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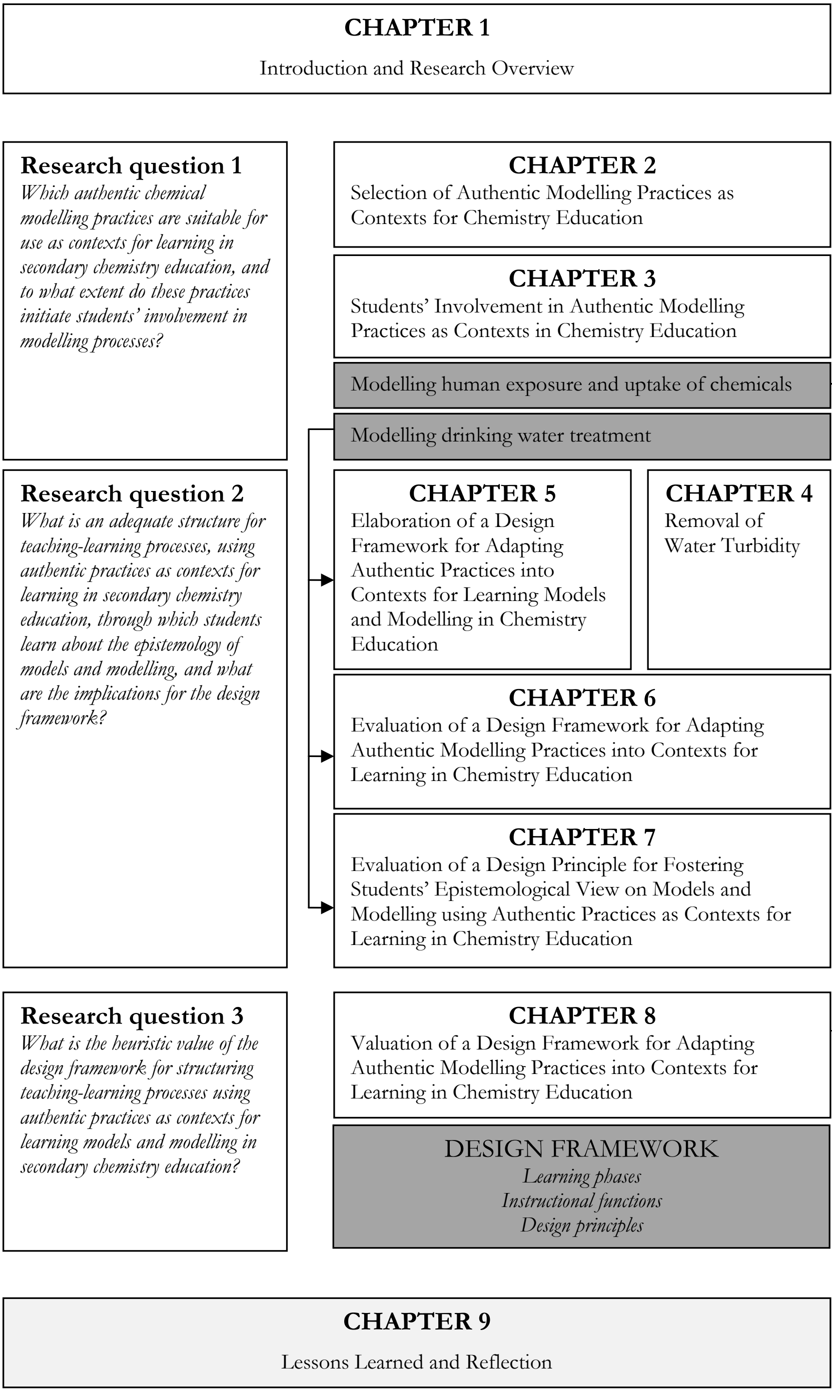
Lessons Learned and Reflection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Introduction

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

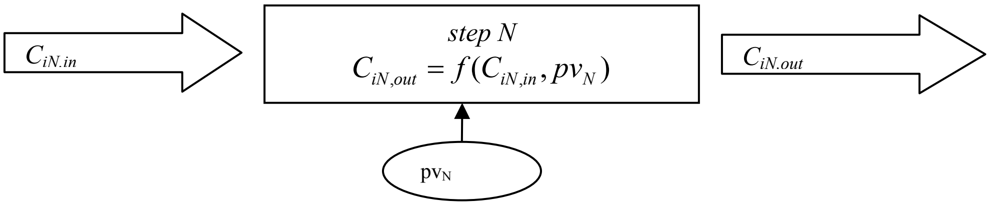

Figure 1. Conceptualised scheme of the modelling of the drinking water treatment process. The block arrows indicate the incoming water stream, containing contaminants ($C_{iN,\ in}$) to be removed, and the outflowing water stream, with a residual concentration of contaminants ($C_{iN,\ out}$). The quantitative 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.

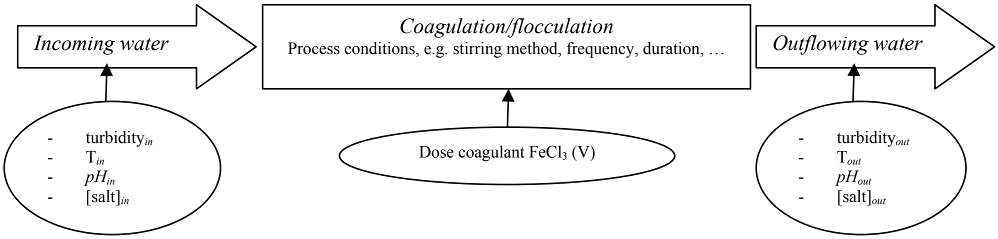

Figure 2. Conceptualised scheme of the coagulation/flocculation treatment process including relevant process variables. The block arrows indicate the flow of water.

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

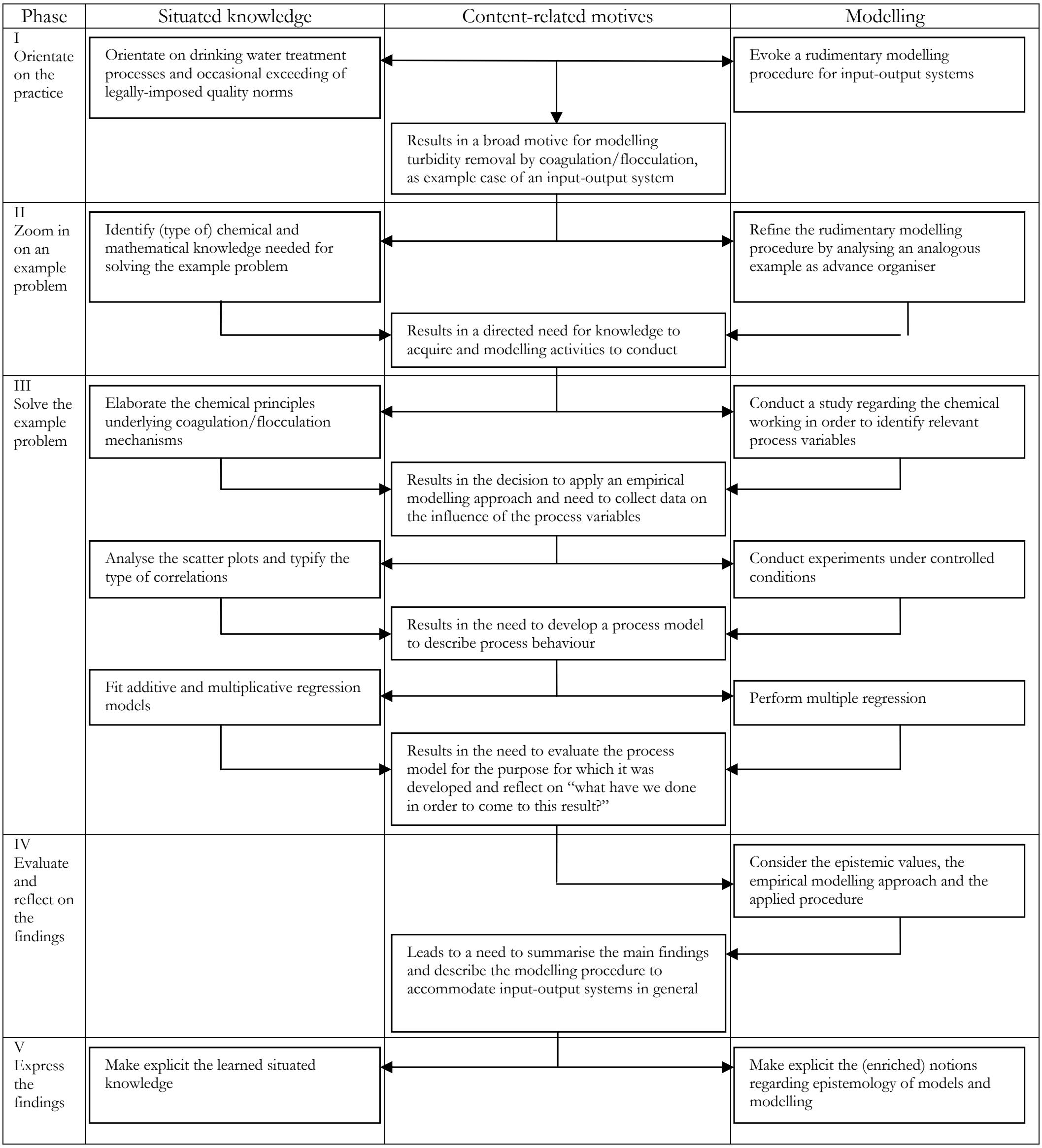

Figure 4. A structure of the teaching-learning process using the authentic practice 'Modelling drinking water treatment' as a context for learning. The blocks represent major stages in the teaching-learning process. The arrows indicate the flow of the process.

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.

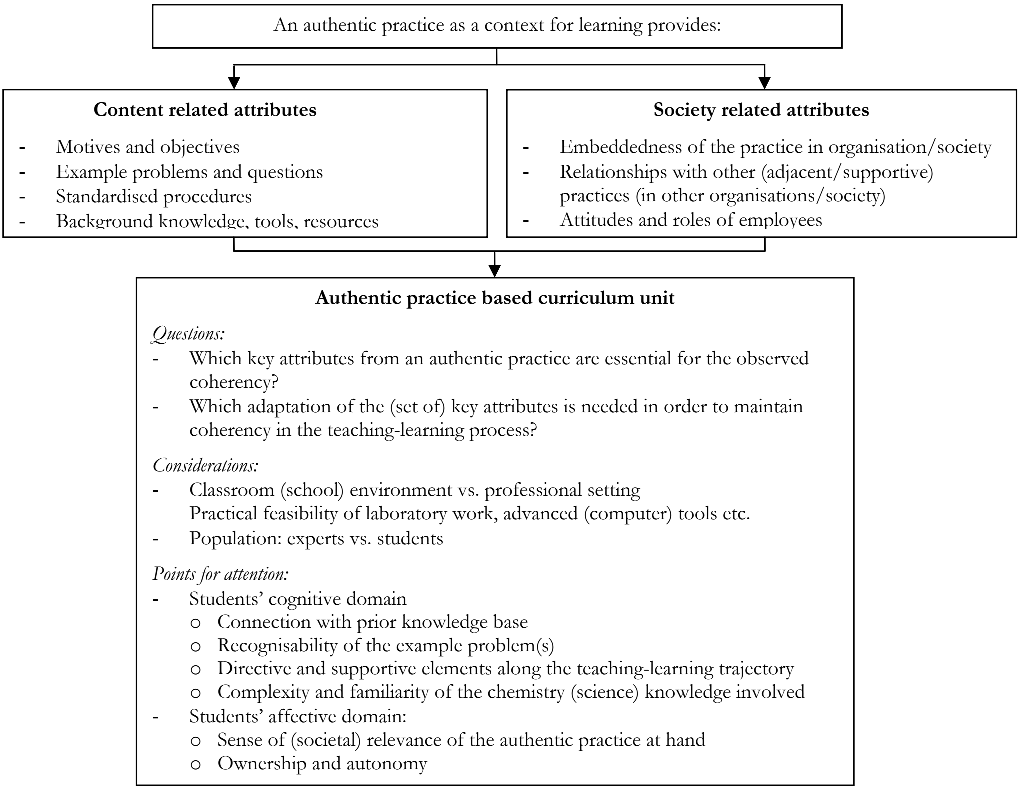

Figure 5. A schematic representation of the design challenges of adapting an authentic practice into a context for learning in terms of major questions, considerations and points requiring attention.

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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