the practices. The tasks were enacted with a focus group of students. During the learning process students' interests and ownership were mapped. Their familiarity with the modelling problems and perceived complexity were investigated, and the modelling procedures devised by students in response to the modelling problem, as expressed by them, were analysed. The results revealed that students appreciated the approach, were motivated by the authenticity of the modelling problems and challenged to devise a solution themselves. When it came to ownership, the results indicated that both units in theory allow students to act relatively autonomously. As for the cognitive domain, it was concluded that students were sufficiently familiar with the chemical concepts involved, but were unfamiliar with the employed mathematical models. As regards the latter, students struggled with the number of variables involved and the unknown origin of the constants. Despite students' unfamiliarity with the models and the perceived complexity, the modelling procedures devised by students were complete and of high quality. In general, the results showed that students' involvement was successfully initiated, as evidenced by motivated students, willingness to continue and the completeness and quality of the realised modelling procedures.
From this point on it was decided to continue with the authentic practice of modelling drinking water treatment as a context for learning.

Research question 2: What is an adequate structure for teaching-learning processes, using authentic practices as contexts for learning in secondary chemistry education, through which students learn about the epistemology of models and modelling, and what are the implications for the design framework?

Chapter 4 reports the design of a laboratory experiment feasible in the classroom. The laboratory experiment was incorporated in a teaching-learning process using the authentic practice of modelling drinking water treatment as a context for learning. The laboratory experiment involves the removal of fine silt, causing water turbidity, by the treatment step of coagulation/flocculation. The focus is investigation of the influence of various process variables, such as dose coagulant, starting turbidity and temperature, on the end turbidity of the water after treatment.
Chapter 5 describes the first design of a teaching-learning process using the authentic practice for modelling drinking water treatment as a context for learning. The knowledge involved was captured in a design framework, a synthesis of learning phases, instructional functions and design principles. Design principles are theoretically and empirically grounded constructs linking *strategy components* (e.g. *what*, *when* and *how* to do in the teaching-learning process) with *intended pedagogic effects* (e.g. students see the point of modelling and achieve improved understanding of epistemic notions), underpinned by *arguments* (e.g. literature on educational research, empirical findings from previous applications and/or practical considerations). The design principles were elaborated by a design team consisting of six experienced chemistry teachers and three researchers. Three design principles were formulated, labelled 'context', 'content modelling' and 'chain of activities'. The principle of *context* dealt with involving learners in a practice embedded in its cultural setting. This implies the behavioural environment, the specific language and the extra-situational background knowledge. The principle of *content modelling* dealt with focusing learners on the essential content regarding models and modelling. This implies advanced model features, such as goodness of fit and validity, and notions regarding the epistemology of the black box modelling approach. The principle of *chain of activities* dealt with constructing a sequence of teaching-learning activities such that learners constantly know what to do, and why, at every step in the process. Each stage and activity in the teaching-learning process needs to be justified and evaluated from the students' perspective.

Chapter 6 reports the application in the classroom of a curriculum unit using the authentic chemical practice for modelling drinking water treatment as the context for learning. The findings were used to evaluate the formulated design framework in the light of the overall functioning of the teaching-learning process in the classroom. Throughout the field tests, research data were collected by means of classroom observations, interviews, audio-taped discussions, completed worksheets and written questionnaires. The results showed that students were able to reflect on the model aspects of goodness of fit and reliability, and showed awareness of the empirical foundation of the developed model. Inducing meaningful reflection on the modelling procedure proved, however, to be difficult. The results led to changes in the design principles and the instructional functions in terms of inducing students to evaluate and reflect on the applied modelling procedure.

Chapter 7 reports the second application in the classroom of the teaching-learning process. In this second cycle the primary focus was on the learning gain of students as regards epistemology of models and modelling, as embodied in the design principle *content modelling*. In addition, the functioning of the redesigned instructional functions regarding evaluation and reflection was evaluated. The findings showed that students are able to reflect on the epistemic value of goodness of fit and reliability, and to a lesser extent on that of validity. Although the redesigned teaching-learning process led to improved learning results, it still proved difficult to induce meaningful evaluation and reflection on the modelling procedure applied. The findings (again) gave rise to slight alterations in design principle *content modelling*.

All acquired results were implemented into the design framework, as depicted in Figure 1. The design framework provides heuristic guidelines for structuring teaching-learning processes using authentic modelling practices as contexts for learning.

Design Framework			
Learning phases / Instructional functions	Design principles: Context	Design principles: Chain of activities	Design principles: Content modelling
I: Orientate on the practice ***(a)*** Connect to prior conceptual knowledge base ***(b)*** Connect to prior procedural knowledge base ***(c)*** Evoke motivation to study the problems posed in the practice ***(d)*** Evoke a motive to zoom in on a example problem	**Strategy component 1:** Provide students with an orientation base: supply broad overview of the subject dealt with as well as the authentic practice at hand **Strategy component 2:** Give students a rich, whole task		**Strategy component A:** Visualise and conceptualise for students the example problem they are going to work on
II: Zoom in on a example problem ***(e)*** Make explicit and build on the prior conceptual knowledge base ***(f)*** Make explicit and build on the prior procedural knowledge base ***(g)*** Evoke a motive to solve the example problem		**Strategy component i:** Give students a clear assignment concerning the example problem they are to work on and direct their attention to the end product they are to deliver	**Strategy component B:** Supply students with a worked-out analogous modelling problem as leading example
III: Solve the example problem ***(h)*** Proceed through the sequence of activities and learn/apply knowledge until a satisfactory solution for the example problem can be presented	**Strategy component 3:** Select essential situated knowledge and supply it to students by means of articles and/or manuals **Strategy component 4:** Organise students to ensure that they keep track of situated knowledge	**Strategy component ii:** Construct a sequence of teaching-learning activities for students using the modelling procedure applied in the authentic practice as source of inspiration **Strategy component iii:** Plan regular class meetings with students to look ahead to future activities	**Strategy component C:** Discuss with students different modelling approaches and point out an appropriate one for the example problem at hand **Strategy component D:** Involve students in a series of teaching-learning activities emphasising the nature, characteristics and wording of the model(s) at hand
IV: Evaluate and reflect on the findings ***(i)*** Evaluate the learned conceptual and procedural knowledge ***(j)*** Reflect on the procedural knowledge			**Strategy component E:** Let students apply the constructed model in a real-world setting **Strategy component F:** Let students compare different modelling approaches and reflect on the assumptions and estimations made, and the possible effect of neglected variables
V: Express the findings ***(k)*** Make explicit the learned conceptual and procedural knowledge	**Strategy component 5:** Select an end product, matching the example problem, to assess students' performance		

Figure 1. A design framework providing heuristic guidelines for structuring teaching-learning processes using authentic modelling practices as contexts for learning.

Research question 3: What is the heuristic value of the design framework for structuring teaching-learning processes using authentic practices as contexts for learning models and modelling in secondary chemistry education?

In Chapter 8 the heuristic value of the design framework was evaluated by using it as a design tool for adapting the authentic practice of modelling human exposure and uptake of chemicals from consumer products into a context for learning. The adaptation was undertaken by six experienced chemistry teachers, who were well informed about the design framework. The heuristics were assessed on the dimensions of completeness, instructiveness and appreciation. The results showed that the design framework is complete and highly appreciated. The instructions could be further improved, however, by incorporating explicit guidelines to evoke students' motives to become engaged in a sample modelling problem and to induce reflection.

Chapter 9 gives an overview of the major findings and conclusions regarding the three central research questions as well as some reflections.

In conclusion, the results show that involving students in the adapted authentic practice of modelling drinking water treatment enriched their understanding of advanced model features, such as goodness of fit and reliability. In addition, the majority of the students put forward relevant notions regarding the empirically driven modelling approach, e.g. the absence of a sound theoretical foundation and the need for a good-quality (number and accuracy) data set to describe the process behaviour. It has, however, proven difficult to induce meaningful reflection by students on the applied modelling procedure. Despite the observed shortcomings in students' reflection, the use of authentic practices as contexts for learning, if properly adapted, do lead to the intended learning outcomes.

An authentic practice offers a rich source of inspiration for designing teaching-learning processes. The educational challenge is to adapt the practice so that it suits students' abilities and leads to desired learning outcomes. Further design-based research is needed to exploit the potential benefits of adapting authentic practices in which other modelling approaches and levels are applied, such as theory-driven, causal and dynamic modelling.

Samenvatting

In het natuurwetenschappelijk onderwijs in de bovenbouw van het havo/vwo dienen leerlingen inzicht te verkrijgen in de rol, functie en betekenis van modellen. Ook dient er aandacht te zijn voor aanleidingen, strategieën en argumentaties voor het ontwikkelen, evalueren en aanpassen van modellen. Deze studie exploreert de mogelijkheden van het gebruik van authentieke modelleerpraktijken als leercontext. Deze benadering sluit aan bij de activiteitstheorie, die geworteld is in de sociaal-cultuurhistorische visie op leren en onderwijzen. Een authentieke praktijk wordt gedefinieerd als een gemeenschap van professionals, die werken aan een afgebakend vraagstuk of probleem met duidelijke doelen en motieven, volgens een goed omschreven karakteristieke procedure met gebruikmaking van relevante (natuurwetenschappelijke) kennis. Bij het gebruik van een authentieke praktijk als leercontext dient rekening te worden gehouden met de (grote) verschillen tussen professionals en leerlingen, en tussen werksituatie en schoolomgeving. Dit onderzoek was gericht op het ontwerpen van onderwijsleerprocessen, gebaseerd op een authentieke modelleerpraktijk als leercontext, waardoor leerlingen:

- het doorlopen van een modelleerproces betekenisvol vinden;
- inzicht krijgen in de theoretische en empirische fundering van modellen;
- leren over epistemologische waarden, zoals de passendheid, betrouwbaarheid en geldigheid.

Op een meer generiek niveau beoogt dit onderzoek een bijdrage te leveren aan een kennisbasis voor het ontwerp van onderwijsleerprocessen in het natuurwetenschappelijk onderwijs, zodanig dat leerlingen meer inzicht krijgen in modellen en het proces van modelleren. Deze kennisbasis wordt beschreven in een ontwerpraamwerk: een synthese van leerfasen, onderwijskundige functies en ontwerpprincipes. Er zijn drie centrale onderzoeksvragen geformuleerd:

1. Welke authentieke chemische modelleerpraktijken zijn geschikt voor gebruik als leercontexten in het scheikundeonderwijs in de bovenbouw van het vwo?
2. Hoe ziet een onderwijsleerproces eruit, gebaseerd op het gebruik van een authentieke praktijk als leercontext in het scheikundeonderwijs in de bovenbouw van het vwo, waarin leerlingen leren over de epistemologie van modellen en modelleren, en wat zijn de implicaties daarvan voor het ontwerpraamwerk?
3. Wat is de heuristische waarde van het ontwerpraamwerk voor het structureren van onderwijsleerprocessen met gebruik van authentieke modelleerpraktijken als leercontexten in het scheikundeonderwijs in de bovenbouw van het vwo?

Elk hoofdstuk in dit proefschrift is gericht op het beantwoorden van (een deel van) één van bovenstaande onderzoeksvragen.

Onderzoeksvraag 1: Welke authentieke chemische modelleerpraktijken zijn geschikt voor gebruik als leercontexten in het scheikundeonderwijs in de bovenbouw van het vwo?

Hoofdstuk 2 gaat in op de selectie van authentieke modelleerpraktijken die geschikt zijn als leercontexten in het secondair scheikundeonderwijs. De geschiktheid is beoordeeld vanuit het perspectief van de leerling aan de hand van de volgende criteria: interesse, eigenaarschap, bekendheid met het onderwerp en complexiteit, toegepaste modelleerprocedure, benodigde relevante kennis en de praktische uitvoerbaarheid van experimenten op school. Twee praktijken zijn geselecteerd, namelijk: 1) modelleren van blootstelling en opname van chemicaliën uit consumentenproducten, en 2) modelleren van waterzuiveringsprocessen. De twee praktijken voldoen beide aan alle gestelde criteria. In beide gevallen vormden duidelijke, voor leerlingen herkenbare problemen aanleiding voor het ontwikkelen van de modellen. De karakteristieke modelleerprocedures komen in grote mate overeen met de verwachte intuïtieve noties van leerlingen over modelleren. Bovendien bieden beide praktijken mogelijkheden aan te sluiten bij de bestaande kennisbasis van leerlingen, bijvoorbeeld door in te zetten op één goed gekozen zuiveringsstap of chemicaliën in een consumentenproduct. Daarnaast lijkt het mogelijk experimenteel werk in de school uit te voeren voor modelcalibratie en -validatie.

In hoofdstuk 3 is geëvalueerd in hoeverre leerlingen worden aangesproken door de twee geselecteerde authentieke modelleerpraktijken. Er zijn leeractiviteiten ontwikkeld waarin leerlingen zich eerst oriënteren op de authentieke praktijk en vervolgens een plan van aanpak opstellen voor het aanpakken van een exemplarisch modelleerprobleem uit de betreffende praktijk. De leeractiviteiten zijn uitgevoerd door een focusgroep van leerlingen. Gedurende de uitvoering is de interesse en eigenaarschap van leerlingen in kaart gebracht. Daarnaast is de bekendheid van leerlingen met de exemplarische modelleerproblemen onderzocht en de door leerlingen ervaren complexiteit van de problemen. Tenslotte zijn de door leerlingen opgestelde modelleerprocedures geanalyseerd. De resultaten lieten zien dat leerlingen de algehele aanpak waardeerden, gemotiveerd werden door de authenticiteit van de modelleerproblemen en zich uitgedaagd voelden om zelf met een oplossing te komen. De geselecteerde praktijken leken ook eigenaarschap bij leerlingen te initiëren, getuige het feit dat de leerlingen de exemplarische modelleerproblemen op eigen wijze konden aanpakken. Voor het cognitieve domein lieten de resultaten zien dat leerlingen voldoende vertrouwd waren met de benodigde essentiële scheikunde concepten, maar niet met de wiskundige modellen die toegepast werden. Daarnaast hadden leerlingen moeite met het aantal variabelen en het begrijpen van de herkomst en betekenis van de constanten. De door leerlingen opgestelde modelleerprocedures waren echter van hoge kwaliteit. Concluderend kan gesteld worden dat leerlingen in voldoende mate worden aangesproken en betrokken zijn geraakt, afgaande op de motivatie van leerlingen, hun bereidwilligheid en de volledigheid en kwaliteit van de opgestelde modelleerprocedures.

Voor het vervolg is besloten door te gaan met de authentieke praktijk modelleren van waterzuiveringsprocessen als leercontext.

Onderzoeksvraag 2: Hoe ziet een onderwijsleerproces eruit, gebaseerd op het gebruik van een authentieke praktijk als leercontext in het scheikundeonderwijs in de bovenbouw van het vwo, waarin leerlingen leren over de epistemologie van modellen en modelleren, en wat zijn de implicaties daarvan voor het ontwerpraamwerk?

In hoofdstuk 4 wordt een experiment beschreven dat leerlingen in de klas kunnen uitvoeren. Het experiment is een belangrijk onderdeel van het ontworpen onderwijs over het modelleren van waterzuiveringsprocessen. Het experiment behelst het verwijderen van fijn slib door de zuiveringsmethode vlokbehandeling. Het fijne slib veroorzaakt troebeling van water. In het experiment wordt de invloed van diverse procesvariabelen, zoals de dosis coagulant, de begintroebeling van het water en de temperatuur op de eindtroebeling van water na vlokbehandeling onderzocht.

In hoofdstuk 5 wordt het eerste ontwerp van het onderwijsleerproces beschreven waarin de authentieke praktijk modelleren van waterzuiveringsprocessen fungeert als leercontext. De ontwerpkennis is vastgelegd in een ontwerpraamwerk. Het ontwerpraamwerk is een synthese van leerfasen, onderwijskundige functies en ontwerpprincipes. Ontwerpprincipes zijn opgebouwd uit theoretisch en empirisch gefundeerde relaties tussen strategiecomponenten en beoogde pedagogische effecten. De strategiecomponenten geven aan *wat*, *wanneer* en *hoe* te doen in het onderwijsleerproces om de beoogde pedagogische effecten te bereiken, zoals leerlingen een motief laten ontwikkelen voor modelleren of leerlingen inzicht laten verkrijgen in de epistemologische waarden. De onderbouwende argumentatie kan zowel theoretisch als empirisch van aard zijn, bijvoorbeeld gebaseerd op bestaande literatuur, eerder opgedane ervaringen in de klas of praktische overwegingen. De ontwerpprincipes zijn opgesteld door een ontwerpteam bestaande uit zes ervaren scheikundedocenten en drie onderzoekers. Er zijn drie ontwerpprincipes geformuleerd, namelijk ‘context’, ‘inhoud modelleren’ en ‘keten van activiteiten’. Het principe *context* gaat over het interesseren van leerlingen in een authentieke modelleerpraktijk en het motiveren van leerlingen om deze praktijk te bestuderen. Aspecten waar aandacht aan moet worden besteed zijn de omgeving waarin de praktijk functioneert, essentiële kenmerken, specifieke taal en benodigde achtergrondkennis. Het principe *inhoud modelleren* gaat over het verankeren van de essentiële leeropbrengst voor modellen en modelleren in het onderwijsleerproces. Dit impliceert de generieke modeleigenschappen, zoals de passendheid en geldigheid, en epistemologische noties over de empirische modelleeraanpak. Het principe *keten van activiteiten* gaat over de constructie van een serie onderwijsleeractiviteiten, zodanig dat leerlingen op ieder moment weten *waarom* ze *wat* aan het doen zijn. Elke fase en activiteit in het onderwijsleerproces moet daarvoor worden verantwoord en geëvalueerd vanuit het perspectief van de leerlingen.

In hoofdstuk 6 wordt gerapporteerd over de uitvoering in de klas van het ontworpen onderwijsleerproces waarin de authentieke praktijk modelleren van waterzuiveringsprocessen fungeert als leercontext. De resultaten zijn gebruikt om het ontwerpraamwerk te evalueren in het licht van het algehele functioneren van de module in de klas. Tijdens de uitvoering in de klas zijn gegevens verzameld in de vorm van observaties, interviews, discussies, ingevulde werkbladen en schriftelijke enquêtes. De resultaten lieten zien dat leerlingen begrip ontwikkelen over modeleigenschappen passendheid en betrouwbaarheid, en inzicht kregen in de empirische onderbouwing van het model. Maar, het bleek moeilijk om de leerlingen te laten reflecteren op de doorlopen modelleerprocedure. De bevindingen hebben geleid tot aanpassingen in de drie ontwerpprincipes *context*, *inhoud modelleren* en *keten van activiteiten*. Tevens zijn de onderwijskundige functies evaluatie van en reflectie op de doorlopen modelleerprocedure gewijzigd. De belangrijkste veranderingen zijn ook in dit hoofdstuk beschreven.

In hoofdstuk 7 wordt het tweede experiment in de klas, met het aangepaste onderwijsleerproces, beschreven. Dit experiment was vooral gericht op de gerealiseerde leeropbrengst van leerlingen over de epistemologie van modellen en modelleren. Deze leeropbrengst is met name verankerd in het ontwerpprincipe *inhoud modelleren*. Daarnaast is het functioneren van de aangepaste onderwijskundige functies evaluatie en reflectie geëvalueerd. De resultaten laten zien dat leerlingen in staat zijn te reflecteren op generieke modeleigenschappen passendheid en betrouwbaarheid, en in mindere mate op de geldigheid. Alhoewel het aangepaste onderwijsleerproces betere leerresultaten liet zien, bleef het moeilijk om leerlingen aan te zetten tot een betekenisvolle reflectie. De resultaten gaven aanleiding tot een aantal kleine aanpassingen in ontwerpprincipe *inhoud modelleren.*

Het uiteindelijke ontwerpraamwerk waarin alle bevindingen zijn verwerkt is weergegeven in Figuur 1. Het ontwerpraamwerk geeft heuristische richtlijnen voor het structureren van onderwijsleerprocessen met gebruikmaking van authentieke modelleerpraktijken als leercontexten.

Onderzoeksvraag 3: Wat is de heuristische waarde van het ontwerpraamwerk voor het structureren van onderwijsleerprocessen met gebruik van authentieke modelleerpraktijken als leercontexten in het scheikundeonderwijs in de bovenbouw van het vwo?

In hoofdstuk 8 wordt de heuristische waarde van het ontwerpraamwerk geëvalueerd door dit toe te passen bij de omzetting van de authentieke praktijk modelleren van blootstelling en opname van chemicaliën uit consumentenproducten in een leercontext. De omzetting werd uitgevoerd door zes ervaren scheikundedocenten, die goed bekend waren met het ontwerpraamwerk. De heuristische waarde werd beoordeeld op drie dimensies: volledigheid, mate van instructie en waardering. De resultaten laten zien dat het ontwerpraamwerk volledig is en wordt gewaardeerd door de gebruikers. Maar de mate van instructie kan worden verbeterd, vooral door het opnemen van expliciete richtlijnen voor het interesseren en betrekken van leerlingen bij een praktijk, en dan met name voor het exemplarische probleem. Ook dienen er richtlijnen te komen voor het oproepen van reflectie.

In hoofdstuk 9 wordt een overzicht gegeven van de belangrijkste bevindingen en conclusies over de drie onderzoeksvragen en wordt gereflecteerd op de opbrengsten.

Het gebruik van de authentieke praktijk modelleren van waterzuiveringsprocessen als leercontext heeft bij leerlingen geleid tot inzicht in generieke modeleigenschappen, zoals passendheid en betrouwbaarheid. Daarnaast heeft de meerderheid van de leerlingen meer inzicht verkregen in de empirische modelleerbenadering. Dit omvat onder meer de notie van het ontbreken van een goede theoretische fundering en het belang van een kwalitatief goede set data (het aantal meetpunten en nauwkeurigheid) om het procesgedrag goed te kunnen beschrijven. Het bleek echter moeilijk om leerlingen aan te zetten tot een betekenisvolle reflectie op de doorlopen modelleerprocedure. Concluderend kan gesteld worden dat, ondanks het mislukken van de reflectieactiviteiten, het gebruik van authentieke praktijken als leercontexten, indien op goede wijze vorm gegeven, kan leiden tot de beoogde leerresultaten.

Een authentieke praktijk is een rijke bron van inspiratie voor het ontwerp van onderwijsleerprocessen. Het is een uitdaging om de praktijk zo aan te passen dat die aansluit bij de capaciteiten van leerlingen en leidt tot de beoogde leerdoelen. Er is echter verder ontwerponderzoek nodig om na te gaan in hoeverre deze aanpak ook succesvol is voor andere authentieke praktijken waarin andere modelleerbenaderingen worden toegepast

Ontwerpraamwerk			
Leerfasen / Onderwijskundige functies	Ontwerpprincipes		
	Context	Keten van activiteiten	Inhoud modelleren
I: Oriëntatie op de authentieke praktijk ***a)*** Sluit aan bij de bestaande conceptuele kennisbasis ***b)*** Sluit aan bij de bestaande procedurele kennisbasis ***c)*** Roep motivatie op voor bestuderen van de problemen gesitueerd in de authentieke praktijk ***d)*** Roep een motief op om in te zoomen op een exemplarisch probleem	**Strategiecomponent 1:** Geef leerlingen en brede oriëntatie basis: geef een breed overzicht van het onderwerp en de authentieke praktijk **Strategiecomponent 2:** Geef leerlingen een volledige, rijke taak		**Strategiecomponent A:** Visualiseer en conceptualiseer voor leerlingen het exemplarische probleem waar zij aan gaan werken
II: Zoom in op een exemplarisch probleem ***e)*** Expliciteer en bouw voort op de bestaande conceptuele kennisbasis ***f)*** Expliciteer en bouw voort op de bestaande procedurele kennisbasis ***g)*** Roep een motief op tot oplossen van het exemplarische probleem		**Strategiecomponent i:** Geef leerlingen een duidelijke opdracht over het exemplarische probleem en besteed aandacht aan het eindproduct dat zij moeten opleveren	**Strategiecomponent B:** Geef leerlingen een uitgewerkt analoog modelleerprobleem als voorbeeld
III: Oplossen van het exemplarische probleem ***h)*** Voer een serie activiteiten uit, waarbij kennis wordt geleerd en toegepast, totdat een toereikend resultaat voor het exemplarische probleem kan worden gepresenteerd	**Strategiecomponent 3:** Selecteer de essentiële gesitueerde achtergrondkennis en geef deze aan leerlingen door middel van artikelen en handleidingen **Strategiecomponent 4:** Organiseer dat leerlingen zicht houden op de gesitueerde kennis	**Strategiecomponent ii:** Construeer een sequentie van onderwijsleeractiviteiten, geïnspireerd door de modelleerprocedure zoals toegepast in de authentieke praktijk **Strategiecomponent iii:** Organiseer werkbesprekingen met leerlingen om vooruit te kijken naar komende activiteiten	**Strategiecomponent C:** Bespreek met leerlingen diverse modelleerbenaderingen en maak duidelijk welke benadering de voorkeur geniet voor het **Strategiecomponent D:** Betrek leerlingen in een serie onderwijsleeractiviteiten waarin zij zicht krijgen op de achtergrond, eigenschappen en ontwikkeling van het model
IV: Evalueer en reflecteer op de resultaten ***i)*** Evalueer de geleerde conceptuele en procedurele kennis ***j)*** Reflecteer op de procedurele kennis			**Strategiecomponent E:** Laat leerlingen het ontwikkelde model toepassen in een 'echte' situatie **Strategiecomponent F:** Laat leerlingen verschillende modelleerbenaderingen vergelijken en reflecteren op de gemaakte aannames, schattingen en het mogelijke effect van verwaarlozingen
V: Expliciteer de resultaten ***k)*** Expliciteer de geleerde conceptuele en procedurele kennis	**Strategiecomponent 5:** Kies een eindproduct, passend bij het exemplarische probleem, om de prestaties van de leerlingen te beoordelen		

Figuur 1. Een ontwerpraamwerk met heuristische richtlijnen voor het structureren van onderwijsleerprocessen met gebruikmaking van authentieke modelleer praktijken als leercontexten.

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Curriculum vitae

Gjalt Prins werd op 2 oktober 1970 geboren in Leeuwarden. In 1989 behaalde hij zijn VWO diploma aan de Christelijke Scholengemeenschap Assen te Assen. In 1989 startte hij met de studie Scheikunde aan de Rijksuniversiteit Groningen, die hij 1995 afrondde met specialisatie bioprocestechnologie. Daarna volgde hij de 1^{e} graads lerarenopleiding Scheikunde en werkte als docent scheikunde op het H.N. Werkman College te Groningen en het Zernike College te Haren. In september 1999 kwam hij in dienst bij het departement Scheikunde van de Universiteit Utrecht als medewerker ICT & Onderwijs bij het Freudenthal Instituut - sectie Chemiedidactiek en het departementale Onderwijsinstituut. In deze functie ondersteunde hij docenten bij het inzetten van ICT middelen binnen het scheikunde onderwijs, zowel binnen het departement Scheikunde als in het voortgezet onderwijs. Hij gaf mede vorm en inhoud aan het door stichting SURF gesubsidieerde en in samenwerking met de Technische Universiteit Eindhoven uitgevoerde project ‘Virtuele Projectruimten voor leren Ontwerpen en Onderzoeken’. Daarnaast participeerde hij in het door het ministerie van OC&W gesubsidieerde ontwikkelproject ‘Computerondersteund modelleren’. In 2004 is hij gestart met het promotieonderzoek bij de sectie Chemiedidactiek. Het promotieonderzoek is in deeltijd uitgevoerd.

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