Macro-meso-micro thinking with structure-property relations for chemistry education

An explorative design-based study

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Macro-meso-micro thinking
with structure-property relations
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An explorative design-based study

Macro-meso-micro denken
met structuur-eigenschap relaties
voor het chemieonderwijs

Een exploratief ontwerponderzoek

(met een samenvatting in het Nederlands)

Proefschrift

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aan de Universiteit Utrecht
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Marijn Roland Meijer

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Promotor: Prof.dr. A. Pilot
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‘*Do we teach biology, chemistry, physics, mathematics, or do we teach young people how to cope with their own world?*’
Fourez, 1997. Social Studies in Science, 27(6), p.907.

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Chapter 1

Introduction and overview

I learnt unconsciously more easily because we had a goal in mind. Once we were started, we kept going (Student remark, S8, during the final interview of cycle 1)

If we knew the structures we could zoom in several times …. This is what we did … (Student remark, S9, during activity 13 of cycle 2).

Macro-micro thinking

Macro-micro thinking is considered to be a key conceptual area in the domain of chemistry, which is concerned with the understanding of properties and transformations of materials. Chemists construct *submicroscopic* models for investigating, explaining and using properties of known and new substances and their transformations at *macroscopic* level (Justi & Gilbert, 2002). Within this respect, the macro level refers to directly observable phenomena, e.g., colour, smell, conduction of heat or electricity, mass or taste. The submicro level refers to models with structures at the level of molecules or atoms, or in general, invisible particles with a dimension of about 10^{-9}-10^{-10} m and much smaller than we can observe.

The scientists' macro-micro thinking is to understand and to use the relations between the observed phenomena at the macro level and the models of the invisible particles at the submicro level. In other words, scientists try to describe, understand and predict the properties of materials by relating these to the scientific models of structures at a submicroscopic level. Some of these models imply evident relations between macroscopic properties (boiling point, solubility) and submicroscopic models like molecules or atoms. However, in many other models in contemporary science and technology (e.g., nanotechnology, genomics and micro-structured materials), the relevant structures appear to be at levels other than the submicroscopic. In addition to models at the submicroscopic level, these models refer to structures at an intermediate meso level, such as micelles, cells and crystals with typical dimensions of 10^{-4} to 10^{-8} m.

In chemistry education, macro-micro thinking is however, very difficult for students to learn. This difficulty is described as a two-fold problem:

1. Students have difficulty to relate macroscopic properties to submicroscopic models;
2. Students do not experience that the submicroscopic models are relevant for explaining the world they live in.

Problems in learning to relate macroscopic properties to submicroscopic models

In traditional chemistry education, macro-micro thinking is restricted to two levels: macro and submicro (Johnstone, 1991). The huge step between these two levels has a magnitude of a factor of 10^9 (or 1,000,000,000), causing many problems for students (Millar, 1990). Problems about macro-micro thinking in chemistry education have been frequently reported (e.g., Harrison & Treagust, 2002; Wiser & Smith, 2008) and can be illustrated by the following exemplary statements from students (in italics):

- *Water molecules are blue.* Similar statements made by students are frequently found in the literature. Students consider properties at macro level to be applicable also for the smallest particles. In this example: a water molecule is not blue. Due to the interactions between water molecules some wave lengths are reflected, so the substance water has a blue colour, not the molecule itself.

- *A rubber molecule is elastic.* The problem here is that the property elasticity is a result of the interactions between many large molecules which can move along each other to a certain extent. The term emergence is often summarized in the popular statement that “the whole is more than the sum of the parts” (Luisi, 2002). Emergence is a characteristic of properties and is not incorporated and not explicitly described in traditional chemistry education at secondary school.

- *Particles show the same behaviour as billiard balls.* This statement can be used in a plausible explanation for some phenomena (e.g., pressure of ideal gases). However, in other situations interactions between particles are very important, so the statement is not valid for all situations. Other models describe that particles are not as hard as billiard balls (e.g., quantum mechanics). It is difficult for students to understand when and how the explanatory power of scientific models is limited. For teachers it is difficult to choose the right words, also due to the meaning words already have in the daily life of students.

There is a difference between the intuitive notions, used to explain phenomena in our concrete world, and the scientific models, used in chemists’ thinking about a submicro level. People’s intuitive notions are greatly influenced by their perceptions of the behaviour of concrete, visible and tactile materials. They interpret materials as continuous and static, while typically scientific models are discontinuous and dynamic, describing materials as consisting of continuously moving particles at a submicroscopic level.

Relevance of learning about submicroscopic models in chemistry education

The conceptual area of macro-micro thinking with activities, concepts and relations is one side of the educational problem with respect to macro-micro thinking. Another side is the general and widely recognized problem that students experience a lack of relevance to learn about the submicroscopic models in science (Bennett & Holman, 2002; Gilbert, 2006; Osborne & Collins, 2001). More than ever, students are asking themselves and their teachers: 'why do we have to learn this?'

To address this problem, in many countries, for example, the Netherlands, Germany, the UK and the US, a context-based approach to learning chemistry has been implemented (Bennett & Lubben, 2006; Driessen & Meinema, 2003; Parchmann et al., 2006; Schwartz, 2006). The use of context should legitimize the students' learning of chemistry concepts. However, it is a challenge to connect a chosen context to the learning of the chosen concepts (Gilbert, 2006). This challenge has been investigated in previous design-based research studies (e.g., Westbroek, 2005; Prins, Bulte, Van Driel & Pilot, 2009). In these studies, the chosen contexts are based on authentic scientific and technological problems, which are adapted for the purpose of chemistry education, whilst defining 'relevance' as: students understand and experience at every moment within the teaching-learning process *what* they have to do, *why* they have to do it and *how* they can do it.

Theoretical perspectives of this study

This research project on macro-micro thinking investigates the twofold problem described above by means of designing and evaluating a new strategy for learning macro-micro thinking which is situated within a context. The following section summarizes the theoretical perspectives and argumentation for this study.
Macro-micro thinking implies the use of explicit structure-property relations in which models of intermediate meso structures of crystals, micelles, globules, etc. are necessary. This way of macro-micro thinking reflects a more authentic way of reasoning as is available in contemporary professional chemistry, chemical technology and materials science. However, Aguilera (2006) poses that in this professional world, professionals use structure property-relations as tacit knowledge in a rather implicit way; seldom are such guidelines for macro-micro thinking made explicit. For enabling students to learn macro-micro thinking by using structure-property relations a new conceptual analysis is necessary in which structure-property relations are made explicit (Gilbert & Treagust, 2009; Han & Roth, 2006). Subsequently, this new conceptual analysis needs guidelines for implementing structure-property relations within an educational design for which actual contemporary scientific problems can serve as a context.

In this study context is considered as activity (Van Oers, 1998). For enhancing the relevance of learning, activity theory is used as a base to understand, describe and design the learning process of students (Leont'ev, 1978; Vygotsky, 1972). In this theory, an activity is a cultural-historical phenomenon in which human beings understand their world. Activity both integrates human actions in a coherent whole, and provides a basis for learning relevant actions. According to Van Oers (1998), a specific concept or action is relevant for people when it makes sense for them in certain situations and, consequently, these situations constitute contexts for relevant learning. The meaning of these actions, necessary tools and language is constituted by the role they play, as well as by the values they get in the social cultural activity in the eyes of the person who acts. This means that when students are engaged in an activity by a specific task, the context emerges from the interactions between these students. When students are involved in the activity and have a motive to perform the given task, and when the task lies within the students' zone of proximal development, a plan of subsequent actions and a series of procedural steps to address such tasks, can be intuitively evoked (Van Oers, 1998).

Based on the activity theory, three aspects can be distinguished to consider the relevance of an activity: the goal of a specific task, the sequence of actions and the tools to be used:

a. The goal of a specific task. This must provide students with a broad motive to start addressing this task. The focus for the designer of a teaching-learning process is to evoke broad motives by students, such as, *we want to accomplish the task because we understand that it involves helping ill people,* or, *we want to develop a food product, because no one has ever achieved this.*

b. The sequence of actions to address a task. With respect to (a chain of) actions, students have to experience every teaching-learning activity as necessary to accomplish the given task. The designer has to focus on a strategy to evoke a motive for students to start each of the teaching-learning activities. An example of an expected motive is: *we understand that we have to perform these experiments because we do not have the right information to do this task*.

c. The tools, that is, the (chemistry) concepts, relations, language and all type of representations which are useful in achieving the goal of the task. Students have to experience a necessity to extend their knowledge, because otherwise it will be difficult to perform their (learning) task. To be more specific, students have to extend their intuitive notions with regard to the necessary concepts in a productive way. In a designed teaching-learning process students should have a motive to know more and to extend their understanding of those specific (chemistry) concepts.

Consequently, 'relevance' has three challenges, which will be explored in the design of teaching-learning processes:

a. The context is relevant from the students' perspectives;

b. Every teaching-learning activity is relevant for students because they have motives about what they are doing, and why and how they are going to proceed;

c. Students experience it as relevant to extend their knowledge with regard to the necessary concepts for macro-micro thinking with structure-property relations.

This study is to generate deeper understanding of the students' learning of macro-micro thinking with structure-property relations and the incorporation of intermediate meso levels in teaching-learning processes within an appropriate relevant context for students in pre-university chemistry education. Therefore, the central research question for this study is:

> *How to incorporate macro-micro thinking with structure-property relations and intermediate meso levels in pre-university chemistry education so that it is experienced as relevant by students?*

The study is situated in the Netherlands and conducted in the years 2004-2009. In this period and beyond, a major curriculum innovation takes place to redesign chemistry education into a context-based approach (Driessen & Meinema, 2003) with the learning of 'macro-micro thinking' as one of the key-concepts.

Outline of the thesis

The research activities of this study can be roughly divided into three parts:

I. A new conceptual analysis of macro-micro thinking with structure-property relations using intermediate 'meso' levels;

II. A design-based research approach with two cycles of design, enactment and evaluation of the teaching-learning process which includes the new conceptual analysis; and

III. A reflection on the methodological steps of the design-based research approach developed during both design cycles.

The three parts with the specific sub questions are described below and schematically presented in Figure 1.

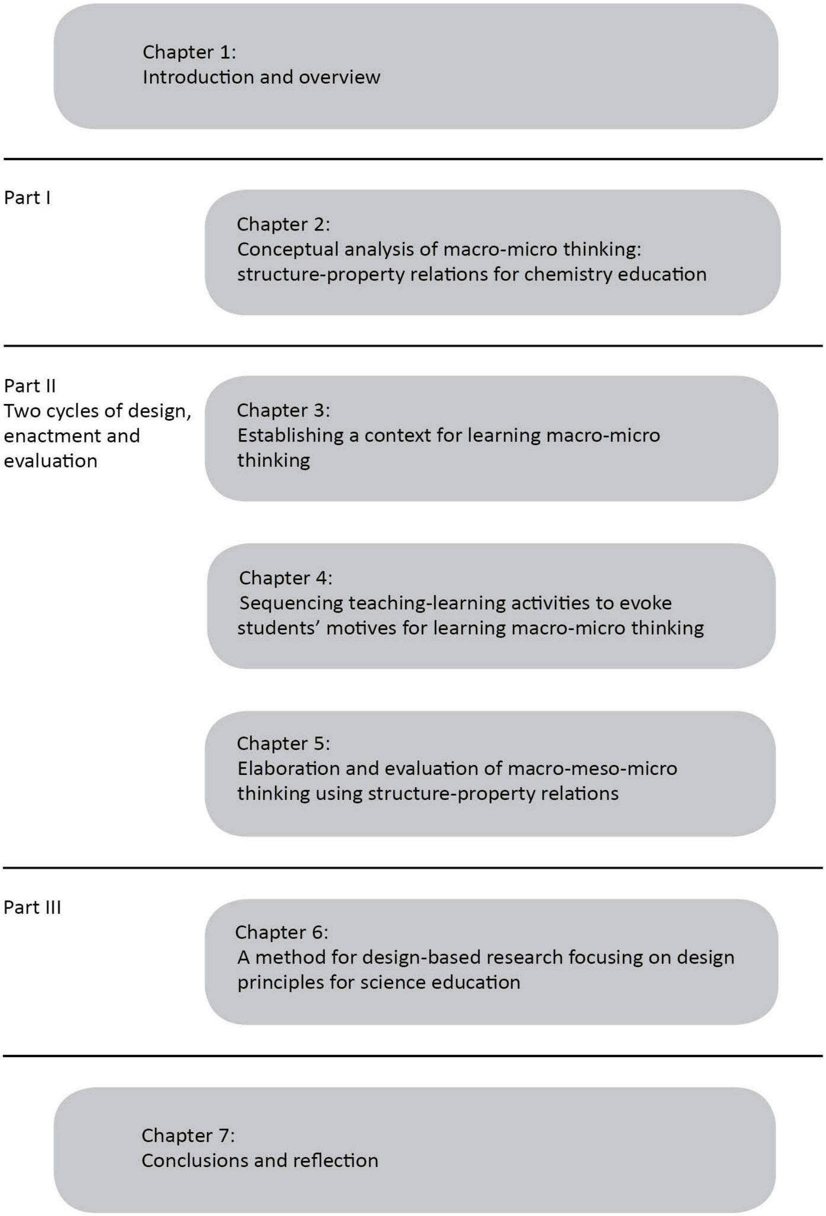

Figure 1 Outline of this thesis

Part I: Conceptual analysis of macro-micro thinking with structure-property relations and intermediate meso levels

This part of the study is inspired by the model of educational reconstruction (Komerek & Duit, 2004). In contrast to the conventional way of relating macroscopic phenomena to submicroscopic models, we argue that a new conceptual analysis of macro-micro thinking with structure-property relations is needed to address the students' learning problems. Chapter 2 presents the conceptual analysis which includes the following components: the macro level, intermediate 'meso' levels, the submicro level, structures, properties and structure-property relations. In this study, we frequently use the term meso level, which refers to all structures at a scale between the macro and submicro level. Although most components can be described from document analysis, relations between the components are not explicitly described in the literature. To validate and elaborate our conceptual analysis, this study investigates how experts use structure-property relations in their scientific work.

To study implicitly used knowledge about macro-micro thinking in order to describe this explicitly, three themes have been selected: A. gluten-free bread; B. a bullet-proof jacket; and C. unbreakable crockery. These themes come from different areas of chemistry research and product design: biochemistry, polymer organic chemistry, and inorganic chemistry respectively. Experts from these different fields address a given task within these themes while thinking aloud. This chapter provides an answer to the following sub question:

> What structures, properties and explicit structure-property relations can be identified within the domain of chemistry and material science and how to make the connection between macroscopic phenomena and submicroscopic models explicit within a conceptual schema?

Part II: Exploration of macro-micro thinking in a teaching-learning process; the development of design principles

Theories about teaching and learning do not provide specific guidelines and strategies for designing a teaching-learning process with specific intended pedagogical effects. Therefore new heuristic guidelines are necessary to relate the essential strategy components, underlying theoretical argumentation and the specific intended pedagogical effect (Figure 2). These three elements together form a design principle (McKenney, Nieveen & Van den Akker, 2006).

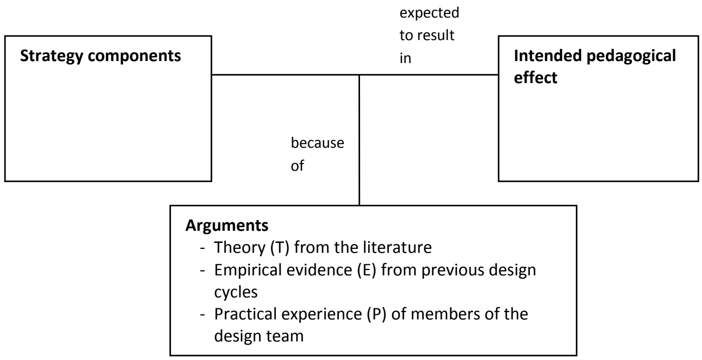

Figure 2 General representation of a design principle

Chapters 3, 4, and 5 subsequently describe the elaboration of the strategy components within two cycles of a designed teaching-learning process for the theme of gluten-free bread. Three design principles are formulated to address the three challenges a-c discussed above. By means of the design and evaluation of a teaching-learning process in which the strategy components are elaborated, the three related design principles are developed using an empirical basis.

a. The context is relevant for students

The first design principle is formulated as the context-principle. The intended effect is to establish an adapted version of an authentic practice as context for learning macro-micro thinking with structure-property relations. We take an adapted version of an authentic practice as a context (Bulte et al., 2006; Prins et al., 2009). In authentic practices, common motives for the participants, their common goals, values and rules, procedural steps and the necessary chemical concepts are a coherent whole for achieving a certain practice-related task. The selected task should be relevant from students' perspective. The focus is to provide students as participants of a community to set their own goals or plans and to try to monitor and control their own cognition, motivation, and behaviour in line with the goal of the task. We used three strategy components to achieve the intended effect:

i. Select a task.

ii. Use intuitive notions of students with regard to the procedural steps.

iii. Enable productive interaction between the participants of the community.

In Chapter 3, the focus is on the formulation and development of the context-principle at the start of learning macro-micro thinking, by elaborating the strategy components in the teaching-learning process; it provides answers to the following sub questions:

1. To what extent does the elaboration of the strategy components lead to the intended effect: the establishment of a context as a condition to make the students' learning relevant?

2. What is the formulation of the empirically underpinned context-principle?

b. Every teaching-learning activity is relevant for students because they have motives about what they are doing, and why and how they are going to proceed

This design principle is formulated as the sequence-principle; it focuses on the sequencing of students' teaching-learning activities. The intended effect is that students always must know what they are doing, why they are doing it and how they are going to proceed to achieve their goal. We used two strategy components to reach this intended effect:

i. Use an authentic procedure based on intuitive notions of students; and

ii. Sequence motives in which the reflection on one activity provides the orientation for the next

These strategy components are based on the idea that humans act intentionally and on Galperin's cycle that a reflection on an action provides an orientation for the next action (Arievitch & Haenen, 2005). The elaboration of the strategy components in a teaching-learning process and the formulation of this sequence-principle is described in Chapter 4, and provides answers to the following sub questions.

3. To what extent does the elaboration of the strategy components lead to a sequence of teaching-learning activities in which students realise that they know 'what to do next, and why' when learning about macro-micro thinking using structure-property relations?

4. What is the formulation of the empirically underpinned sequence-principle?

c. Students experience it as relevant to extend their knowledge with regard to the necessary concepts for macro-micro thinking with structure-property relations

The third design principle is formulated as the content-principle. The conceptual analysis provided by Chapter 2 is used to formulate two strategy components for the learning of macro-micro thinking. Materials are considered as a system of structures at different meso and submicro levels and can be considered to be built from structural elements which are also built from smaller structural elements. This leads to strategy component:

i. Use systems thinking with structure-property relations;

These structures can be causally related to properties with a property as an emergent result of interactions between the structural elements which form the nature of the material. For students, there must be a reason to descend from the macro level to a lower one. This can be achieved by evoking the notion that the cause of a property can be found in the material itself. This leads to strategy component:

ii. Use the intuitive notion about the cause of a property.

The intended pedagogical effect of the content-principle is that students are able to acquire macro-micro thinking with structure-property relations. The development of this content-principle in macro-micro thinking is described in Chapter 5. It presents how both strategy components are elaborated into the design of a teaching-learning process, with the following sub questions:

5. To what extent does the elaboration of the strategy components lead to the intended effect that students acquire in macro-micro thinking using structure-property relations?

6. What is the formulation of the empirically underpinned content-principle?

The designed teaching-learning processes are enacted and evaluate in the classroom in a small scale setting in two cycles, each with a group of 8-12 students in pre-university chemistry education and a teacher. The main reason for choosing this explorative setting is the unfamiliarity with the new ideas on macro-micro thinking in chemistry education. We choose to explore these new complex ideas on macro-micro thinking with a student population at the end of their chemistry curriculum.

Part III: The methodology of the design-based research approach

For this study the approach of design-based research (DBR) is used as a research method (Van den Akker, Gravemeijer, McKenney & Nieveen, 2006). Within this design-based research approach, the teaching-learning processes are designed with a detailed description about 'why' and 'how' each part of the teaching-learning processes is expected to function. The design of the teaching-learning processes is enacted and evaluated in a real classroom setting. During the evaluation of the enactment, a detailed analysis is made as to *why* and *to what extent* the enactment does or does not proceed according to expectations. Based on this analysis, the teaching-learning processes are redesigned, tested and evaluated with new argued expectations of 'why' and 'how' they were expected to function. Chapter 6 describes a specific set of procedural stages which are applied in this design-based research study to obtain a valid insight and knowledge claim. We argue how the stages, and instruments are to be used with the purpose to contribute to the specific body of knowledge on design-based research.

The framework with teaching-learning phases with specific expectations as concrete descriptions of the intended effects and the three empirically underpinned design principles can be considered as a knowledge claim of this research for educational design purposes.

Chapter 7 presents the major conclusions regarding the elaboration of the strategy components, the three design principles, followed by a reflection discussing the implications of this study for further educational research.

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Chapter 2

Conceptual analysis of macro-micro thinking

Structure-property relations for chemistry education

Abstract

Scientists construct submicroscopic models of materials in order to gain an understanding of macroscopic phenomena and to explain and predict properties. As reported in the literature, chemistry students in secondary education appear to have great difficulty with this micro-macro thinking. In order to improve students´ ability to relate macroscopic phenomena in a for students relevant way to submicroscopic models, we argue that a new conceptual analysis of micro-macro thinking with structure-property relations should improve this situation by introducing meso levels in between the macroscopic level and the models presented at the submicroscopic level. To empirically underpin the schemata, we designed three tasks, using research papers and other literature in the field of biochemistry, polymer chemistry and inorganic chemistry. These tasks were to be performed by expert consultants to validate the schemata. We used both the literature survey analyses and the empirical data from the expert consultations to construct a generic pattern how macro, meso and submicro levels are connected with structure-property relations. In the discussion, we argue how the empirically validated schemata should serve as the basis for the design of instructional materials for secondary education on micro-macro thinking in chemistry education when addressing the reported learning problems of students.

Introduction

Our macroscopic world is full of phenomena that arouse the curiosity and interest of scientists in many fields, ranging from nanotechnology, physical chemistry, biochemistry and health studies to food production. Scientists and engineers model both the phenomena they observe and the ideas that are used to explain such phenomena (Justi & Gilbert, 2002). They construct (computational) models for studying known and new substances and their transformations (Justi & Gilbert, 2002; Hill, 2004; Gani, 2004; Wintermantel, 1999). Such models represent microstructures such as amorphous and crystalline phases, particles, colloids, molecules and atoms.

As these models play an essential role in chemistry, it is evident that secondary and higher education should teach students to use such models. Therefore, secondary school curricula commonly include models of the particulate nature of matter. Such particle models serve as a basis for understanding the many macroscopic phenomena dealt with in chemistry and science curricula (Harrison & Treagust, 2002). However, learning how to relate macroscopic phenomena to submicroscopic models, here referred to as micro-macro thinking, is problematic for students (e.g. Eilam, 2004; Harrison & Treagust, 2002; De Vos & Verdonk, 1996; Gilbert & Treagust, 2009a; Wiser

& Smith, 2008). Students have difficulty to bridge the huge mental gap between macro and micro. Consequently, several problems are reported regarding this micro-macro thinking in chemistry education, for example the use of macroscopic properties in the submicro world (Anderson, 1990; Rappoport, 2008).

We aim to address the students' learning problems regarding micro-macro thinking by the introduction of a new conceptual analysis. This is inspired by the procedure of educational reconstruction (Komerek & Duit, 2004) in which a careful and reflective conceptual analysis of the content to be learned is part of the development of education when addressing learning problems. In our conceptual analysis of the content, we propose to break up the huge gap between the macroscopic phenomena and submicroscopic models by introducing smaller steps in between through 'meso levels'. We start by arguing how a conceptual schema with models at intermediate levels can be an address to the existing learning problems, and how this schema is grounded in the field of science and technology. Subsequently, we provide the conceptual analysis with an empirical basis: to explore the reasoning of scientists when they link macroscopic phenomena with different meso and submicroscopic models of structures and to understand how the connection of macroscopic phenomena to submicroscopic models can be made explicit (McVee, Dunsmore & Gavelek, 2005). At the end of this chapter, we argue how this new conceptual analysis may by applied in chemistry education in schools.

Addressing students' problems regarding micro-macro thinking

In the next, we start by describing how micro-macro thinking is conceptualised in school chemistry, and relate this to the students' learning problems that are reported in the literature. In a next section, we argue how a new reorganisation of this content can be an address to the reported learning problems.

Students' problems regarding micro-macro thinking

In school chemistry, micro-macro thinking is conceptualised as follows. According to Johnstone (1991) three levels (domains) of representations can be distinguished: a phenomenological macroscopic level (macro); a level of models usually involving entities such as atoms and molecules that are too small to be seen using optical microscopes (submicro) and a symbolic level of representations where symbols, such as H, H_2, $C_6H_{12}O_6$ (aq) (Gilbert & Treagust, 2009a, p.4). The symbolic representation can both refer to atoms and molecules at the submicro level, as well as to phenomenological representations such as solubility, and the physical state of substances. These three types of representations in chemistry (macroscopic, submicroscopic and symbolic) are commonly used to understand the multilevel thought within chemistry (Johnstone, 1991): macroscopic representation related to observable phenomena, experiments and experiences; submicroscopic representation related to mental images such as structural formulas and ball-and-stick models; and symbolic representations related to pictorial images and algebraic formulas, for instance graphs and chemical equations.

Students' learning problems regarding micro-macro thinking can be explained in two ways:

1. by the huge gap between the metre to centimetre scale in which macroscopic phenomena are observed and the nanometre scale of submicroscopic models; and

2. by the different nature of the students' intuitive notions about matter and the scientific use of submicroscopic particle models.

First, the step from the level of macroscopic phenomena to the level of submicroscopic representations is a huge one. When people are not trained to interpret the submicro world, it is usually beyond their capacity to understand such a space gapping a difference between materials and substances at a scale of metres or centimetres to a scale of nanometres (Tretter, Jones & Minogue, 2006).

Second, students' intuitive notions are greatly influenced by their perceptions of the behaviour of concrete, visible and, tactile materials (related to macro). They interpret materials as continuous and static. Typically, scientific submicro models are described as discontinuous and dynamic: models of materials consist of continuously moving particles (submicro). Pinker (2008) relates this difference to our linguistic distinction between 'mass' words (related to macro) and 'countable' words (related to submicro, cf. De Vos & Verdonk, 1996; Wiser & Smith, 2008). The corpuscular character of materials as a representation or model is not embedded in peoples' daily language which is guided by daily life experiences (e.g., Penner, 2000). The cause for this is that people discriminate between what can be interpreted as a category, expressed with mass nouns: continuous materials as liquids, bread, Kevlar, etc. and what can be counted, expressed in countable words ('there are x objects'; Pinker, 2008).

The learning of micro-macro thinking implies the discrimination between the materials and entities from which they are made. This discrimination between continuous entities (expressed with mass nouns) and countable discrete objects is needed to make the difference between e.g., sugar and crystals (Pinker, 2008). 'Mass words' as dough, ceramic and food indicate that these are respectively made from the 'materials' dough, ceramic and food. For this reason, students need to understand that materials are *made of* other materials (Wiser & Smith, 2008, p. 209) and can be conceived of 'countable' discrete (invisible) entities. Consequently, the learning of micro-macro thinking requires a specialist language for characterising materials in terms of discrete particles. So, there is a gap between students' intuitive notions and scientific models as presented in school chemistry. Above this, teachers and textbooks use macroscopic language in models that are related to the submicroscopic level (Taber & Coll, 2002; Han & Roth, 2006; Penner, 2000; Meijer, Bulte & Pilot, 2009; Taber, 2009).

As a result of the huge step in scale and the huge mental step in specific language, students do not scientifically connect macroscopic phenomena to models of submicroscopic entities, and students do not develop an appropriate understanding of the nature of the presented scientific models (Nahkleh, 2005; Harrison & Treagust, 2002; Justi, Gilbert & Ferreira, 2009; Taber, 2009, p.99). They use macroscopic properties for the submicro world (Anderson, 1990; Wiser & Smith, 2008). For example, if a material is elastic, then students conceptualize molecules as elastic. Or: the particles making up the materials are considered to be hard or soft, hotter or colder, sharp, etc. (Taber, 2009; p.99). Students do not understand that macroscopic properties are emergent, i.e. that properties of a system come into view as a result of underlying interactions among components of that system (Penner, 2000; Rappoport & Ashkenazi, 2008).

Constructing a new conceptual schema: a system of structures and properties with intermediate meso levels

To address the two-fold learning problem, we propose to reconceptualise micro-macro thinking by incorporating two strategies into a new conceptual scheme. We will argue how both the use of intermediate meso levels and the use of the students' intuitive notions, which should start at the macro level, can make the conceptual scheme suitable for chemistry education. Because of this further on we will use the term *macro-micro thinking* instead of *micro-macro thinking*.

First, we concur with Millar to bridge the huge step from the macroscopic to the submicroscopic level with smaller steps in between. Millar (1990) argues that it is unnecessary 'to go straight from the observable to the atomic/molecular (submicro) level; there are steps in between' (p. 289) and 'that learning necessarily proceeds via a series of intermediate steps, or 'models', … (p. 285). For students, these intermediate steps may become manifest when they use a microscope and hidden structures within materials become visible. In electron microscope photographs, structures as small as 50 nm can be distinguished, though these are still removed from the atomic or molecular level by a factor of 100. In contemporary science, many structures at these 'intermediate' levels or *meso levels* are used by scientists when explaining or predicting properties and designing new materials. In their terminology, scientists often refer to these 'intermediate levels' as *microstructures* (Gani, 2004; Besson et al., 2004).

Second, to overcome the huge mental step in learning to relate macroscopic phenomena to models with discrete entities, a rather intuitive understanding about properties of materials may be extended in the following way. Structures of materials at meso level can be used to facilitate the students' understanding that properties of a system come into view as a result of underlying interactions among components of that system. For example, a jumper can be 'warm', that is, it prevents that body heat is transported to a colder environment. By studying the nature of the several weaving patterns of the fibres, students may come to understand how this property is related to the structuring of sub systems. Isolation against the cold is not related to the specific fibres used; this property is related to how the different layers of textile are constructed, including the inclusion of air in between the textile. When students understand that the chemical composition of a fibre in terms of polyamides, polyesters does not provide solely for the isolation value they may understand that properties are emergent: the fibre itself does not have the property of the jumper.

The new conceptual schema incorporating these two strategies is presented in Figure 1 and is an extended version of that of Millar (1990). It shows a complex system of components, organised around phenomena at macro level, microstructures at meso levels, and molecular models at submicro level. This complex hierarchic system is composed by sub systems that in turn have their own sub systems, and so on (Luisi, 2002). The example used in this schema is an item of clothing (Gulyaev et al., 2002). Clothes can be described in terms of a system of woven parts of fibres. The fibres can be considered as a subsystem of filaments, which are composed of other components (Buck, 1990). Using scanning electron microscopy (SEM), even the smallest structures can be 'perceived', but not directly measured. Reiher (2003) states that the object to be studied on length scales which vary from the femtometre domain up to micrometre-sized objects should allow us to think in terms of nested systems (Buck, 1990). The systems correspond with the structures and meso levels (scale). The nesting of subsystems in larger systems is visualised in Figure 1 by zooming in or out for each structure. The visualisations on the left are scientific models which are developed to explain related phenomena (Gilbert & Treagust, 2009a). These schematic drawings can be replaced to some extent with scientifically prepared and interpreted images: measurements made with the help of analytical techniques, such as SEM pictures.

A sequence of specific teaching-learning processes may guide students how to use models related to the different scales. The use of models at meso level scales, for example models of glass reinforced fibres, composite materials, etc. may facilitate students to develop an understanding of the process of modelling in primary and/or lower secondary education, whilst the nature of the models is not as complicated as the development of models with molecules and atoms. Gradual learning of submicroscopic models may take place by a gradual development of models related to meso structures with smaller and smaller sizes. For example, the relation between different models of (polymeric) crystals and the strength of fibres (Figure 1). Such a developmental process of learning chemistry from primary education until upper secondary education also allows the introduction of contemporary scientific and technological contexts (Meijer et al., 2009).

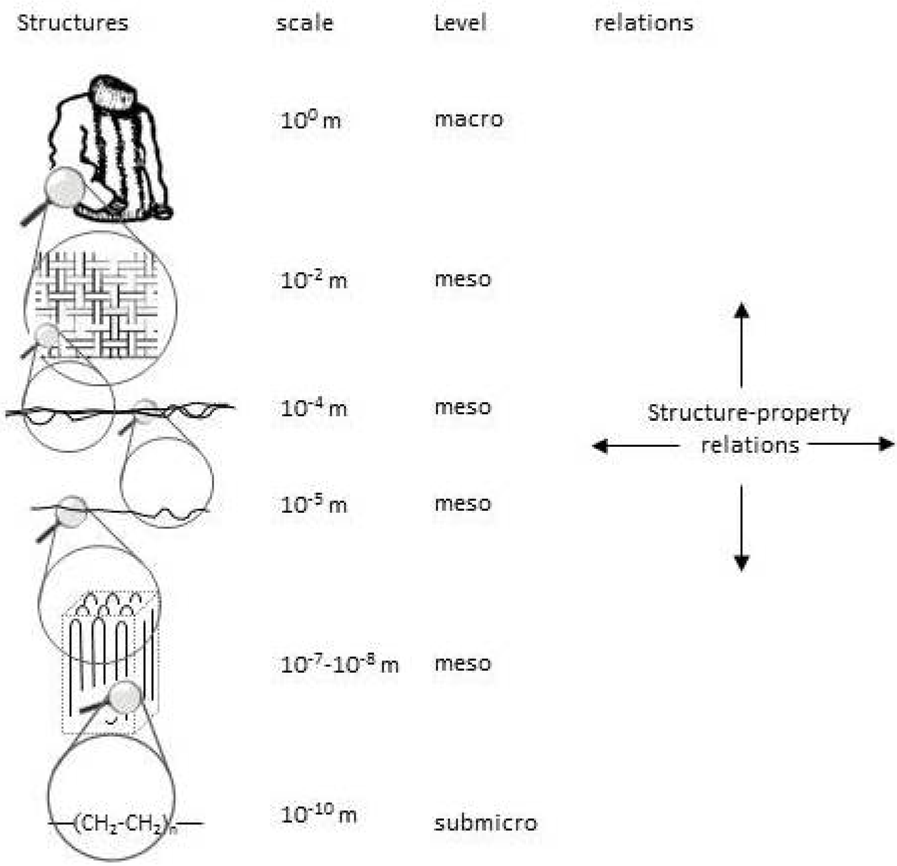


Figure 1 Exemplary conceptual schema for macro, meso and submicro levels containing properties and systems of structures

To further extend this new conceptual schema (see Figure 1) for the use in chemistry education, we need to elaborate several components and relations:

- the appropriate definition and the use of the wording 'structure';
- the appropriate definition and the use of the wording 'property';
- the incorporation of explicit structure-property relations.

'Structure' (first column; Figure 1) can be defined as the distribution in space of the components in a system. Physical building blocks of such a system are regions that are bounded by a closed surface (Walstra, 2003), where at least some of the properties within such regions are different from those in the rest of the system. These building blocks can exist of stacks of atoms or molecules, for example, which of course form other blocks such as fibres, crystals, networks or membranes. Other examples are amorphous and crystalline phases combined, weaved twill or the structure of paper. Structures are dynamic systems (Smith, 1967), because they can be changed by processes. Structures are also related to particular sets of properties (Aguilera, 2006; p. 1153), in which temperature and pressure are important variables. Structures have a range of several factors of ten in length scales and become associated and stabilized at different levels.

'Properties' are defined as measurable physical and chemical characteristics of materials. Examples of properties are: boiling point, melting point, conductivity of heat or current, density, viscosity, hardness or elasticity. Apart from these physical properties any useful attribute to the system itself is a property (Reiher, 2003): charge, degree of hydrophilicity, solubility, energy of heat, flammability and chemical reactivity. Cussler & Moggridge (2001) state that the meta-stable state of many products with structures at *meso levels* means that their properties are not only a function of their current condition, but also of processing the path by which that state is reached (Cussler et al., 2001, p.138). Properties can be divided into intrinsic (depending on the chemical composition, the structures at submicro level) and extrinsic properties (depending on the structures at meso levels).

The conceptual schema in Figure 1 is constructed using the presented terms. At each level, a structure can be related to one or more properties. For example, at the scale of 10^{-7}-10^{-8}m, a crystalline structure may be present in polymeric material. The polymers in the crystalline structure are fixed. The interactions between the polymer chains hinder the mobility of segments of the chains. At the glass transition temperature (T_g), the thermal energy is just sufficient to overcome the interaction between the chains. For this reason, the interaction between polymer chains is an important parameter beside chain flexibility to determine the value of T_g.

In general, structure-property relations can be expressed by relating a specific structure to a specific property. Material scientists and engineers aim to unveil structure-property relations or the causal connection between the structure and the way a product behaves (Aguilera, 2006, p.1153). Thus, a structure-property relation should preferably be unambiguously formulated and logical (in scientific terms). A general formula for this type of relation is (Stenning & Van Lambalgen, 2001): if X (antecedent), then Y (consequence) in condition Z. For example in the situation of whipped cream: 'if the air bubbles are surrounded by a stabilized structure of fat globules then the foam is stable'. In the situation of ceramics in which the structure is changed because a process of sintering takes place: 'if the porosity of porcelain decreases due to a sintering process, then the strength of porcelain increases'. The phrase 'due to a sintering process' is a specific condition for this causal relation. The condition makes the connection between antecedent and consequent more dynamic and can be a specific situation or content related theme or scientific theory in which the causal relation is valid (Driver, Newton & Osborne, 2000). Therefore, this formula for structure-property relations can be used in arguments on predicting or explaining a phenomenon (Giere, 2001). The if-then formula for 'structure-property relations' must be included in the conceptual schema for explicit relations between structures and properties.

In summary, the new conceptual scheme with intermediate meso levels as constructed in Figure 1 is an extended version of Millar's (1990) proposal. Macro-micro thinking should start at a macro level related to students' experiences in their daily life. However, explicit relations between structures and properties which are grounded in the literature are not available. Scientists use these relations in their profession in a rather implicit way; it is part of their (tacit) knowledge. Additionally, in many contemporary authentic tasks, properties of materials are explained and predicted by 'models' that do not immediately relate to structures at a molecular or atomic level. For example, this is the case for biochemical research on the functioning of cell membranes in relation to diseases, in research on catalysis, colloids, nano tubes synthesised in the field of nanotechnology, the design of micro-structured materials, and in the field of genomics research.

For the use of the conceptual scheme in chemistry education, there is a need for establishing an empirical basis of macro-micro thinking with explicit structure-property relations. It is necessary to investigate the nature and number of the different meso levels in relation to sub domains of chemistry and/or in relation to specific settings, tasks, contexts and/or social practices. This is extensively described in the section 'Results' below, including an empirical underpinning of the nature of structure-property relations and meso levels. It is to this empirical underpinning to which we now turn.

To explore the nature of these intermediate levels to be used in chemistry education, we study authentic tasks originating from authentic scientific and technological practices (cf. Aguilera, 2006; Cussler & Moggridge, 2001) for which these intermediate levels between the macroscopic and the submicroscopic worlds are needed using structure-property relations. In such authentic practices, scientists use structure-property relations to explain a certain property. An authentic practice is defined as a situation in which there is a coherent whole between a task, connected actions to accomplish it, the knowledge necessary to perform these actions, norms, values, skills and attitude. Exemplary authentic practices provide for the elaboration of the conceptual analysis in terms of structure property relations. In their adapted versions, these authentic practices can be used as contexts in chemical education (Bulte, Westbroek, Klaassen & Pilot, 2006), using the real life phenomena as a starting point for learning.

Consequently, the research question for this empirical part, with respect to macro-micro thinking is as follows.

> What structures, properties and explicit structure-property relations can be identified within the domain of chemistry and material science and how to make the connection between macroscopic phenomena and submicroscopic models explicit within a conceptual schema?

Method and sample

The conceptual schema for macro-micro thinking (Figure 1) is used as a starting point for further empirical elaboration in two steps, first by a literature survey on relevant documents and second by expert consultation. To study implicitly knowledge used about macro-micro thinking in order to describe this explicitly, we have selected three different themes: A) baking of bread, B) bullet proof jacket; and C) unbreakable crockery, since these themes cover a broad range in the different areas of chemistry research and product design: biochemistry, polymer organic chemistry, and inorganic chemistry, respectively (Table 1). We designed three theme-specific tasks (Table 1; second column). These tasks are related to authentic scientific issues in the present (A) or the past (B, C), and were chosen because the tasks can be related to the everyday life of students (A, C) or issues in the media (B). Short descriptions of the three themes are presented in the 'Results'.

The design of the theme-specific tasks

To obtain the necessary knowledge for the three themes, textbooks and journals on the related areas of chemistry were studied, as well as other theme-specific literature (first author, MM). Examples of these documents are mentioned in Table 1. First, knowledge had to be acquired about the specific circumstances of baking bread (theme A), the molecular structure of polymers used for bullet proof jackets, which have a high E modulus (theme B), and the cause for crack formation in ceramic materials (theme C). For each of the themes, first versions of the specific tasks were designed (Table 1; second column).

Step 1 Literature survey of documents

The first author analysed the relevant literature for each task. This analysis was checked by second and third author[1] on scientific clarification, interpretation of documents and understanding of the used concepts and relations. The analyses of the three literature surveys were discussed in depth in three different sessions, resulting in adapted versions of the designed tasks. This resulted in a possible solution for each of the three tasks.

1 Both the first and second authors have a Master's degree in Chemical Engineering Science, with an emphasis on Material Science. The third author has a Master's degree in Chemistry with extensive experience in developing courses in Material Science for university engineering education.

Table 1 The three themes and tasks that are used in the validation of the conceptual schema.

Theme	Theme-specific task	Addressed by expert	Research field and chemistry in the theme
A. Baking of bread	Development of gluten-free corn bread.	A	Field: Biochemistry Chemistry: Influence of the baking process (temperature, mixing time), mixture, yeast and hydrocolloid on the properties of bread. Literature: e.g. Dobraszczyk, 2004; Don et al., 2005; Özboy, 2002; Rojas et al., 2000, Belitz et al., 1999.
B. Bullet proof jacket	Development of a bulletproof jacket.	B	Field: Polymer chemistry Chemistry: A polyamide, whose molecules can be organized in a very regular patron, caused by regularity in the chain and interactions between them. Literature: e.g. Kitagawa et al., 1998; Gellert et al., 1998; Jacobs, 2001.
C. Unbreakable Crockery	Development of unbreakable cups.	C	Field: Inorganic chemistry Chemistry: Crack formation between particles, inorganic compounds, ion transport through amorphous phases and sintering process. Literature: e.g. Braganca & Bergmann, 2003; Kuang et al., 1997; Andreeva, 2002; Berby et al., 1992.

Step 2 Selection and consultation of experts

For further elaboration and validation of the conceptual schemata with specific meso levels and structures resulting from step 1, three different experts were selected and consulted to address the designed tasks while thinking aloud. The goal of this consultation was not to provide us with a clear solution of the tasks, but to have them explicitly express their way of macro-micro thinking. These consultations, led by the first author during a two-hour session, were observed, recorded on audio tape and transcribed verbatim. At the end of the consultation, the expert was asked to reflect on his/her thinking process. There was also an opportunity for the researcher to ask for some clarifications if needed. Both, the reflection and clarification, were recorded on audio tape. The three experts were selected for their familiarity with the relevant field for each theme; they are also members of research groups active in the fields of chemistry corresponding to the tasks. Expert A studied Chemical Engineering Science, completed his PhD in Process Engineering and now works in the food process engineering group of an academic Food Technology department. One of the topics of his current research is the behaviour of protein during dough preparation and bread baking. Expert B is currently conducting research for his PhD in Polymer Chemistry, having obtained a Master's degree in the same field. He has extensive knowledge of product design and his research concerns the development of a new initiator for a specific polymerisation reaction. Expert C is an academic, specialised in modelling and experimental verification of the *microstructure* development of metals, polymers, and sensor materials for aerospace applications.

Data analysis

The outcomes of step 1 and step 2 need to lead to theme-specific conceptual schemata with systems and subsystems of structures, properties and their relations which are scaled to the relevant macro, meso and submicro levels (Figure 1).

Table 2 Description of the categories used to analyse the experts' macro-micro thinking

Category	Description	Example
Macro level	General phenomenal descriptive statements close to the real perceptible world.	The chocolate has a brown colour, but tastes awful.
Meso level	Statements which describe structures or properties. These structures or properties become manifest at a certain scale between the macro and submicro level.	Homogeneity of crystals of beta fat acids in chocolate is caused by the regular structure of a specific triglyceride.
Submicro level	The structure or properties which exist at an intra- or intermolecular level.	Triglycerides with unsaturated oleic acid.
Structure	The distribution in space of the components in a system. Physical building blocks of such a system are regions that are bounded by a closed surface, where at least one of the properties within such a region is different from those in the rest of the system (Walstra, 2003).	Spheres of fat in ice cream; Starch granules in potato; Particles; Air bubbles in a liquid.
Property	Aspects in which an object (material/substance) differs from another object (material/substance). Properties can be intrinsic (determined by the chemical compounds) or extrinsic (determined by the production process or distribution of structures but not by the chemical compounds).	Boiling point; Colour; Density; Porosity; Strength/toughness; Viscosity.
Structure-property relation	Causal relation between a structure at a certain scale and a property at the same or another scale.	The pleasant cooling of chocolate in the mouth is caused by the melting of fat crystals. The well-defined crystal structure of triglycerides has an exact melting point of 35°C.

Consequently, for both the outcomes of step 1, the literature surveys, and step 2, the expert consultation, we used the categories 'macro', 'meso' and 'submicro' levels, 'structures', 'properties' and 'structure-property relations' as presented in Table 2. Before starting the analysis of both steps, the authors held general discussions about the criteria for the categories in order to reach a precise agreement on the meaning of each category. The results of step 1 are presented in an elaborated theme-specific version of the conceptual schema (see above, Figures 2a, 3a and 4a).

In step 2, the transcripts of the expert consultations were categorized. To validate the findings, this analysis of each relevant phrase was carried out independently by two reviewers (first and second author, MM and AB), according to the procedure shown in Table 3. This procedure was followed by a comparison of their findings for each theme for which they reached 95 per cent initial agreement (inter rater reliability). In case of disagreement, they tried to reach consensus on a single judgement. Using this outcome, they both independently constructed a theme-specific conceptual schema based on this analysis of the expert's consultation leading to the Figures 2b, 3b and 4b, which were discussed in the entire research team.

Table 3 The procedure of the analysis in step 2, expert consultation

	Action
a	Read the protocol to obtain a general impression of the interview.
b	Mark (part of) statements that belong to one of the categories mentioned in Table 2 as a unit of analysis. Use the following procedure: I. Does the marked unit refer to a structure or a property? Yes → II; No → III II. Is the marked unit part of one statement? Yes → II-i, No → III i. Is the statement further deepened/developed/elaborated in the subsequent statement? **Yes** → analyse these sentences → II. **No** → II-ii ii. Is there an explicitly formulated causal relation between structure and property? **Yes** → II-iii, **No**. These are two independent facts or one of the terms is too general, which contains a lot of implicit knowledge → III iii. Is it possible to reformulate the statement in 'if … then …' form? **Yes** → This can be accepted as a structure-property relation, **III.** **No** → III: This is not a structure-property relation.
c	Mark every unit that is a structure, property or relation between them as referring to macro, meso or submicro level. Connect the level to a scale.

The elaboration of the theme-specific conceptual schema was completed by combining the results of step 1, the literature survey, and step 2, the expert consultation. The findings for each theme are presented in the form of a schema for each theme (Figures 2-4). Based on the theme-specific outcomes, both reviewers independently drew conclusions from their analyses with respect to more generic patters in such conceptual schemata for macro-micro thinking.

Results

Theme A: Baking of bread

Special food products need to be developed for consumers who cannot digest gluten. The bread produced for these consumers is usually prepared from corn, which does not contain gluten. However, gluten (a composite of proteins) is needed for the rising of dough, and consequently for the texture of bread (e.g., smaller gas cells, thinner cell walls and an even distribution of bubble sizes). To obtain the same quality as for wheat bread, it is necessary to know more about the properties of gluten. Gluten is responsible for the elastic property of dough which makes it possible to capture the gasses (CO_2) released by yeast during fermentation. Hydrocolloids seem to be an acceptable gluten replacement because they can form a network of long chains by absorbing water and can capture gasses. The stages 'preparation of dough' and 'fermentation' mainly determine the properties that are fixed during the baking stage.

In the analysis of the textbooks and research papers (step 1), we identified different representations of structures (such as interconnected cavities with gas cells or a protein matrix with granules), and properties (such as visco elasticity and taste). However, these structures were seldom related to scales, nor were they systematically organized into a schema. When addressing the theme using the analysed documents, six different meso levels were found (Figure 2a). At a scale of 10^{-2} m the dough rises due to fermentation. The dough contains gas cells (10^{-4} m), enclosed by walls made up of a matrix with embedded starch granules (10^{-5} m). The highly degraded granules due to enzyme attack (10^{-6} m) are held together by gluten fibres made up of gluten particles with a diameter of 10^{-7} m. The particles form a chain by sharing the long (protein) molecular chains (10^{-8} m) made up of a single unit (amino acids) (10^{-9} m).

Table 4 shows a part of Expert A's statements with respect to the categories macro, meso, submicro, structure, properties and structure-property relations (step 2).

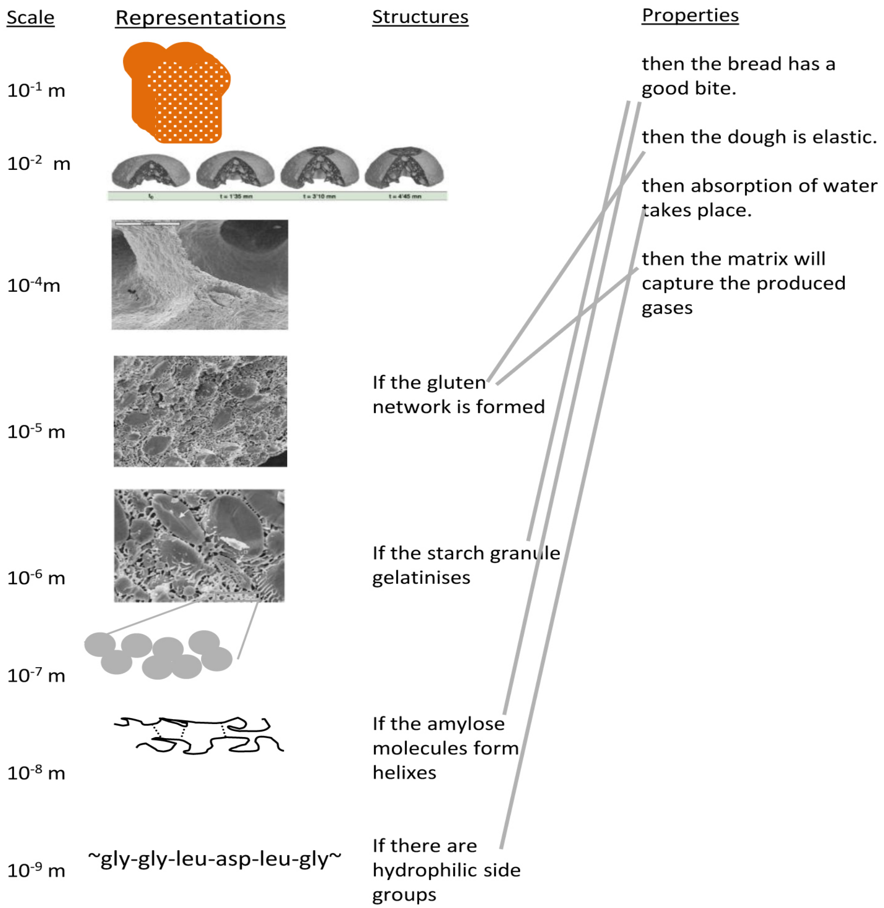
Table 4 Examples of categorizing statements of Expert A

Statements by Expert A (relevant phrases in italics)	Category
The gluten can be divided into a *soluble*....insoluble fraction.	Property (macro)
A kind of *network* will be formed. But it is not known which material that network is made of. In these [given SEM] pictures we are looking at a wrong scale. You have to look at a larger scale.	Structure (meso)
During mixing of dough *larger aggregates* arise from gluten.	Structure (meso)
This [structure] *is mentioned in sentence above is essential because the dough has to rise.*	Structure-property relation
It has a *density* of 7 litres per kg.	Property (macro)
If gluten is too loosely distributed in the matrix, then the dough will collapse.	Structure-property relation
With the use of optical technology you can perceive *agglomerate of parts* of gluten.	Structure (meso)
If the distribution is loose then the bread rises badly.	Structure-property relation

While working on his task, Expert A referred to structures, properties and structure-property relations. An example of a macroscopic property is: 'the dough has to rise'. The relation 'if gluten is too loosely distributed in the matrix then the dough will collapse' can be seen as a prediction of a macroscopic property with a structure at a meso level. In the expert consultation, three different meso levels were distinguished, at the scales of 10^{-5}, 10^{-7} and 10^{-8} m (Figure 2b).

During much of the consultation, Expert A restricted his comments to meso levels near the macro level. Expert A expressed an unwillingness to make statements about the submicro level or meso levels near the submicro level. Attributing this to the complexity of food technology research, he claimed that extensive fundamental research would be needed in order to make a clearer statement then is done in the literature (Don et al., 2003). Bread baking research and technology is still based to a great extent on empiricism and observation, while there are few established theories about the submicro level. According to Expert A, it would have been too speculative to reason at the submicro level, although he did refer to the submicro level by stating: 'If there are interactions, then particles are formed'. By using the term interaction, Expert A was referring to the interactions between molecular chains of gluten.

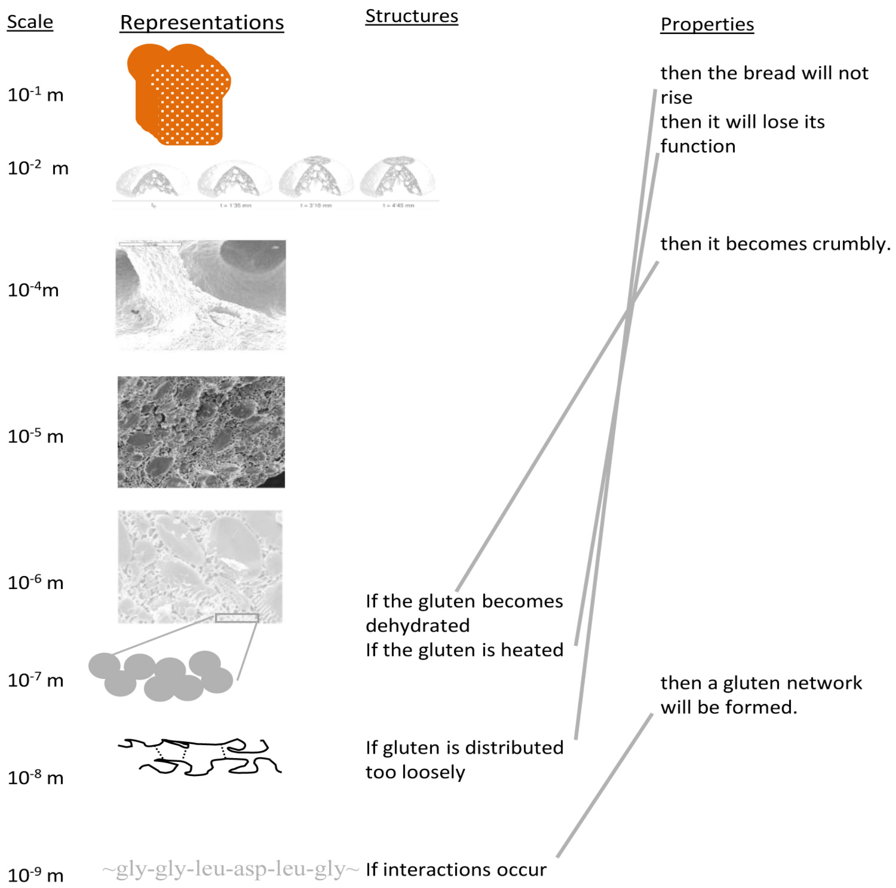
When we combined the elaborated conceptual schema that resulted from the literature survey with the expert consultation (Figure 2a & 2b respectively) no contradictions were found. In both schemata, structure-property relations take a slanted, diagonal, direction. All structure-property relations could be rewritten as if-then constructions. Other relations were also found, such as property-property or structure-structure relations (these are not presented in Figures 2a & 2b). These kinds of relations maybe part of implicit knowledge of the expert. For example, Expert A used property-property relations mainly at or near the macro level, such as the relation ‘dough is elastic; thus, it is able to capture the released gases, so the bread rises’. Possibly this type of relation is a combination of two other structure-property relations which the expert does not mention explicitly. For example, the elastic property of dough can be caused by the existence of a gluten network [structure] which is impermeable to gases [property]. This gluten network is elastic [property] because chains of gluten particles [structure] are able to move in relation to each other.



Other structure-property relations used in the literature survey:

- If amylose diffuses out of the granule (10^{-8} m) then the viscosity of dough (10^{-2} m) increases
- If the percentage of amylose (10^{-9} m) increases then the degree of crystallinity (10^{-8} m) decreases.
- If the length of the gluten substitute increases (10^{-9} m) then the extent of interaction between starch and substitute (10^{-8} m) increases.

Figure 2a Conceptual schema of the development of gluten-free corn bread based on the literature survey. Examples of relations are presented as lines.



Other structure-property relations used by the expert:

- If the distribution of gluten (10^{-7} m) is loose then the dough will collapse (10^{-2} m).
- If the starch granules (10^{-6} m) start to gelatinise then they will gradually take over the function of the gluten (10^{-5} m).
- If recrystallization of amylopectine (10^{-8} m) takes place then the aging period (10^{-1} m) of bread decreases.
- If calcium ions are present and have interactions with hydrocolloids (10^{-9} m) then a solid mass will be formed (10^{-1} m).

Figure 2b Conceptual schema of the development of a gluten-free corn bread based on the expert's consultation. Examples of relations used in the thinking process are presented as lines.

Theme B: Development of a bulletproof jacket

The function of a bulletproof jacket is to absorb all the energy needed to stop bullets. To improve a bulletproof jacket in order to increase its energy absorbance, we need to understand polymer fibres, the elastic modulus and the high degree of crystalline phases in the fibre, i.e. the strength of polymer chains by stretching the fibres directly after polymerisation.

The textbooks and research papers that were analysed (step 1) contained different representations of structures (such as fibres, filaments, and sheets of molecules), and of properties (such as strength and E modulus). These structures were related to scales, however, as was the case for theme A, the representations in the documents were not systematically presented into a schema. Based on our literature survey, a theme-specific conceptual schema could be constructed for the development of a bulletproof jacket (Figure 3a). We found that structures, such as a woven mat, fibres and polymer chains, and properties, such as E modulus, weight and energy absorption, are scaled in textbooks and research papers.

Expert B's statements with respect to the categories macro, meso, submicro, structure, properties and structure-property relations are presented in Table 5 (step 2).

Table 5 Examples of categorizing statements of Expert B

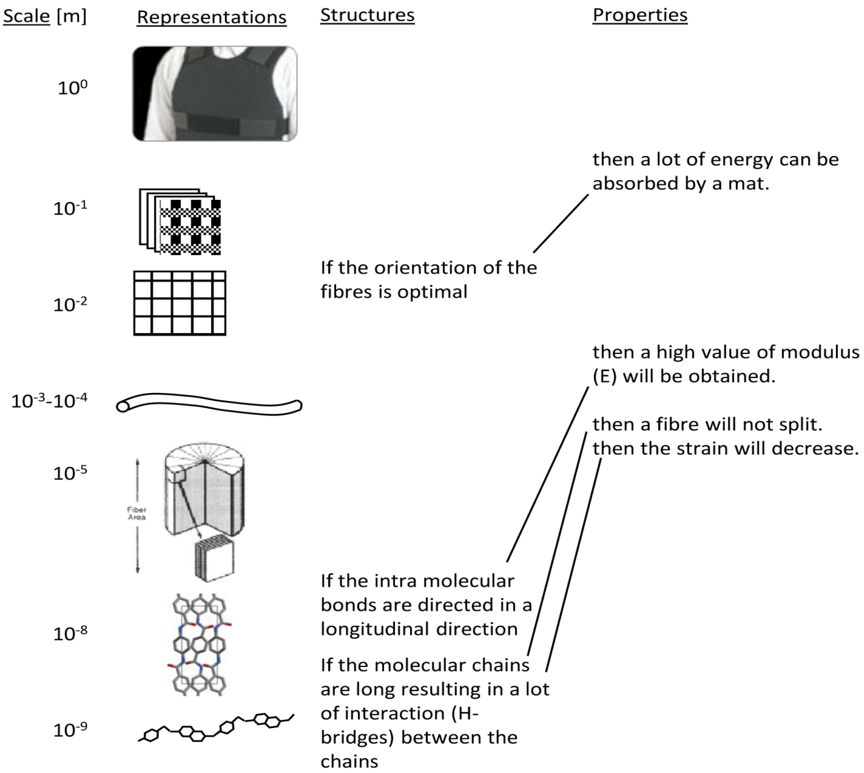
Statements by Expert B (relevant phrases in italics)	**Category**
… When you place all the *molecular chains* in the same direction and then stretch them under cold conditions.	Structure (meso)
And then you get a certain crystalline structure which we called *a cis-kebab-structure. This structure strengthens the fibre, so to speak.*	Structure-property relation
But that concerned the fibre. Finally, you make *a mat* which is used.	Structure (meso)
… from a scientific point of view, this evidence is quite beautiful, but if you produce *a mat* we will not use it.	Structure (meso)
One fibre has this direction and another one that direction [makes an angle with both hands,]	Structure (meso)
and one *filament is directed* that way and the other one another way. And the benefit is unclear to me	Structure (meso)
I want to create a gradient of layers of mats. From the *heaviest* material to the *lightest*, one that is sufficiently *strong* to decrease the speed of the bullet. (creates a drawing)	Property (meso) Property (meso)
Strong and… *flexible* and here the mat is very *flexible* … *lighter* (putting properties in different places in the drawing)	Property (meso) Property (meso)

Expert B frequently referred to meso levels, but only once to the submicro level. In the analysis of the thinking process of Expert B, five different meso levels were distinguished: the woven material (10^{-1} m); a single mat (10^{-2} m); the fibre (10^{-4} m); filaments (10^{-5} m) within the fibre and sheets (10^{-8} m) of molecular chains (10^{-9} m) (see Figure 3b).

Expert B claimed that the macroscopic properties were a consequence of the microstructures (at meso levels). However, when one has to design a new product using existing materials, as was required by the task we defined, a designer needs to know the properties of each material. In this case a designer is not interested in the causes of the desired properties, making the manipulation of structures or molecules unnecessary. However, if the task had been defined as synthesizing a new polymer then it had been necessary to direct the expert's attention to the submicroscopic level. For this reason, Expert B did not reason much at the submicro level. His arguments did not adhere to a fixed macro → $(\text{meso})_n$ → submicro or submicro →$(\text{meso})_n$→ macro pattern. Rather, he used his own knowledge in two ways: by reorientation and iteration, starting again in the same or a different way, and by reflection, while testing his reasoning against prior knowledge. For example, while working on his task, Expert B reasoned about the use of a composite to keep the fibre together during the impact of the bullet. Then he decided to use more layers on top of each other. This increased the weight of the jacket, so instead he used new material with a lower surface density.

Expert B frequently referred to structure-structure relations near meso levels with a scale smaller or equal to 10^{-5} m. For example, the speed of the bullet decreases to zero when the fibres absorb kinetic energy. This can only be achieved if the fibres stay in 'position' during the impact. In order to achieve this Expert B chemically connected the resin and the fibre. The resin (e.g. epoxy) has to react with the outer side groups of the fibre. In this situation the fibres are fixed and cannot diverge, thus the bullet cannot pass. Expert B stated 'with an epoxy it works'. The term 'epoxy' is problematic when it comes to the interpretation of structure versus property. Firstly, epoxy can refer to structure (a cyclic structure of three atoms: two carbon and one oxygen). Secondly, epoxy can be interpreted as a very reactive group of chemicals (property, 'it works') due to the high internal tension of the cyclic bonding. Because the term has two meanings it is difficult to categorise epoxy as a structure or a property.

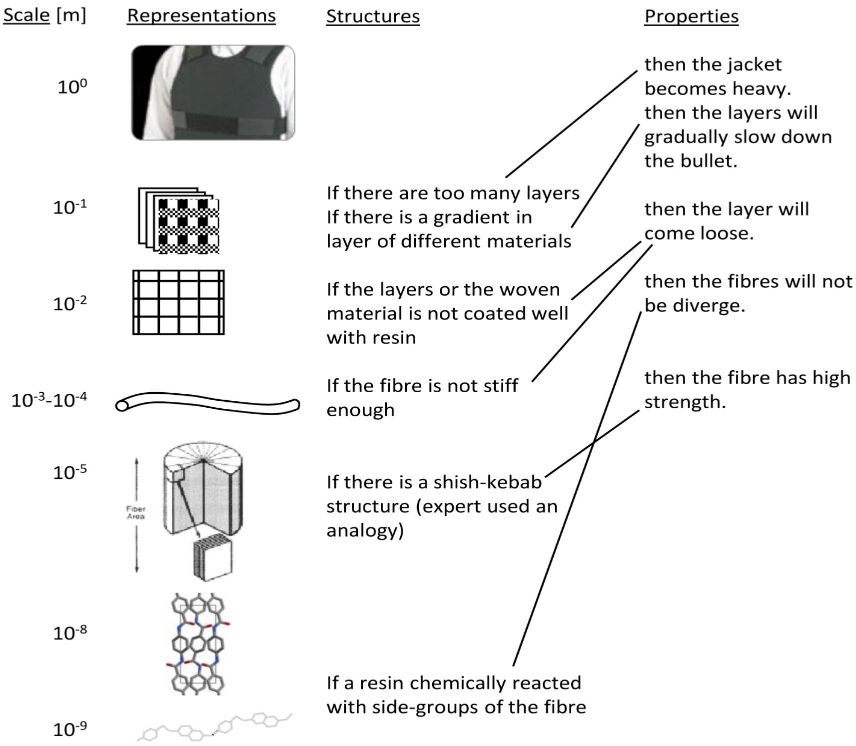
A combination of the conceptual schema that resulted from literature survey (Figure 3a) and from expert consultation (Figure 3b) shows that Expert B did not use the submicro level as much as was to be expected from the literature survey. The difference is caused by the need to understand the molecular structure of fibres, which is necessary to explain the high strength (Figure 3a). In this case, the explanation of the property is related to a structure at the submicro level, or at a meso level close to the submicro level: high crystalline regions which are aligned parallel to the fibres. These high crystalline regions are caused by the regular pattern of molecules. However, for Expert B his common phenomenological knowledge sufficed and Expert B used this as implicit knowledge. The following statement illustrates this point: '*I look at these structures* [pointing to the additional documentation supplied by the interviewer]. *But it was unnecessary; I already know these things*'.



Other structure-property relations used in the literature survey:

- If the orientation of the chains (10^{-8} m) is very regular then the strain (10^{-4} m) at bullet impact will decrease.
- If a composite structure (10^{-3} m) is presented then the energy dissipation (10^{-2} m) will increase at a constant value of E modulus.

Figure 3a Conceptual schema of the development of a bulletproof jacket based on the literature survey. Examples of relations are presented as lines



Other structure-property relation used by the expert:

- If a flexible resin (10^{-4} m) is chosen in between the layers, then it is able to bend the layers (10^{-1} m).

Figure 3b Conceptual schema of the development of a bulletproof jacket based on the expert's consultation. Examples of relations used in the thinking process are presented as lines

Theme C: Development of unbreakable cups

The strength of porcelain cups is determined by the avoidance of crack growth. This can be achieved by using particles with a very small diameter, addition of grain growth inhibitors, and high sintering temperatures. Changing these factors results in a dense (low porosity) amorphous phase (with a low content of silica) which results in limited crack growth (Figure 4a). Such ceramic material will not break easily.

The literature survey (step 1) revealed six meso levels. At a meso level (10^{-3} m) the ceramics are coated with a glaze. The ceramic is porous material (10^{-4} m) which is a result of the sintering process (10^{-5} m). In this sintering process, particles (10^{-6} m) form necks. A particle is made up of amorphous and crystalline phases (10^{-7} m). Between these phases defects or regular parts (10^{-8} m) are found which are made up of ions (10^{-9} m).

Expert C (step 2) tried to optimise the design of unbreakable crockery. Firstly, he described desired properties for using ceramic as the main material. From this first step, he concluded that ceramic had some advantages over metals or composites. Expert C made a sharp distinction between intrinsic and extrinsic properties. According to Expert C this composition of ions as building blocks of salt crystals did not significantly influence the desired extrinsic properties because the difference in bonding strength between several combinations of ions is small. Consequently, the choice of different ceramic materials did not significantly influence the properties of ceramic materials. Because of this, Expert C barely mentioned atoms or ions. Only when asked why he did not use the submicro level he explained: ‘it was not necessary because this [the desired property] is not decided at atomic level at all.’ The statements of Expert C were analysed into a similar pattern as for the Experts A and B (Tables 4 and 5). The result of this analysis of the expert consultation is given in Figure 4b.

Like the other experts, Expert C did not sequence his reasoning in a fixed manner between macro and submicro levels. We observed that this expert used reorientations (he started again at another level) and iterations (he switched between levels). Examples are presented below.

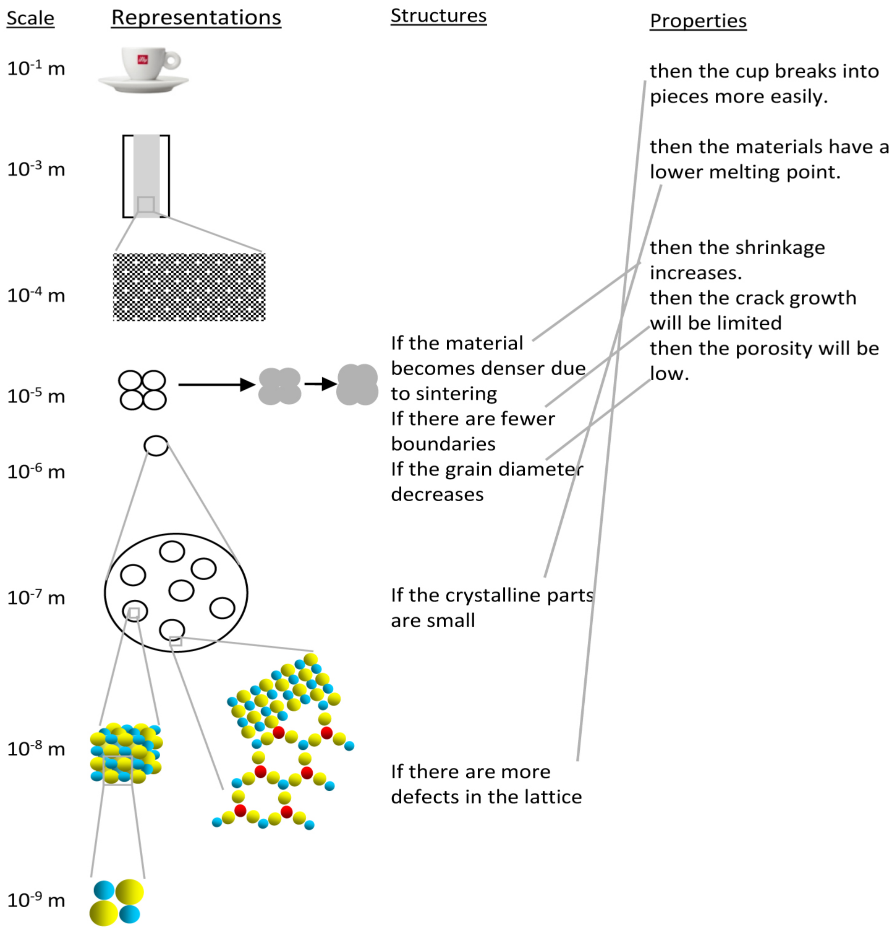
Reorientation	-	What must I do? I can do two things. Keep defects small. If I want to keep defects small, I must begin with small particles [grains].
	-	Route A is to keep the defect small. Made small by impregnating.
	-	Two ways. Then you get route B. That’s the strain.
Iteration	-	Then we get ceramics…
	-	And ceramic is essentially brittle.
	-	And I can think of impregnating the defects. If I make them large, yes exactly, that would be the alternative.

When we combined the conceptual schema of the literature survey (step 1) and the consultation of Expert C (step 2), a similar system of structures, properties and their relations can be constructed as was found for themes A and B. A comparison of the literature survey and the expert consultation for theme C, however, shows two important differences: the expert's thinking process is (1) more general, and (2) is less focused on the submicro level (Figure 4a and 4b). Firstly, the expert started with a much broader set of materials (metals, polymers and ceramics). Then the expert wanted to find a clear argumentation for using ceramic as the main material. The literature survey started at this point, which makes the expert's approach more general. Secondly, Expert C had no reason to use detailed information about the chemical components. Properties were only a result of micro structures (at meso level) and not of the substances. This implies that Expert C used his knowledge about general properties of the class of materials (ceramic). The conceptual schema resulting from the literature survey (Figure 4a) includes the frequent reference to chemical information about several types of ceramics, the influence of whiteners, grain growth inhibitors, and the amount of silica and mullite in porcelain. The expert did not need these details when working on his task. Expert C's reasoning is more generally applicable, including the use of only the necessary relations.

Expert C referred to one structure-structure relation ('If I keep defects [structure] small then I must start with particles with a small diameter [structure]'). This sentence can be interpreted as a construction of two other structure-property relations between the particle diameter and strength and between defects and strength.

Expert C also referred to property-property relations. These relations can also be interpreted as a combination of two or more structure-property relations. For example, porosity [property] means fewer holes and pores between the sintered particles [structure], which results in a decrease of possible pathways for crack forming [structure]. A limitation of crack forming results in higher strength [property].

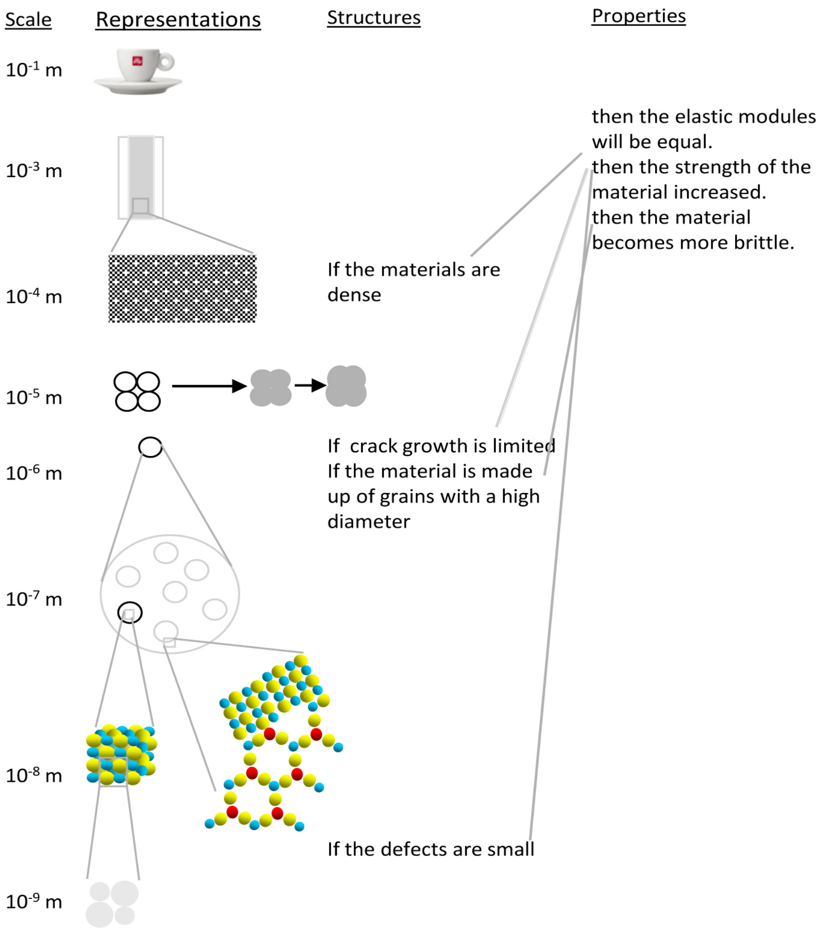
Connecting the properties to a scale leads to the conclusion that the properties used in this task are linked to the macro level or a meso level close to the macro level.



Other structure-property relations used in the literature survey are:

- If the grain diameter (10^{-6} m) decreases then the product is more homogenous (10^{-4} m) due to increased viscosity of the melt
- If the grain diameter (10^{-6} m) is small then the neck forming between the grains (10^{-5} m) increases (due to the increase of surface energy)

Figure 4a Conceptual schema of the development of an unbreakable cup based on the literature survey. Examples of relations are presented as lines



Other structure-property relations used by Expert C:

- If you have grains (10^{-6} m) with a small diameter then a higher strength is obtained (10^{-3} m).
- If there is a bonding between an anion and a cat ion (10^{-9} m) then it is brittle (10^{-1} m).
- If the surface between grains (10^{-6} m) increases then the connection between the grains is less strong (10^{-5} m).
- If I observe a high value of shrinkage (10^{-5} m) then a decrease of the porosity (10^{-4} m) is possible.

Figure 4b Conceptual schema of the development of an unbreakable cup based on the experts' consultation. Examples of relations used in the thinking process are presented as lines

Conclusions: generic pattern in the three analyses

To extend the conceptual schema of Figure 1, we have empirically explored the nature of intermediate meso levels and the structure-property relations for using these in chemistry education, and have studied authentic tasks originating from authentic scientific and technological practices (cf. Aguilera, 2006; Cussler & Moggridge, 2001). The empirical question was:

> What structures, properties and explicit structure-property relations can be identified within the domain of chemistry and material science and how to make the connection between macroscopic phenomena and submicroscopic models explicit within a conceptual schema?

Based on the literature survey and the experts' consultations, we constructed theme-specific conceptual schemata as an extension of the initial schema presented in Figure 1 using systems with several nested sub systems (Figure 2, 3 and 4). The construction of theme-specific conceptual schemata was achieved by scaling structures at the macro level, the relevant microstructures at different meso levels, and a submicro level in two cases. For all themes, relevant intermediate levels (and models of the structures) were needed for the specific theme-related task, however, the schemata do not contain a fixed number of meso levels. The number of meso levels and the presence of the submicro level depend on the definition of the task. Properties are frequently assigned to meso levels and are usually closer to the macro level.

The documents analysed (Table 1) did not reveal systematic visualisations of (micro) structures within nested subsystems. Structures at a meso level are presented in a rather isolated way, very often without clear identification of scales. In texts, explicitly formulated structure-property relations, in the form of an if-then-construction, are seldom mentioned. Additional exploration of expert reasoning was necessary to reveal the nature of structure-property relations.

Whilst reasoning, the experts did not sequence their reasoning in a fixed macro → $(\text{meso})_n$ → submicro, or submicro → $(\text{meso})_n$ → macro pattern. They frequently used reorientation (starting again at another level or with the task in a reflective way) and iteration (switching between levels as check or by weighing of the alternatives).

Reconstructed within the schemata (Figures 2, 3 and 4), most structure-property relations take a slanted, diagonal direction and bridge a gap of three or four orders of magnitude of ten between a property and the related structure used to explain or predict this corresponding property. In the analyses of the three theme-related tasks, direct relations between macro and submicro levels are very rare (we found three out of 22 in the three expert consultations). Structure-property relations are usually qualitative (causal relations in words) and can be expressed as if-then constructions valid within specific conditions. This is related to the condition Z which was an element in the general description of the if-then formulation. In general, a structure-property relation can be written as 'if this is an existing property, then it is caused by this type of structure' or 'if this is the existing structure, then this property can be expected'. We did not find structure-property relations at the same (horizontal) scale: all relations were links between two different (meso) levels. The number of structure-property relations in the document analysis and experts' reasoning is different due to the implicit knowledge used by the expert and our explicit conceptual analysis of the task.

Limitations of this study

For the extension of the conceptual analysis presented in Figure 1, we have analysed relevant documents (Cussler & Moggridge, 2001; Millar, 1990; Hill, 2004; Aguilera, 2006; Smith & Burke, 1967; Wintermantel, 1999), and consulted three experts to validate our conceptual analysis. This empirical basis allows us to draw meaningful conclusions.

There are three reasons why we would like to argue that more consultations with other experts will lead to similar conceptual schemata:

1. In the construction based on the literature survey we used scientific sources which are accepted by peer-reviewers as currently scientifically valid.
2. The selected experts are representative of the community of scientists in this domain.
3. The experts have different backgrounds but generally reason in a similar way, referring to structures, properties and their relations.

We designed three tasks originating from different areas in the field of chemistry research. Strength and elastic modulus had to be addressed in all these tasks. Moreover, the qualitative nature of structure-property relations can be explained by the nature of the designed tasks. Although these aspects limit our conclusions, we think it is possible to extend the use of our conceptual analysis to other problems in which microstructures (at a meso level) determine the final properties of a material or a product (Aguilera, 2006; Hill, 2004). For example, in biochemistry, health studies, physical chemistry, nanotechnology, catalysis, and genomics research.

Discussing the conceptual analysis and its use in chemistry education

The explicit (re)construction of the conceptual schemata as deducted from document analysis and expert consultation is a first stage, to make this kind of macro-micro reasoning available in an explicit way for education. Especially the nature of the structure-property relations reconstructed in a slanted diagonal direction within the conceptual schema is an important extension of the initial analysis presented in Figure 1. However, such a first conceptual analysis is not necessarily directly accessible to students. A careful analysis of students' ideas and difficulties in learning steps is necessary to investigate the challenges ahead. A few questions and considerations are discussed below.

First, the question is how to carefully comply with complexity when choosing a theme, defining a certain (learning) task and starting with a number of meso levels.

As we argued, a certain degree of complexity within a system of structures and sub structures is necessary for the students' understanding of emergent properties. However, depending on the age and ability level of students, complexity should not lead to a too high cognitive demand, complexity depending on the number of meso levels, and the type of models related to these meso levels. For example, in a gradual learning line starting at primary and/or lower secondary education, a (learning) task could be directed to the argued selection of ceramic materials: strength being depended on the choice of grain size and sintering temperatures whilst producing ceramic materials. Modelling, for example, is directed towards the process of sintering depending on temperature (Meijer et al., 2009; p.209). Models are related to meso structures at the size of micrometres or larger, which can be visualised with representations of a less complex nature compared to atoms and/or molecules. Another possible start could take place with the theme of bullet proof vests, in which a first modelling step can be related to the influence of the thickness of the threads and the weaving of the mats at scales of millimetres and centimetres. Or in relation to such an example, the use of fibres and materials used for sports clothing: isolation against cold weather conditions, wind breakers, etc. Whilst the emergence in chemistry can come to the fore, the less complicated nature of the models can be used to come to a better understanding of modelling.

Subsequently, a more complex theme can be used for extending the students' understanding of materials. There are numerous polymeric materials applied for items used in everyday life that are challenging to improve: the improved water absorbance of diapers that would need the elaboration of smaller meso structures with different and more advanced models. A learning task may be directed towards material improvement with existing polymers (mixtures, blending, spinning of fibres, etc.) or towards the development and/or synthesis of new polymeric materials. In the latter case, students need to focus on different types of characteristic groups at a submicro level. When the different, but related tasks are sequenced in a row, students may find out that an 'earlier' model of the material does not suffice to address the problem. In this way they can be involved in the tentative nature of modelling.

A similar argument can be applied when selecting biochemistry related tasks. In biology-related tasks, the use of wood, bamboo or cardboard as construction materials involves meso structures at the size of centimetres, millimetres or smaller. Models of the remainders of wood cells, bamboo cells, models of composite materials such as cardboard can be understood without knowing the underlying submicroscopic nature of cellulose, the latter knowledge not even necessary to address a construction task. The task about gluten-free bread is far more complex, using the raising of bread, the functioning of yeast, the elasticity of dough, and the gluten network within the protein network. Such complex tasks are more appropriate at the end of secondary education. This may also be the case for the functioning of enzymes, the molecular understanding of mechanisms in genomics, etc. It is a new and interesting challenge to construct a curriculum line in which a sequence of themes facilitates the students' macro-micro thinking.

A second and third question is the extent to which students can be facilitated to construct this type of schemata themselves, and how the use of such schemata can be transferred from one theme to another. How can teaching-learning processes be designed such that students are actively involved in their learning, and to what extent should the schemata be presented? If a schema is constructed for one theme, how can it be helpful and be adapted to make it useful for another theme?

Students' thinking can start at a concrete, phenomenological level, i.e., they can observe phenomena or properties and explain them by using existing intuitive notions (Duschl, Schweingruber & Shouse, 2007, p.18-19). By gradually introducing appropriate scientific concepts and relations, students may be enabled to develop a more scientific explanation of the observed phenomena or properties. The structures (at meso levels) can be introduced by visualising them and, when necessary, by modelling rather 'invisible' structures to arrive at the necessary structure-property relations and experiments, using analogues (Treagust et al., 1998). The reference to structure-property relations in argumentation (Driver et al., 2000) is at the core of our proposed conceptual schema for macro-micro thinking (Figure 1). Although, we have to take into account our linguistic discrimination between 'mass' words and 'countable' words which could be avoided by a careful distinction between structures and sub structures within the design of educational materials.

This new conceptual analysis is also promising for the inclusion of authentic contemporary science and technology issues in the chemistry (science) curriculum. Secondary chemistry education may benefit from using intermediate structures and structure-property relations when using authentic tasks for learning macro-micro thinking, for example as contexts in context-based chemistry education. The use of structures (at meso levels) may also account for the influence of the production processes of products which cannot always sufficiently be explained by particle models at the submicro level. Thus, contemporary science and technology can become a more integrated part of the chemistry curriculum in secondary schools, and consequently improve its relevance (Stevenson, 2004; Bennett et al., 2002; Van Berkel, De Vos & Pilot, 2000; Van Berkel et al., 2009; Osborne & Collins, 2001; Osborne, Simon & Collins 2003).

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Chapter 3

Establishing a context for learning macro-micro thinking for pre-university chemistry students

Abstract

Students cannot link their macroscopic daily life experiences with chemistry concepts or models related to entities at submicroscopic level; they do not experience the relation between the macro world and submicroscopic models as relevant. As a theoretical perspective, an adapted authentic practice was taken aiming to establish a context for learning macro-micro thinking at the start of the teaching-learning process. A design-based research approach was applied to study this intended effect by elaborating three strategy components, with the formulation of an initial design principle. Based on literature and experience, the strategy components were: the selection of a relevant socio-scientific task, the use of the students' intuitive notions about procedural steps, and enabling productive communicative interactions between students and teacher. Through two design cycles, the strategy components were adapted and led to the refinement of the elaboration into the teaching-learning process. The findings were that the task had to be clearly focused. This enabled students intuitively to understand the necessary procedural steps. A fictive company as a setting for the authentic practice in which students have to take up the role of junior participants was not necessary. We conclude that the elaboration of the three strategy components has led to the intended effect, and consequently has established an empirically underpinned design principle.

Introduction

The use of context has been advocated as a means to address typical problems in chemistry education (Van Oers, 1998; Bennett & Holman, 2002; Bulte, Westbroek, De Jong & Pilot, 2006; Gilbert, 2006; Parchmann et al., 2006). A context is used to create a setting in which students are able to experience that learning of chemistry concepts could contribute to their daily life or experiences (Bennett & Lubben, 2006). In such a way, students should come to see the relevance of learning chemistry. For example, in the case in which students do not experience a relevant connection between macroscopic phenomena and the learning of abstract and invisible models of atoms and molecules (Harrison & Treagust, 2002; Gilbert & Treagust, 2009). This study focuses on the establishment of a context for learning at the start of the teaching-learning process, as a necessary condition to enable students to experience the relevance for learning chemistry.

There are different views on how to establish a context for learning chemistry. For example, contexts can be interpreted as themes (Schwartz, 2006), case studies of industrial socio-economic and environmental issues (Hofstein & Kesner, 2006), or related to the use of chemistry in daily life (Bennett & Lubben, 2006). However, in all of these studies, a clear positioning on the meaning and the models of context is lacking (Gilbert, 2006; Pilot & Bulte, 2006; Sadler, 2009). Besides, at the level of the design of a teaching-learning process, there is a lack of clear guidelines or design principles to prescribe which strategies, elaborated in a certain way, can be used to obtain the intended effect: that, especially at the start, students experience that it is relevant to connect their own life-world experiences to the learning of chemistry (Bennett & Lubben, 2006; Gilbert, 2006; Parchmann et al., 2006).

Therefore, this chapter has a twofold focus: 1) formulation and elaboration of argued strategy components for the establishment of a context as a condition to make the learning of chemistry relevant for students and, 2) the understanding, formulation and the development of a design principle to establish such a context. In this chapter we present both foci for the case of macro-micro thinking (Meijer, Bulte & Pilot, 2009). We apply a design-based research method (cf. Van den Akker, Gravemeijer, McKenney & Nieveen, 2006).

Theoretical framework

In the next, we argue that for learning in context, it is essential to meet Gilbert's criteria I and II (2006) as a first condition to initiate the students' involvement (cf. Prins, Bulte, Van Driel & Pilot, 2009). These criteria imply the establishment of a context for learning at the start of the teaching-learning process implies the creation of

I a setting as a social, spatial, and temporal setting for a community of practice within the classroom from the start of this teaching-learning process in which

II a practice-related task must clearly bring the procedural steps of an authentic practice that are used as a behavioural environment for the accomplishment of the task (Bulte et al., 2006; Westbroek, Klaassen, Bulte & Pilot, 2010).

Additional to criterion I, in discourse all learners as participants of the community of practice should experience productive communicative interactions.

The establishment of a context for learning implies the creation of a community of practice within the classroom from the early start of this teaching-learning process. This actually means that criterion I, that is, students value the setting, is essentially important for any successful teaching-learning process. To establish such a context for learning, we take the adaptation of an authentic social practice into a context for learning as a theoretical perspective (Bulte et al., 2006; Van Oers, 1998; Prins, 2010, p.56). In authentic practices, common motives for the participants, their common goals, values and rules, procedural steps and the necessary chemical concepts are a coherent whole for achieving a certain practice-related task (Prins et al., 2009). The coherency of an existing authentic social practice embodies a social, spatial and temporal setting (cf. criterion I); the common goals, motives and procedures guide the type of behavioural environment (cf. criterion II) for the application and extension of the necessary chemical concepts as common language. Through the adaptation of an authentic social practice for the sake of learning, we intend to maintain this coherency between (learning) task, goals, procedural steps, values, rules and chemical concepts which are embedded in a cultural entity in society (Engeström & Sannino, 2010). Depending on the specific circumstances within an entire chemistry programme (ability level, age of students, year, teachers' preferences), different choices can be made. The main learning goals for students can be directed towards learning of chemistry concepts and procedures or towards learning of the active participation as citizens (Sadler, 2009; Marks & Eilks, 2010). When maintaining the coherency of the setting, the behavioural environment and the specific chemistry language within an adapted authentic practice, both types of learning goals can come to the fore.

When adapting an authentic practice for the sake of learning in relation to criterion II, Van Oers (1998) describes that a social practice becomes relevant for students when they experience a chain of coordinated actions that is important for achieving a certain practice-related task. When this task lies within the students' zone of proximal development, a plan of subsequent actions or a series of procedural steps to address such tasks can be intuitively evoked (Van Oers, 1998). Only then the objects, tools and symbols as a specific (chemical) language can form a particular meaning (see Engeström & Sannino, 2010; Wenger, 1998). In this way, the students can be enabled to oversee intuitively the necessary procedural steps as the focus of the behavioural environment. If students accept the task as 'significantly important' or 'relevant to perform' then a broad motive to accomplish the practice-related task is spontaneously evoked as a behavioural environment (criterion II; Gilbert, 2006).

The establishment of 'productive communicative interaction' is an essential element in forming a community of practice (Lemke, 2001). According to Ryan & Deci (2000) students should experience to belong to other persons or to some group, implying that students within a classroom work together at the same task. Students will become members of a community by showing engagement with the task (Wenger, 1998). The students will then share personal experiences, references and memories with others. Besides providing a broad motive at students, there is a need to pay attention to the students' input (Westbroek, 2005) and self-regulation (Pintrich, 2003; Ryan & Deci, 2000) to fulfil Gilbert's criteria I and II.

Self-regulation means that students set goals or plans, and try to monitor and control their own cognition, motivation, and behaviour in line with these goals (Pintrich, 2003). Self-regulation seems an evident component in the design of teaching-learning processes, but it requires a more bottom-up approach, rather than a top-down approach in which the teacher determines learning goals and the steps required to achieve the goals through assessment. A balance between top-down and bottom-up processes is essential for a teaching-learning process in which students have the opportunity to construct their own meanings based on prior knowledge and experiences (Lijnse & Klaassen, 2004). This can be achieved by discourse between teacher and students, when they decide which strategies and/or actions to select (Lemke, 2001; Kelly, 2007). Thus productive interaction between all participants is essential for experiencing the learning of chemistry as relevant (criterion I; Gilbert, 2006).

We argue that three strategy components can be formulated for the intended establishment of an adapted version of an authentic practice as a context, in the following order:

i. Select a task,

ii. Use intuitive notions of students with regard to procedural steps and,

iii. Enable productive interaction between the participants of the community.

To establish a context as a necessary condition for learning at the start of the teaching-learning process, these three strategy components must be elaborated within the first phases of a teaching-learning process. Therefore, the elaboration of these argued strategy components to reach the intended pedagogical effect will give the opportunity to formulate a heuristic guideline in the form of a design principle.

A *design principle* (Figure 1) consists of a *strategy* based on *arguments,* leading to an intended *effect* (Edelson, 2001; Hofstein & Kesner, 2006; McKenney, Nieveen & Van den Akker, 2006). The term *strategy* refers to a process and / or a sequence in which stages or activities in a designed teaching-learning process are planned and / or executed. A principle contains underlying *argument*s (theory for learning and teaching, and evidence-based and practical experiences) that relates the chosen *strategy*, containing one or more strategy components, to the *intended pedagogical effects* (see Figure 1). Design principles have a heuristic nature (McKenney et al., 2006), with a limited validity when it is embedded within a certain educational situation: students, teachers, chosen contexts, etc.

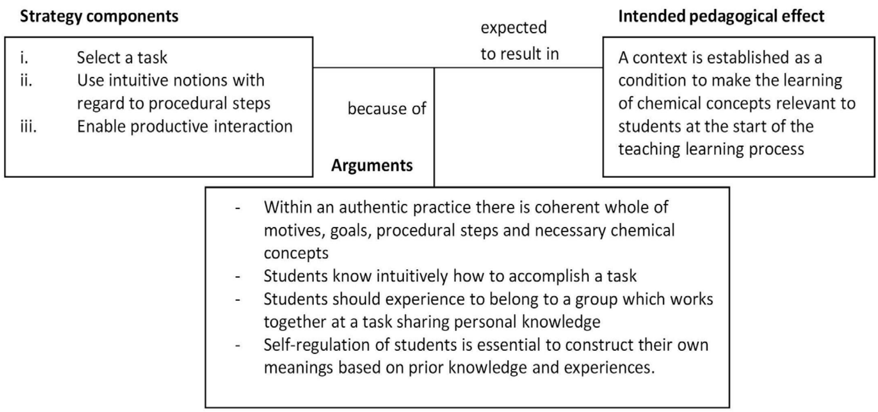

Figure 1 Representation of the context-principle used in this study

We position this study in the case of macro-micro thinking in chemistry. Several authentic practices as contexts are available in which macro-micro thinking is an essential activity (cf. Chapter 2). In line with the expected interests of students and the practical aspects of school facilities, the chosen practice is embedded in the societal need for gluten-free food products because of the increasing number of people with coeliac disease (Chapter 2). The students' learning task is taken from a corresponding authentic practice in which professionals develop gluten-free food products for people with gluten intolerance. These professionals improve the specific properties of such food products to answer the needs of consumers (Sadler, 2009). In these activities they apply the concepts of macro-micro thinking whilst using structure-property relations (Chapter 2). In food products, wheat, and so gluten, is often used. Corn, that does not contain gluten, may be used as an alternative for wheat. For professionals, the addressing of this issue is not straight-forward. Even in scientific literature there is no unambiguous solution to the problem of developing gluten-free food products.

For this case, we explore the arguments and elaboration of the strategy components, and formulate the design principle for establishing a context as a condition for learning with an empirical basis obtained in two research cycles. The initial context-principle is formulated as follows:

> **If** students as participants of a community of practice within the classroom are provided with a practice-related task *(strategy component i)* **and** have their own plan of action based on intuitive notions *(strategy component ii)* **and** productive interaction is enabled *(strategy component iii)* **then** a context is established at the start of the teaching-learning process as a condition to make the learning of chemical concepts relevant to students (*intended pedagogical effect*).

The research questions which we will answer in this chapter are:

1) *To what extent does the elaboration of the strategy components lead to the intended effect: the establishment of a context as a condition to make the students' learning relevant?*

2) *What is the formulation of the empirically underpinned context-principle?*

By answering these two questions, the formulation of the context-principle gets an empirical basis by designing a teaching-learning process which is studied in two cycles of designing, enactment, evaluating and redesigning (Figure 2). A teaching-learning process is a complex whole of participants, tasks, motives, actions and chemical concepts. In this study we focus specifically on creating a context for the learning how to relate macroscopic phenomena to abstract and invisible models of atoms and molecules at the start of the teaching-learning process (macro-micro thinking). For the design of the entire teaching-learning process, at least two other principles are needed: a sequence-principle, so that students experience that each activity is needed in addressing the practice-related task during all the activities of the teaching-learning process, and a content-principle related to the representation of the specific contents of macro-micro thinking using structure-property relations. In this study, the focus is on the early establishment of this context for learning. Since this is a first condition to be met, the context will serve as setting for learning chemistry (cf. Prins et al., 2009). Aspects related to the other design principles are beyond the scope of this chapter and are described elsewhere (Chapter 4 and 5 of this thesis; Meijer et al., 2009).

Method

Research approach

The research approach includes the elaboration of the strategy components of the context-principle into a teaching-learning process. It includes the enactment of this teaching-learning process in a classroom and the subsequent analysis thereof leading to a redesign of the teaching-learning process and a reflection on this design principle. This research is informed by a design-based research approach with an empirically established design principle as a knowledge claim (cf. Van den Akker et al., 2006; McKenney et al., 2006) for which details and procedures are described in Chapter 6 of this thesis. In the method we apply, the enacted teaching-learning process is compared with the designed teaching-learning process and the specified expectations about how each of the teaching-learning activities should function (Lijnse & Klaassen, 2004). The expectations are concrete descriptions of the intended pedagogical effect which is described in the design principle. Expectations can refer to the written or oral answers or products, or actions of students. The arguments for the design principle and the expectations are based on the literature, empirical evidence from previous design cycles and practical experiences of the members of the design team (Figure 1). The evaluation of the teaching-learning process may give rise to a redesigned version of a teaching-learning process, and if necessary to the adaptation or refinement of the strategy components in the design principle including the arguments. In this chapter two design cycles are described. The first cycle is intended to verify or adapt the elaboration of the strategy components and the formulation of the initial design principle (see Figure 2). The second cycle should lead to a further understanding of the theoretical arguments and the establishment of the design principle with an empirical basis.

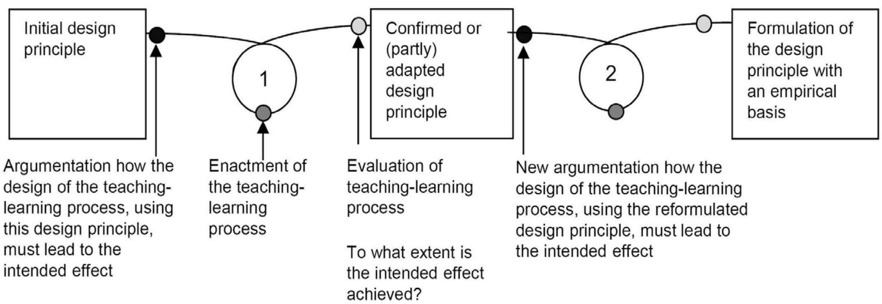

Figure 2 The development of a design principle within two cycles of design and evaluation of a teaching-learning process

Data collection and analysis

For the two cycles, the strategy components were elaborated into a teaching-learning process (Appendix A and B respectively). Connected to each of the strategy components, the intended effects for each cycle were described as concrete detailed expectations embedded within the teaching-learning process (see further for each cycle in the Tables 1 and 4). These concrete expectations which embodies the described intended effect of the design principle (Figure 1) were connected with the function of a teaching-learning activity (see Appendix A and B).

Data collection took place by multiple data sources.

A. Video and voice recordings were taken during enactment of teaching-learning process.

B. The first author took field notes during classroom observations.

C. Student questionnaires were administered before (pre questionnaires), during and after enactment (post questionnaires).These questionnaires (cf. Table 2 and 3 in the next sections) were especially designed to verify whether the students had an outlook for the next teaching-learning activities. Questions in these students' questionnaires were: a) How do you judge each teaching-learning activity on a five-point Likert scale, and provide an argumentation for your judgement; b) How do you judge this teaching-learning process with regard to difficulty, personal interest and information; and c) Can you formulate the purpose of this teaching-learning process and describe an outlook to the next teaching-learning activities?

D. Copies of student work in terms of worksheets and reports were collected.

E. At the end of cycle 1, students were individually interviewed. A focus group interview is held at the end of cycle 2. As a preparation of that group interview, students filled in a short questionnaire about their role, about the experienced relevance of the community of practice, and the advantages and disadvantages of this type of education. These questions were to guide the focus group interview. The teacher interview was held after each teaching-learning phase. The purpose of the interview was to reflect on the previous phase and to prepare for the next one.

Analysis and interpretation of the data sources were performed according to the following procedure (Bulte, Westbroek, De Jong & Pilot, 2006).

- Fragments of video and voice recordings in relation to the formulated expectations were selected and transcribed verbatim when necessary (data source A). These fragments in combination with the related field notes (data source B) were used to analyse whether the elaboration of the strategy components into the teaching-leaning process proceeded according to the formulated expectations (cf. the Table 1 and 4 in the next sections). In this analysis, the discourse of the whole group of students and their teacher was the unit of analysis. The number of students who acted as intended was counted to determine their active involvement during classroom discussions.

- Additionally, to analyse whether each of the formulated expectations was achieved (Tables 1 and 4), at least two of the five data sources (A - E) were used.

This analysis resulted in a 'thick description' of the enactment (prepared by the first author, MM) with respect to each of the formulated expectations and was judged on a three-point scale ('not' – 'partly' – 'fully'). We used the criterion 'fully' when 80 per cent of the students acted according to at least 80 per cent of the expectations (Juran, 1974). If only none, one or two of the students acted according to the intended expectations, we used the term 'not achieved'. The term 'partly' refers to outcomes in between 'not achieved' and 'fully achieved'. This is considered sufficient for the purposes of this study.

The judgment on a three-point scale was performed by two researchers independently (first cycle: first and second author; second cycle: first and third author). We regarded 80% as lower limit for a substantial level of agreement (inter rater reliability; Miles and Huberman, 1994, p.64; Prins et al., 2009). The first qualitative judgement of the whole set of expectations was discussed among the two researchers until they had reached consensus about the findings. Subsequently, the whole set of 'thick descriptions' was discussed in the entire research team in a peer review process (all authors). We used three validation strategies: triangulation of data sources (see above A - E) for providing detailed thick descriptions, independent analysis of data by two raters and a peer review process, thus meeting the criteria required for a valid study (Creswell, 2009, p. 209).

Participants and enactment of the teaching-learning process

All students, pre-university education, were recruited from one school in an urban area in the Netherlands. As volunteers they had positively responded to a letter distributed in their school. All students within cycle 1 (numbered S1 to S8; average age ≈ 17.6) had chosen at least two of the subjects out of mathematics, physics and chemistry for their final exam. All these students had marks between six and seven (on a scale of 1 to 10) for the science subjects (average = 6.8). The fourteen voluntary students of cycle 2 (numbered S9 to S22; average age ≈ 17.2) had marks for their scientific subjects between five and nine with an average of 6.7. The students of both cycles can be regarded as average students. By participating in this project, students gained a mark for their practical exam.

The teacher within cycle 1 (T1) taught chemistry for seven years in all classes in secondary school. T1 was involved in the development of science education at the school. Furthermore, T1 participated in a developmental group of chemistry teachers who were designing, enacting and evaluating teaching-learning processes within the new chemistry curriculum development. The second author was the teacher in cycle 2 (T2). She was a chemistry teacher for five years in secondary education before taking up her present post at the university and has been actively involved in curriculum development for chemistry education in secondary school.

In the first cycle, the enactment of the teaching-learning process took place during eight afternoons (each of two to three hours) during the period February to March 2006. The second cycle was enacted within one week in July 2007 (24 hours in total). In both cycles the task was the development of gluten-free bread based on corn for people with coeliac disease as a specific context (Meijer et al., 2009). Translated and modified authentic research papers were used to introduce the chemistry concepts.

The results of our design study are presented as follows (see also Figure 2). For each cycle we describe the following.

- 'The context-principle in the teaching-learning process'. This section describes the arguments (Figure 1) for the choices made in the design of the teaching-learning process.

- 'The elaboration of all three strategy components: i. select a task, ii. use intuitive notions of students with regard to procedural steps and, iii. enable productive interaction between the participants of the community'. This section describes how these strategy components were elaborated into the designed teaching-learning process. Connected to each of the strategy components, the detailed expectations were formulated. Together these expectations form the concretised intended effect.

- 'The evaluation of the strategy components' that were elaborated into the designed teaching-learning process, leading to reflection on the design principle.

- 'The (re)formulation of the context-principle in the next cycle including the (new) arguments'.

The findings of cycle 1 are more briefly described compared to the more extensive descriptions of the findings of cycle 2.

Cycle 1: design, elaboration and evaluation

The context-principle in the teaching-learning process

We argue that the development of food products for people with coeliac disease is a realistic and authentic socio-scientific issue. It is relevant to students, because food is close to the experiences of students and it relates to illness and helping other people (Osborne & Collins, 2001). By introducing a range of food products, we argue that students are enabled to extend their findings and obtain knowledge about properties of gluten which is useful for different situations to design other food products. As an authentic element of the related social practice, we refer to a company which develops food products in which students are invited to become junior employees. To enable the intended productive interaction, we argue that the whole group and the teams of students hold frequent discussions about developing food products for people with coeliac disease and how to accomplish this task.

For the development of gluten-free food products, the removal of gluten from wheat is too complicated to perform in secondary education. So in this study, corn is presented to students as a useful replacement for wheat. The use of corn, however, leads to low-quality bread. Gluten contains proteins which form an elastic network which can capture the carbon dioxide gas formed during fermentation of the yeast. Due to this property, the dough will rise and produce an acceptable quality of bread. The students have to find a replacement for gluten to add to the corn (or dough).

Therefore, at the start of the teaching-learning process, students have to notify that they need to know more about the way gluten forms a network, why it absorbs water and why this network can capture gases. In this way, we argue that the activities at the start of the teaching-learning process are directed towards the students' formulation of motives to understand more about the chemistry of baking bread, for which they develop motives to descend from macro (the bread) to meso structures at a scale from 10^{-5} to 10^{-9} metres, which is described elsewhere (Meijer et al., 2009).

Elaboration of the strategy components

The establishment of a context at the start of a teaching-learning process as a condition for learning is mainly connected to the start of the teaching-learning process. At the start the specific setting must make the practice-related task relevant for students and thus evoke a broad motive for participating in the specific community of practice (criterion I; strategy component i). Second, the students should be enabled to express their intuitive notions about procedural steps to achieve the practice-related task (criterion II; strategy component ii), and third, students and teachers must develop a productive interaction (strategy component iii). All three strategy components were elaborated in the first two phases of the teaching-learning process: orientation to the task and definition of the task (Appendix A). This elaboration resulted into six teaching-learning activities divided over both phases.

At the start of the teaching-learning process (see Appendix A), the task included the presentation of the fact that about 15% of the human population has gluten intolerance (strategy component i). The setting was realised by the introduction of a possible business idea of a virtual senior co-worker of a food company who intends to develop gluten-free food products. This introduction was modelled on an authentic practice dealing with such problems in reality. The task was to develop one gluten-free product as an example: bread based on corn instead of wheat (strategy component i). The group of students as a whole needed to formulate the procedural steps necessary to perform this practice-related task (strategy component ii). As participants in such an authentic practice, teams of two students as junior developers of food products, needed to formulate their own proposal for a new project in productive discourse (strategy component iii). Subsequently, the students' formulation of the practice-related task should be accepted by the management of the virtual company (this role is in fact fulfilled by the teacher; strategy component iii).

Based on the arguments for the design, expectations were described as concrete realisations of the intended pedagogical effect. We expected the students to recognise the socio-scientific task (expectation i-a; Table 1). We introduced a fictive company to introduce the authentic practice, and expected that students recognise that the task is part of this authentic practice (expectation i-b; Table 1). We expected the students to be able to formulate the necessary procedural steps to accomplish the practice-related task: to choose corn instead of wheat, to zoom from a range of food products into one product (expectation ii-a; Table 1) and to extend their knowledge of the baking process of bread (ii-b; Table 1). This baking experiment should lead to the expected conclusion: corn bread does not rise and is not attractive to eat. Consequently students were expected to refine their task: find a replacement for gluten to add to corn dough that has chemical properties similar to gluten (expectation ii-c; Table 1). Students as junior-food product developers were expected to experience that they are able to influence the task and process (iii-a; Table 1), and become participants in the community of practice by accepting their role (expectation iii-b; Table 1).

An overview of the detailed expectations of the three strategy components in the orientation phase of the teaching-learning process of cycle 1 is presented in Table 1. The elaboration of the related teaching learning process is given in Appendix A.

Table 1 Overview of the detailed expectations of the three strategy components in the orientation phase of the teaching-learning process of cycle 1

Strategy component	Detailed Expectation
i. Select a task	(a) Students recognise the socio-scientific task, which becomes relevant for them. (b) Students recognise that the practice-related task exists within an authentic practice; students develop a shared motive to accomplish the task.
ii. Use intuitive notions of students with regard to procedural steps	(a) Students restrict the task by zooming from a range of food products into one product (bread) and use corn instead of wheat. (b) Students have a notion about the main procedural steps of the development process: exploring the problem, finding an explanation, designing and evaluating. (c) Students are able to extend their notions about the procedure with the use of a replacement for gluten and knowledge about baking bread.
iii. Enable productive interaction between participants	(a) Students experience being able to influence the task and the process to accomplish the task. (b) Students become participants in the community of practice by accepting their role as junior designers of food products.

Evaluation of the strategy components

Strategy component i: Select a task

Expectation i-a (Table 1) was ‘fully’ achieved; students recognised the socio-scientific issue and it was relevant for them (voice and video recordings of activity 1). The motivation of students to participate in this project came to the fore in the first group discussion at the beginning of the teaching-learning process (voice and video recordings of activity 1). The coeliac disease problem was an important reason for three students (S1, S3, S4). Two students (S4 and S5) had family members who suffered from the disease. Two others (S7 and S8) knew that gluten-free products are sold because they work at a bakery. During the group discussion, all students displayed the insight that coeliac disease is a problem for people (voice and video recordings activity 1).

Although, students recognised the task of developing gluten-free bread, this only 'partly' evoked a shared motive to accomplish the task (expectation i-b; voice and video recordings of activity 3 and questionnaire after activity 4). First, only two students showed the intended motive to accomplish the task: a formulation that can be considered as a motive was expressed by students (S2 and S8) in wording such as (voice and video recordings of activity 3) *'we have to develop something'* and *'if we develop a new product'* and *'we also want people to buy our product'*. This was interpreted as a sense of ownership of the task. Second, a clear focus of the task was lacking in all descriptions formulated by the students (questionnaire after activity 4). A summary of those formulations is presented in Table 3. In general the students interpreted their task according to the intended direction, but a shared motive to accomplish the task was lacking because the descriptions of the task showed that half of the students mentioned the '*development'* of gluten-free bread as an intended outcome of their project (S1, S2, S3 and S8). Two students used the words *'production'* or *'to produce'* (S4 and S6). Two students (S5 and S7) refer to '*investigations'* with respect to the chemistry to solve the problem of gluten intolerance. One student mentioned 'something innovative', which refers to one single product.

Table 2 Formulation of the task as recognised by students (questionnaire after activity 4 in cycle 1)

The development of a gluten-free bread (S1 and S2),
Set up a project for the development of gluten-free bread (S3)
The production of different breads and experiments, learning from errors, with an excellent bread as outcome (S4)
To investigate the finest method of production of an innovative product (S5)
To produce a perfect gluten-free bread that addresses the following aims …(S6)
Using chemistry to find a solution for the hypersensitivity related to these proteins (S7)
Development of something innovative (S8)

With respect to the strategy component i, 'Select a task' (Table 1), we concluded that it was partly effective. As designers we did not manage to develop a shared motive for the accomplishment of the task, although the students experienced the task as relevant.

Strategy component ii: Use intuitive notions of students with regard to procedural steps

Expectation ii-a about zooming in from a range of food products to one product was 'partly' achieved because only five out of eight students (S1, S2, S3, S4, S6) mentioned bread as an exemplary product to start with (Table 2).

Additionally, expectation ii-b about evoking an intuitive notion with regard to the procedural steps was 'partly' achieved. The students' statements about the main procedural steps are presented in Table 3.

Table 3 Data (questionnaire after activity 6) which show students' intuitive notions about the procedure in cycle 1

Make the perfect bread, according to the aims, produce it and explain everything theoretically (S2)
Make gluten-free bread. Obtain insight into the process of bread baking (S3)
Develop the perfect bread with good properties which tastes and looks good (S4)
To investigate properties of all varieties of bread and think of new products (S6)
Design a gluten-free bread (S7)
Design a bread with sufficient quality and with a low gluten content (S8)

All students (seven out of eight, S1 was ill) mentioned the task. S2, S4 and S6 mentioned 'development'. Other steps like 'designing' and 'insight' are more difficult to interpret because it is not fully clear what is meant in this situation. With regard to the procedural steps, only one or two students mention the steps 'finding an explanation', 'tests' or 'evaluation of tests' for the accomplishment of the task. The task gave students the idea of doing an investigation (*to investigate, to obtain insight, to explain*) and designing a product (*to design, to develop, to make*) which can be derived from student's intuitive notions of the procedure. This was confusing for them and it meant that not all participants shared the same view on *how* to accomplish the task to develop gluten-free bread.

Expectation ii-c was 'fully' achieved because, during the group discussion (student works, video recordings and field notes of activity 6), all students formulated the notion that the baking process is an important step, especially the investigation of the first two stages of baking (mixing of ingredients and the rising of dough) and a replacement for gluten.

Strategy component ii, 'Use of intuitive notions of students with regard to procedural steps', was only partly effective. As designers we did not manage to incorporate the procedural steps from the students' perspective. As a result, there is a lack of focus with respect to the intended behavioural environment.

Strategy component iii: Enable productive interaction between participants

Expectation iii-a about the influence of students on the task and process was 'partly' achieved (voice recordings and field notes of activity 3). On the one hand, some students (S1, S2, S4, S8) showed ownership of the task by talking about *'our bread'* (S2, S8) and '*we have'* (S1, S4) (field notes, voice and video recordings) which means that they wanted to participate and to accomplish the task. The statements below indicate that students (S2, confirmed by the whole group, voice recordings activity 3 and 4) had the impression that the option to choose corn as a replacement for wheat was directed by the available material.

> S2 to T1: *'is there something else you want to push for?'* (field notes and video recordings)
>
> S2 during group discussion: '*I think we are being directed to choose corn, or is that just my impression?'* Every student affirms this opinion of S2. (voice and video recordings)

Opposite indications were found in the questionnaire filled in after the orientation phase by students. The opinion of students ranged from '*interesting'* (S2, S3, S4, S5, S6, S7), *'not pre-cooked, but we have to think by ourselves'* (S8) to *'beautiful way to introduce the project'* (S1).

Students did not accept their role of junior employee (expectation iii-b), as illustrated by the statement of student S5, after reading the text where his role came to the fore (field notes and voice recordings of activity 2): *'let it be'* and *'OK … and now the assignment' (S5).* These statements could be interpreted as expressed by a student in a school situation and do not represent his role-identification as an employee.

Regarding strategy component iii, in spite of their ownership of the task, students did not adopt the role of designers of food products. The students experienced that they were still situated in a school science setting. Although students had formulated their task themselves, the student material guided them too strong in the desired direction. The expectation to enable productive interaction was 'partly' achieved.

In summary, with regard to the elaboration of the strategy components in the first cycle, the intended community of practice was more a community of learners who worked together on the same task. There were clear indications that the students had a motive to accomplish this task because they showed ownership: they accepted the social issue of the setting, however, without becoming members of the intended (adapted) authentic setting (criterion I). The expected procedural steps to accomplish the task as a specifically designed behavioural environment could not be intuitively evoked by students at the start of the teaching-learning process (criterion II). In fact, in reflection, we as designers ourselves entangled a research procedure with a clear design procedure. The context-principle has potential, but it needs adaption in its detailed formulation. The strategy components have to focus more precisely on the core of a community: one clearly *focussed* task which produces one set of procedural steps as a behavioural environment which is defined and accepted through interaction between all participants.

Cycle 2: design, elaboration and evaluation

The context principle revised

The findings in the first cycle show that details in the elaboration of the strategy components within the orientation phase of the teaching-learning process in the first cycle and the arguments need revision. This revision requires a revised formulation of the strategy components in the context-principle. In the next, we refine the formulation of the first strategy component, and argue how this refinement has consequences for the elaboration of the two other strategy components.

Strategy component i: 'Select a *focused* task'. This means to create a setting in which it becomes clear what type of activity has to be accomplished (Van Oers, 1998, p. 480). As a result of the first cycle, we now argue that the task has to be clearly *focused* on the *design process* of a class of gluten-free food products with the purpose to gain knowledge about the properties of gluten which is useful to design other food products. In this way, the task should evoke a broad motive to start with. As a consequence of the *focused* practice-related task, we argue that the necessary steps to accomplish the task are more easily evoked in students in an intuitive way. Secondly, the use of an external motivational aspect, an external supervisor as a member of the authentic practice, should introduce the issue to the students and can thus keep the students more *focused* on the goal of their task. Both students and teacher are then framed by the goal of their task (Sadler, 2009, p. 4).

Strategy component ii: 'Use intuitive notions of students with regard to procedural steps'. To clarify the *focus* for students on one specific task (a design or an investigation), the task is more specified towards the *design* of a class of gluten-free food products. In this way, the intuitive notions of students about the steps of the design procedure can easily be evoked, because a design procedure can be more easily connected with their own naive understandings of the natural world than an entwined procedure of investigation and design.

Strategy component iii: 'Enable productive interaction'. We argue that both students and teacher can adopt more easily their roles as junior designers of food products or project leader, guided by the external aims of their project (enforced and *focused* external pressure). In this way, the role of the teacher changes from teaching to guiding, resulting in more productive participation when accomplishing the task, and allowing an increase of self-regulation by the students. This effect is strengthened by the fact that a clear scientific solution to the task is not yet available in the literature.

Based on these adaptations, the new version of the context design principle can be formulated as (the new element 'focused' in italics):

> **If** students as participants of a community of practice within the classroom are provided with a *focused* practice-related task (strategy component i) **and** have their own plan of action based on intuitive notions (strategy component ii) **and** productive interaction is enabled (strategy component iii), **then** a context is established at the start of the teaching-learning process as a condition to make the learning of chemical concepts relevant to students (intended pedagogical effect).

Elaboration of the strategy components

Again, all three strategy components were elaborated in the first two phases of the teaching-learning process: orientation on the task and definition of the task (Appendix B). In cycle 2, this elaboration resulted into four teaching-learning activities divided over both phases. The task for students, to design a gluten-free food product for people with coeliac disease with the purpose to gain knowledge about the properties of gluten for designing food products, was addressed by an external scientist unknown to the students. An expert (a scientist from a university who works at research of gluten) acted as an employee of a fictive company and as a supervisor of the project. The expert presented the task with a video presentation. The final report written by students had to be directed to him. The teacher, as project leader, had to present the final results to the supervisor. To achieve the task, students needed to design one exemplary food product (gluten-free bread based on corn) and to use the attained knowledge to design another product (gluten-free pasta). The students went through two complete design cycles of gluten-free corn bread using additional sources and experiments.

The task in the project was to search for the possibility to design a new class of gluten-free food products. The expectation was that students should see the task as relevant because a substantial number of people suffer from gluten intolerance (expectation i-a; Table 4). The use of a real scientist can be seen as representative of the community of the authentic practice with its own rules, values, motives to act, and methods. By introducing the task by a real scientist, students were expected to develop a share motive to accomplish the task (expectation i-b; Table 4) and to accept the role of a junior food product developer (expectation iii-b; Table 4). The expectation was that students experience the extension of knowledge about the chemistry content (macro-micro thinking using structure-property relations; expectation ii-b; Table 4) and the design process as relevant for using this in the design of another product. The expectation was that students had a motive to bake bread with variable gluten content (expectation ii-b; Table 4) as the first of the elementary steps of the design process cycle: making, testing, evaluating, and improving the food product (expectation ii-a; Table 4). In this way students needed to experience that their input matters (expectation iii-a; Table 4).The adapted expectations for cycle 2 are presented in Table 4.

Table 4 Overview of the detailed expectations of the three strategy components in the orientation phase of the teaching-learning process of cycle 2

Strategy component	Detailed Expectation	
i. Select a *focused* task	(a)	Students accept the task of designing a class of gluten-free food products as realistic and understand that it is necessary to accomplish the task for people with coeliac disease.
	(b)	Students have the opportunity to participate by developing a shared motive to accomplish the task.
ii. Use intuitive notions of students with regard to procedural steps	(a)	Students have a notion about the main steps of the design procedure: exploring the problem, finding solutions, testing, improving design and reporting the findings.
	(b)	Students are able to extend their notions about the procedure with the use of a replacement for gluten and knowledge about baking bread.
iii. Enable productive interaction between participants	(a)	Students experience that they can influence the task and the process to accomplish the task.
	(b)	Students become participants in the community of practice by accepting their role as junior designers of food products.

Evaluation of the strategy components

Strategy component i: Select a focused task

Arguments that students find the given task relevant (expectation i-a) can be based on several data sources. To the question of why they volunteered in the pre-questionnaire four students (S15, S17, S18, S22) answered that the given task to find a recipe for a gluten-free food product was interesting. Two students (S11, S18) mentioned 'designing' and two (S9, S11) mentioned 'gluten intolerance' as the main reason to participate. According to the pre-questionnaire, seven out of fourteen students (S9, S10, S11, S15, S17, S18, S22) participated in the activity out of interest. The expectation about the relevance of task (i-a) was fully achieved because we found no indications of absence of a motive to perform the task. All students performed equally well in terms of this expectation (video recordings).

Expectation i-b about students' development of a shared motive was 'fully' achieved. The goal of the task was clear to students. This became clear at the beginning of the teaching-learning process. After the video in which the senior scientist gave the task to the students, the teacher (T2) started together with the students to summarise the message of the senior scientist. Protocol 1 showed that the students had a clear goal (Lines: 2, 4, 7).

Protocol 1 (video and voice recordings activity 1)

1	T2	*Where does it proceed? Where do we start and why?*
2	S17	*We must search for a good substitute for the gluten.*
3	T2	*Yes*
4	S17	*You must find something that has the same function as gluten, but not that people become ill even if they have no gluten intolerance.*
5	T2	*Yes… which product did it concern again?*
6	S9	*Corn*
7	S11	*Bread based on corn*
8	T2	*Bread?… gluten-free bread. We start with bread. Which products also contain gluten?*

The acceptance of the task was also found in the statements of students during the focus group interview at the end of cycle 2 (S15): *'the task is necessary because there are people who suffer … and not that there is a company which …'*. From the statement like the one of student S13 it could be concluded that the students liked to be challenged when we pointed out that no one has solved the task: '*That has to be said at the beginning. Then it would be much nicer, because you can find something, you have a goal. Maybe you obtain no acceptable results but even big scientists have the same experience*' (S13).

With regard to strategy component i it can be concluded that the task was perceived as relevant by students. The task could be stated more as a challenge *'You will be the first one to achieve this'*. For students at this level it was sufficient to understand why it is a problem and that people in society are working on the same problem (which has already been solved or not).

Strategy component ii: Use intuitive notions of students with regard to procedural steps

The expectation (ii-a) about the intuitive notions of students about the design procedure was 'fully' achieved. Several arguments support this finding. First, in the pre-questionnaire we asked the students: how do you think designers will plan their work? Six students came up with answers close to our expectations (see Table 5).

Table 5 Intuitive notions of students related to the design procedure (first questionnaire in cycle 2)

Student	Statement
S10	*They try as much as possible to design a component that has the properties of a gluten replacement. They try first to replace it or to keep it out of it.*
S11	*They start with setting up a plan and test their products thoroughly. Subsequently they adapt their product.*
S15	*By every time producing their product and investigate the result. The purpose is to find a replacement for gluten.*
S16	*Try as much as possible until the result is acceptable.*
S18	*First examine the ingredients of the product. Which one gives an allergic reaction in people? Finding alternatives for this ingredient which also has an acceptable taste.*
S21	*They try to replace ingredients by other substances. They care for a good taste. Try out a great amount of raw material and test the product.*

From the statements in Table 5 it can be concluded that students had intuitive notions of components of the design process: 'to find solutions' (S10, S18, S21), 'to test' (S10, S11, S15, S16, S21), and 'to improve the design' (S11, S15, S16, S18, S21). These statements were close to our expectation (ii-a: exploring the problem, finding solutions, testing, improving design and reporting the findings; Table 5). Other students cited more economic motives (S9), or did not know (S12, S19) or wrote 'research' (S13), remove gluten (S14), or a judgement about the quality of the product (S9, S20). One student mentioned designing a new protein (S22).

Second, during the first activity, a group discussion (see Appendix B), it became clear that students were able to extend the design procedure with the expected steps (expectation ii-b). At the end of the group discussion the following steps in the plan to design a new food product were described: know more about gluten, tests, literature search, find a replacement, optimise the product, composition of the replacement, and bread baking (field notes, video recordings and students' work). Jointly the following steps of the action plan were written on the blackboard (field notes) and consequently in students' work: producing the product → analysing the product → improvement of the product→ producing the product →…. Additionally: searching information/reflection/investigations. At the points where more knowledge was needed, students suggested ingredients of bread, bread baking process, and the role of gluten in bread.

Although not every student formulated details of the expected steps of the design procedure, four students had ideas about how to accomplish the task. S9 formulated a next step (voice and video recordings): *'To look at what we can choose as a replacement for gluten or how we can make such improved corn bread'*. Later in the discussion S11 and S14 used similar terms (voice recordings): *'what the best replacement is'*. Student S21 wrote after the discussion: *'what must we add to the corn bread?'* (student work). These four students had explicitly mentioned or written down the next step to accomplish their task. Other students started directly after the discussion with a search on the internet for gluten and replacement (field notes and video recordings). Although not every student explicitly explained why they did what they did, all students knew exactly what to do (field notes and video recordings).

From the findings it could be concluded that expectation ii about evoking intuitive notions of procedural steps and the extension of the procedural steps by students was 'fully' achieved.

Strategy component iii: Enable productive interaction

The expectation about the students' feeling, that they have influence on the task and the process required to complete the task (iii-a), is partly achieved. Arguments were provided by two different group discussions (protocol 2 and 3 during activity 1, see Appendix B). In the first discussion (protocol 2) the teacher determined the direction of the discussion too much, although the group had the chance to adapt the project plan and to formulate the steps of action. Students got the opportunity to formulate their plan of action (lines: 1-10, 17, 22). The teacher guided them too much towards baking bread (lines: 16, 18 and 19). At these moments, students' input did matter less.

Protocol 2 (video and voice recordings activity 1, cycle 2)

1	T2	*We return to the agenda. We must make a project plan for this week. Does anyone have an idea about what we will do? What are the parts of the project plan?*
2	S10	*That you know what are the properties of gluten, what they do exactly.*
3	T2	*Yes*
4	S17	*We must nevertheless search for a substitute*
5	T2	*How do we know more about the properties of gluten*
6	S10	*Can we use Internet or must we test …?*
7	T2	*OK we can do both: tests and literature.*
8	S17	*We must search for a substitute therefore you must in fact look for products which do the same as gluten in bread. Therefore you must have a substance which forms dough otherwise it falls apart, resulting in no bread.*
9	T2	*OK other things*

10	S22	*We must see which substitute is the best*
11	T2	*Oh optimise… oh beautiful words… composition… OK … what do we have to do as a team to obtain some experience?*
12	S22	*Research…*
13	S?	*Baking bread* [it is not heard by the teacher]
14	T2	*Research… yes that is, however, well, what implies that?*
15	S22	*That you look up things concerning the subject from several… Internet search…*
16	T2	*And how you obtain practical experience?*
17	S11	*Baking bread*
18	T2	*Yes… who has experience with bread baking?*
		[some students (S3, S11) have been baking bread before]
19	T2	*If you now act as a research team which has to do the work, is it a good idea to start with baking bread?*
20	S17	*That takes time.*
21	T2	*If we make a list, can you say also something that comes first? What will we do now first?* [Teacher starts writing down the list on the blackboard].
22	S9	*Bread baking*

The second discussion (protocol 3) was exemplary for the influence of the students on the task and process. Students extended the original step-by-step plan as presented on the blackboard themselves. In protocol 3 the teacher gave students the freedom to extend their plan of action (lines: 1-7) by guiding the discussion (lines: 1, 6) and adapting her influence to the statements made by students. The whole group of students arrived by themselves at the necessary steps to accomplish the task: finding a substitute for gluten (line 9) and a step to optimise (line 17). In lines 10-19, students formulated a proposal to adapt the plan of action. Students had the possibility to change the plan of action (line 18) and, to influence the choices which had to be made (line 16).

Protocol 3 (video and voice recordings activity 1, cycle 2)

1	T2	*Now, how to go further? What did we analyse? There is something with corn, there must be added something to corn otherwise it will not be successful. The question is: What? Project proposal: which steps do we have to change or add? What is your opinion?*
2	S9	*There is no need to change the project proposal. We have searched now only for information. We must now go on with what is given. We can choose a substitute for gluten. How can we improve corn bread?*
3	S14	*What was that … Xanthan gum?*

4	T2	*Yes, yes should we examine that? And then you will reflect about that later. We go to the next activity: study the source paper with the title: Hydrocolloids as bread improving additives.*
5	S22	*Table 2 and table 3*
6	T2	*Please tell me what is table 3 about?*
7	S22	*Using this table and the knowledge about what is wrong with the corn bread, then you can conclude what you must add to make that better*
8	T2	*OK, table 3 concerns …*
9	S14	*Wheat*
10	T2	*You say that we can learn from adding substances mentioned in table 3 to corn bread… a type of direction which we can look at. Therefore table 3 is a suggestion where we can look at. Is there anything more to look at …?*
11	S9	*Xanthan gum*
12	T2	*Where do you see that?*
13	S11	*In table 1*
14	T2	*Table 1 contains a complete list with possibilities. There it is written that xanthan erases. .. Therefore my proposal is that you will study this article. I suggest that your look at, for example, experiments …, but I do not want to run ahead of you. …*
16	S11	*I do not know what exactly the outcomes of that article are, but we can look at it, to obtain the best result.*
17	S14	*Yes what is the best substitute?*
18	S11	*What the best substitute is, yes. You must choose the best product. Each team a substitute?*
19	T2	*OK* [teacher makes some organisational agreements]

Expectation iii-b, about becoming participants of a community of practice by accepting a role as junior designers of food products, was not achieved. From statements about the setting in the focus group interview at the end of cycle 2 it became clear that it was not necessary to introduce a specific company as a setting. Seven students stated the following, which is representative for the group:

- *'I am not engaged by the company but I have the feeling that I am engaged by something bigger',*
- *'You stay at school. If this was happening in another building …'.*
- *'It feels like ….. it is like something that was done already two years ago'*
- *'It feels like a show' (clearly confirmed by others) 'It is like if it has happened also two years ago'*

- *'The show around it was not necessary'.*

- *'You have no contact with the rest of the company ...'*

- *'If the external scientist had shown his face or had told us what to do, then it would feel less fake'.*

In the same interview, four students mentioned about the adoption of the role of junior employee:

- *'I do not feel like an employee, because it is not addressed to me personally. I have no motive to do this'*

- *'You are at school, you remain a student',*

- *'The atmosphere does not bring me in a situation that we are real researchers'.*

- *'Present this not like: 'you are now an employee', but more like: 'this is what you are going to do'.*

All students understood well, however, why authentic components like a junior profession within a company and a virtual scientist were used in the teaching-learning process. To the question in the focus group interview about the reason why the external person presented the task, students answered: *'to be more motivated', 'to give the feeling that there is a company behind you', 'to point at the fact that the purpose of the task is real',* and *'not as student'.* Another aspect is found in a statement of student S11: *'Now you got the experience about what is going on in such a project team. If you* (to the researcher) *had said "we are going to test new teaching-learning material", then I had got the feeling of sitting at school. Now I had that feeling less'* .Another statement was given by S22: '*I constantly had the feeling that I had to work towards something* (external pressure), *and that seems not to exist'* (student was disappointed).

Expectation iii was partly achieved. Productive interaction between the participants was enabled, although the students did not adopt a role as junior designers. Students' statements lead to the conclusion that the setting must not be designed as a play, but should be more realistic and as simple as possible in a challenging way. However, they experienced that the setting is real, e.g., they experienced that they did a project, and that there was a company behind it or the purpose was real.

Summarising the evaluation and reflections on cycle 2: students found the task realistic (strategy component i), although the setting of the task was situated at school and not within a fictive company as intended. There were no indications that it was perceived by students as an unrealistic, irrelevant and unrecognisable problem. We concluded from the findings of the second cycle that a motive to design a new food product was evoked in students, which is conditionally for learning macro-micro thinking.

The main steps of the design procedure (strategy component ii), based on intuitive notions of students, could be evoked, together with the step about the replacement of gluten. The expectation about the use of intuitive notions of procedural steps was fully achieved.

Through discussions about 'what to do' and 'how to do', students got the opportunity to influence the task and strategy (strategy component iii). This is an additional component of their intrinsic motivation to accomplish the task. However, students did not accept the role of employee or junior product designer, because the role gives no extras to accomplish the task. According to students, the fictive company had to be introduced more realistically or left out of the teaching-learning process. It did not influence the motive of students for the task and was not necessary to introduce the problem. For students it was sufficient that there was a problem and why it was a problem.

It was important that the students had the opportunity to work together at the task, divide the experiments, and share their knowledge and results. Participation means that students and teacher have to interact orally, to work together and share strategies, experiences and information. As a result of working collaboratively they adopted their role. According to the students the setting in which they are placed was still at school and stayed at school in spite of the introduction of the fictive company.

Conclusion and discussion

The research questions were:

1) To what extent does the elaboration of the strategy components lead to the intended effect: the establishment of a context as a condition to make the students' learning relevant?

2) What is the empirically underpinned context-principle?

For answering the first research question, we conclude that the elaboration of the strategy components in cycle 2 to large extent realised the condition to make learning relevant for students with respect to the learning of macro-micro thinking at the start of the teaching-learning process (Table 6). The designed teaching-learning process did indeed address Gilbert's first criterion: the setting was valued by students as a social framework for a community of practice. In terms of activity theory, the setting provided also appeared to be in the zone of proximal development of the student (Vygotsky, 1978). A clearly focused task which is realistic for students appeared to be necessary. This focused task established a behavioural environment in which students intuitively know which steps they have to execute to accomplish the task. The built-in influence of students on the task and process by working and talking together led partly to the intended effect: enabling productive interaction. In both design cycles, the teacher still determined the direction of teaching process too much. The use of a fictive company represented by an external scientist and a fictive role of students were not necessary to enable productive interaction between the members of the community (students and teacher). The development and results of each of the strategy components are presented in Table 6.

Table 6 Comparison and development of the strategy component over two design cycles

Strategy component		Achieved within cycle 1	Achieved within cycle 2	Comments
i. Select a (focused) task	1a: realistic task	Fully	Fully	This strategy component is strong enough, because the chosen socio-scientific issue was close to the students' daily life and perceived as relevant. During the second cycle, a refinement of this strategy component took place by adding the term 'focused'.
	1b: formulation by students	Partly	Fully	
ii. Use intuitive notions of students with regard to procedural steps	2a: intuitive notions of the procedure	Partly	Fully	In the second cycle the clearly focused task of designing a class of food products gave the students a clearer view of where they have to focus for the purpose of their task. This led to a formulation of a plan of action as expected.
	2b: extension of their intuitive notions of procedure	Partly	Fully	
iii. Enable productive interaction between participants	3a: influence on task and process	Partly	Partly	The influence of students was sufficient for them to experience that their input matters. The design of the teaching-learning process focused too much on the role of students as junior employees of a fictive company, which was not necessary to evoke a broad motive.
	3b: role of junior employees	Not	Not	

To answer the second research question with regard to the empirically underpinned design principle, we have used three strategy components to obtain this result in cycle 2:

(i) Select a *focused* task,

(ii) Use intuitive notions of students with regard to procedural steps, and

(iii) Enable productive interaction between participants.

This led to the establishment of the context-principle as after cycle 2:

> **If** students as participants of a community of practice within the classroom are provided with a focused practice-related task (strategy component i) **and** have their own plan of action based on intuitive notions (strategy component ii) **and** productive interaction is enabled (strategy component iii), **then** a context is established at the start of the teaching-learning process as a condition to make the learning of chemical concepts relevant to students (intended pedagogical effect).

Although the formulation of the design principle was hardly changed during both cycles, the elaboration of strategy component i, select a *focused* task, led to major changes in the concrete teaching-learning process. Consequently, the expectations as concrete descriptions of the intended pedagogical effect also changed in an argued way. The major (new) argument we developed during this design research concerned the precise focus of a (learning) task for students. The start of a teaching-learning process needs to pinpoint what precisely is the behavioural environment (Gilbert, 2006) in which students address their task. Then this behavioural environment sets the frame for the procedural steps to take, and what roles the participants of the (learning) community have to take. This illustrates that both the design principle and the elaboration into the teaching-learning process are outcomes of this design-based research approach (cf. McKenney et al., 2006).

As an additional argument we developed in this study, the explicit use of a fictive company. This appeared to be not essential to evoke an intended motive in students. This conclusion may be in contradiction with Witteck, Most, Kienast & Eilks (2007). In that study, students experienced as positive to learn in a constructed learning company, a constructed classroom structure analogous to existing or 'ideal' companies. However, the role identification itself and the effect of constructed-classroom structure analogous to existing companies were not explicitly evaluated in that study. The observed high positive attitude of students towards the classroom activities (Witteck et al., 2007) may be caused only by the freedom the students experienced when they followed their own ideas and interests and learning pathways. When compared to our study, in the designed and enacted setting not only motives and interests of students were important, but students experienced that it was more than a traditional school setting. Their discourse was framed by the given socio-scientific task. According to Sadler (2009) this is the surplus value of a community of practice as a context.

Some remarks are necessary about the limitations of the general conclusions in this study in relation to the establishment of a context for learning chemistry concepts. First, the presented findings were obtained in research settings with small groups, two experienced teachers with interest in new curriculum developments and in a special class situation at one school. We chose an explorative setting to investigate the potential of this design principle for chemistry education, because at the start of this study there were too many unknown variables with regard to the establishment of a context, the sequence of teaching-learning activities and the intended way of macro-micro thinking with structure-property relations. The progression of students' learning with regard to macro-micro thinking is to be described elsewhere (Chapter 2 and 5; Meijer et al., 2009). Second, a design principle is heuristic in nature. This means that in each and every case the elaboration of the argued strategy components within a teaching-learning process in new circumstances remains to some extent hypothetical and again needs some testing, which will lead to a further validation of the design principles in other situations (cf. Prins, 2010). This way of empirically underpinning of design principles could lead to a generalization of the design principles. The value of the empirically underpinned context-principle derived in this study could thus be improved by further use in other design studies with a similar procedure for analysis (Plomp, 2009).

This study presents a design principle and strategy components based on theoretical and empirical arguments to design a context at the start of a teaching-learning process to make the learning of macro-micro thinking relevant for students by the adaptation of an authentic practice. In our study, it proved to be a challenge to find a fine-tuned balance between a real authentic practice as a context and an adapted practice as a context for learning within the school setting. On the one hand, students can experience the process of acting like chemistry professionals in a realistic setting, making their learning personally relevant. In this way, students have a good opportunity to explore the scientific profession as an option for further education (Hofstein & Kesner, 2006) or to become scientifically literate (Millar, 2006). On the other hand, students perceived that 'school remains school' and such a setting remains a setting for institutionalised learning. In our study, the balance has shifted from a traditional school setting towards a setting in which students were engaged to participate in a community of practice. Students experienced to be empowered to accomplish the practice-related task (Freymier & Schulman, 1994; Vygotsky, 1978). In this way, students can become engaged in science related to social issues and this, consequently, raises the relevance of learning chemical concepts (Sadler, 2009).

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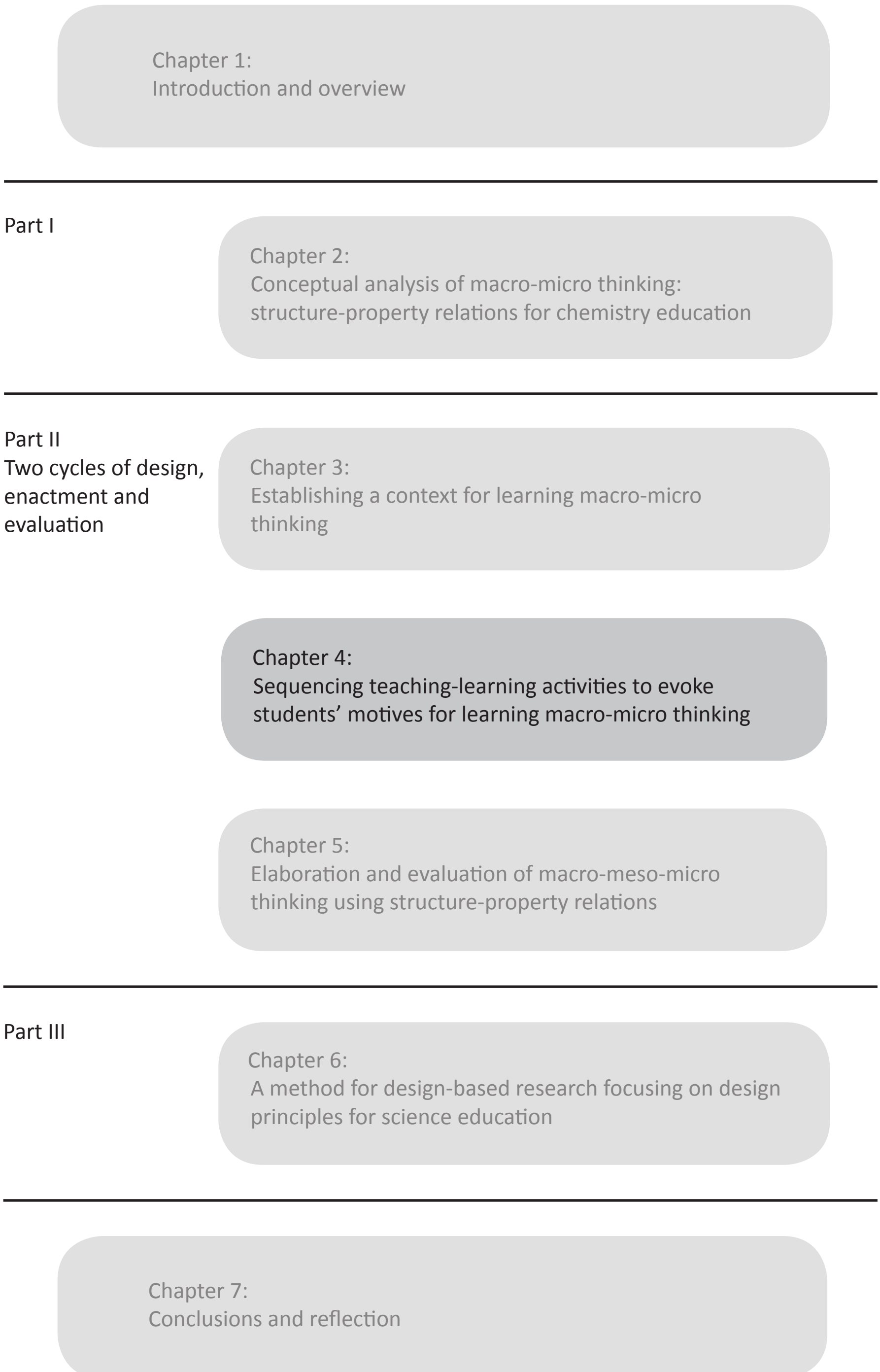
Appendix A The activities in the orientation phase in cycle 1

Phase	Number	Teaching-learning activity
Orientation	1	Given the notes of a senior food developer of food products, students are confronted with the problem of people with coeliac disease.
	2	Students become employees of a (virtual) food production company. Based on given information students have to write a proposal as an internal memo. This proposal contains a primary idea for a solution of the problem: the development of a gluten-free food product.
	3	In the light of additional information, students choose corn to replace wheat, and select bread as exemplary food product.
	4	Students have to write a plan how to develop a gluten-free corn bread.
Definition of the task	5	A guiding experiment is proposed in which three different loaves of bread are baked: 100% of wheat, 100% of corn and half wheat/ half corn. In this experiment, students relate the gluten content to the quality of the bread. This results in the conclusion that a replacement for gluten is necessary for corn dough to yield at least the same quality. Students write a more detailed project plan to develop a gluten-free corn bread.
	6	Focusing the problem on two steps of the baking process: ‘mixing’ and ‘rising’ are essential for this project. The expectation is that students will realise that they need to know more about the properties of gluten to choose a suitable replacement to be added to corn.

Appendix B The activities in the orientation phase in cycle 2

Phase	Number	Teaching-learning activity
Orientation	1	In a video-tape, a senior scientist introduces a problem with respect to food products containing gluten and formulates the task in this project. This leads to a discussion between teacher and students about the adaptation of the project proposal and the procedure how to proceed. Students formulate their intuitive notions about a design procedure. They bake loaves of corn bread. For a reference base, they bake several loaves of bread with a variable ratio of corn to wheat.
Definition of the task	2	In the light of this experiment, students relate the gluten content to the quality of bread. They conclude that a replacement for gluten to add to corn dough is necessary to obtain at least the same quality.
	3	During a group discussion, students adapt the project proposal for designing bread without gluten. For this, they need more knowledge about additives that can be used as replacements for gluten to improve the quality of bread.



Chapter 1:
Introduction and overview
Part I
Chapter 2:
Conceptual analysis of macro-micro thinking:
structure-property relations for chemistry education
Part II
Two cycles of design, enactment and evaluation
Chapter 3:
Establishing a context for learning macro-micro thinking
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Sequencing teaching-learning activities to evoke students' motives for learning macro-micro thinking
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Chapter 4

Sequencing teaching-learning activities to evoke students' motives for learning macro-micro thinking for pre-university chemistry education

Abstract

Students generally find that their learning of chemistry concepts is not regulated by their own motives. To address this problem, we formulated an initial principle for the design of a sequence of teaching-learning activities for learning macro-micro thinking in which students can experience why they have to perform the activities during the entire teaching-learning process. Using arguments from the literature, two initial strategy components of the design principle were formulated to design a sequence of teaching-learning activities in which students experience each of the activities as relevant within its sequence: i. use a procedure adapted from an authentic practice and ii. sequence students' motives. A design-based research approach was applied to design, enact and evaluate the teaching-learning process. The results of two cycles of design are presented in which the teaching-learning process in each cycle was evaluated with a detailed set of expectations as concrete descriptions of the intended effect. With respect to component i, we conclude that the chosen procedure needs to be consistent with the learning goal; then students' intuitive notions with regard to the procedure could be evoked and applied productively. The sequencing of motives (strategy component ii) was less successfully elaborated because of differences between the goal of the task and the learning, and teacher interference. There is a mutual influence between both strategy components. We present a refinement of the principle for designing a teaching-learning sequence in which each of the activities is relevant from the perspective of the student. Furthermore, we conclude that the issue of transfer needs attention.

Introduction

In secondary chemistry education students often do not experience the relevance to learn certain chemical concepts. For example, in the case of macro-micro thinking, students do not find that their learning about atoms and molecules is regulated by their own motives to know more about their experiences of the macro world (Tretter, Jones, Andre, Negishi & Minogue, 2006; Kozma, Chin, Russell & Marx, 2000; Wiser & Smith, 2008). Context-based approaches should connect the learning of science closer to the students' own motives of knowing about their lives and interests (Bennett & Holman, 2002; Bulte, Westbroek, De Jong & Pilot, 2006), for example, by referring to social or technological implications within society (Roberts, 1988; Hofstein & Kesner, 2006, Parchmann et al., 2006).

It is not obvious, however, to design context-based education in such a way that students indeed experience a sequence of motives that guide them from an initial interest in a context to activities that involve their learning of the intended concepts (Parchmann et al., 2006; Westbroek, Klaassen, Bulte & Pilot, 2010). For the establishment of a context, we have used Gilbert's criteria (Gilbert, 2006). A model for context-based education set around a focal event, together with cultural justifications, and taught with a socio-cultural perspective on learning is likely to meet most fully the challenges of making chemical education relevant and the transfer of chemical concepts. Following Van Oers (1998), we adopted the setting of an authentic practice as a theoretical perspective. The selected context is then modelled on a related authentic practice in which experts in the field of science and technology address a (socio-) scientific and/or technological issue (Bulte et al., 2006; Meijer, Bulte & Pilot, 2009). We have shown in another study (Chapter 3; Meijer et al., 2009) that such a context appeared to be relevant for students in pre-university education. The designed teaching-learning process did indeed address Gilbert's first criterion: the setting was valued by students as a social framework for a community of practice. In terms of activity theory, the setting provided lies in the zone of proximal development of the student (Vygotsky, 1978).

To proceed the students' learning process regulated by the students' own motives, this study is to understand and to formulate a design principle as a heuristic guideline for the design of an on-going connection between the initial establishment of a setting and every following teaching-learning activity. During the whole teaching-learning process students should experience a motive to proceed from one activity to the next (Lijnse & Klaassen, 2004; Boekaerts, De Koning & Vedder, 2006; Pintrich, 2003). An important issue in this sequence of activities in which an authentic practice is used as a context is the incorporation of two strategy components: i) use procedures that exist in the related authentic practice and ii) address the anticipated students' motives into the design of a teaching-learning process. However, heuristic 'guidelines' for designers of science education are either not available (Van Oers, 1998) or exist only as a proof of principle (Westbroek et al., 2010).

Therefore, this chapter has a twofold focus: 1) formulation and elaboration of argued strategy components for designing a sequence of anticipated students' motives for learning and, 2) the understanding, formulation and the development of a design principle to empirically establish such a sequence. In this chapter we present both foci for the case of macro-micro thinking (Meijer, Bulte & Pilot, 2009). The actual understanding of the conceptual knowledge is beyond the scope of this chapter. This issue is described elsewhere (Chapter 5; Meijer et al., 2009). We apply a design-based research method (cf. Van den Akker, Gravemeijer, McKenney & Nieveen, 2006; Chapter 6), in which we design, enact, evaluate and redesign the teaching-learning process. In this way, the sequence-principle is developed with an empirical basis.

Theoretical background

We adopted the perspective of an authentic social practice as a context (Gilbert, 2006; Van Oers, 1998). The dynamics of the activities of an authentic social practice is founded on the complex interrelationships of the practice's motives, goals, means, actions and operations as negotiated among the members of a community. When students have identified in which community they are going to participate, it becomes clear what they have to do to address the typical tasks in such a community (Van Oers, 1998). As a consequence, when a chosen task lies within the students' zone of proximal development, a plan of subsequent actions or a series of procedural steps to address such tasks can be intuitively evoked (Van Oers, 1998).

Therefore, it is essential to design a teaching-learning sequence in which the intuitive notions with respect to the procedural steps are evoked in students directly after the introduction of the practice-related (learning) task. Such procedural steps can be adapted from existing procedures of related authentic social practices of professionals (Westbroek et al., 2010). The selection of a suitable authentic practice to be adapted to a social practice for learning should evoke the intuitive notions of the procedure in students. Consequently, during the teaching-learning process, these intuitive notions can be extended to a complete procedure when transferring their learning by addressing similar practice-related tasks at the end of the teaching-learning process. Then students can be expected to recognise from their own experience that such a procedure is used by others, e.g. scientific researchers or designers. In this way, students can attain knowledge how to accomplish similar tasks in the future (Millar & Osborn, 1998; Lewis, 2006).

Although students may have an initial intention to perform a given task, this intention requires both beliefs and desires during the entire teaching-learning process. At any time during the process of teaching-learning students should be able to see how and why they perform a particular teaching-learning activity to achieve the overall goal of the task (Lijnse & Klaassen, 2004). Therefore, besides the use of an existing (authentic) procedure, a leading thread or a series of motives is needed to guide students effectively through the entire teaching-learning process (Davidson, 1987; Pintrich, 2003). For the further detailed fine-tuning of the teaching-learning process, Galperin's cycle is used: a reflection on an action provides an orientation for the next action (Arievitch & Haenen, 2005). This means that during the orientation for a next action, students have to understand and accept the motivational and cognitive value of the knowledge to be acquired (p.160), and as a result should be able and willing to perform their actions in a next teaching-learning activity.

For the purpose of designing a teaching-learning sequence in which students experience a series of motives to proceed from one activity to the next, we formulate two strategy components:

i. Use a procedure, originating from the related authentic practice that should result in a sequence of teaching-learning activities which is built on intuitive notions of students about this procedure.

ii. Sequence anticipated students' motives in which the reflection on one teaching-learning activity provides the orientation for the next activity, to be designed from the perspective of students. Thus, students experience a motive to proceed from one activity to the next during the entire teaching-learning process.

These strategy components must be elaborated within a teaching-learning process. Therefore, the elaboration of these argued strategy components to reach the intended pedagogical effect will give the opportunity to formulate a heuristic guideline in the form of a design principle.

Figure 1 represents the formulation of the initial design principle for sequencing teaching-learning activities. A design principle (Figure 1) consists of one or more strategy components based on arguments, leading to an intended *effect* (Edelson, 2001; Hofstein & Kesner, 2006; McKenney, Nieveen & Van den Akker, 2006). Strategy components are potential strategies to achieve certain intended pedagogical effects. As described above, the selection of strategy components is underpinned by arguments based on theory from the literature (T), experimental evidence from earlier design cycles (E), and the practical experience of the designers (P). A design principle can be considered as part of the obtained knowledge claim from a design-based research approach (McKenney et al., 2006).Such design principles have a heuristic value (Pintrich, 2003) and can be used as heuristic guidelines for the instructional designer (Gravemeijer & Cobb, 2006),, with a limited validity when it is embedded within a certain educational situation: students, teachers, chosen contexts, etc.

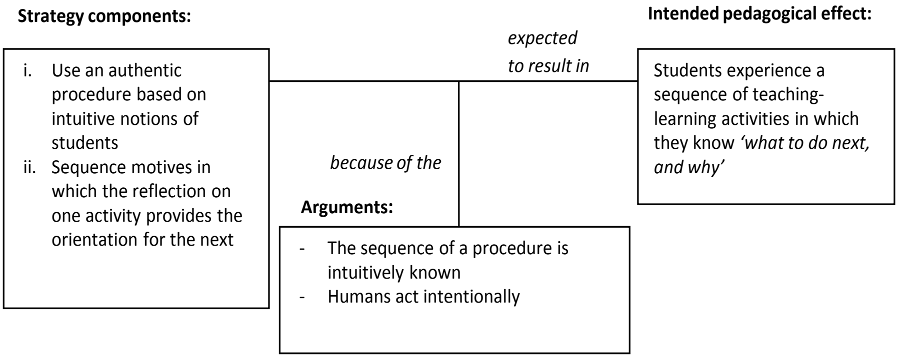

Figure 1 Representation of the sequence-principle used in this study

We position this study in the case of macro-micro thinking in chemistry. Several authentic practices are available in which macro-micro thinking is an essential activity (cf. Chapter 2). In line with the expected interests of students and the practical aspects of school facilities, the chosen practice as context is embedded in the societal need for gluten-free food products because of the increasing number of people with coeliac disease. The students' learning task is taken from a corresponding authentic practice in which professionals develop gluten-free food products for people with gluten intolerance. These professionals improve the specific properties of such food products to answer the needs of consumers. In these activities they apply the concepts of macro-micro thinking whilst using structure-property relations (Sadler, 2009; Chapter 3). In food products, wheat, and so gluten, is often used. Corn, that does not contain gluten, may be used as an alternative for wheat. For professionals, the addressing of this issue is not straight-forward. Even in scientific literature there is no unambiguous solution to the problem of developing gluten-free food products. We adapted this authentic practice, with consumer needs as the social issue, and established a context in which students could see the relevance of developing a food product (Chapter 3). Students were given the task of developing one gluten-free product, bread, as an exemplary food product. Dough usually has to have elastic properties during fermentation, because it needs to capture the released gas (CO_2).

For this case, the use of these two strategy components leads to the following initial sequence-principle:

> ***If*** *a procedure is used which is built on intuitive notions of students (strategy component i),* ***and*** *motives are sequenced in such a way that the reflection on one teaching-learning activity provides the orientation for the next (strategy component ii),* ***then*** *students experience a sequence of teaching-learning activities in which they know 'what to do next, and why' (intended pedagogic effect).*

In this chapter, the presented sequence-principle focuses on the *sequence* of teaching-learning activities. To design a teaching-learning process to achieve the intended effect that students experience why what to do next, explicit instructional and scaffolding strategies are needed for using authentic learning tasks in which scientific reasoning is important (Chinn & Malhotra, 2004; Van Meriënboer, Kirschner & Kester, 2006). Within the whole teaching-learning process our intention is that students and teacher should continuously work and discuss as a community. The designed teaching-learning activities should provide a setting for discourse, because consensus of meanings of concepts is more easily reached by oral interactions between the participants (Vygotsky, 1978; Kelly, 2007). It does not specify the specific chemical concepts, symbols, visualisations and representations related to macro-micro thinking with structure-property relations. These details are described elsewhere (Chapter 5; Meijer et al., 2009).

The present study addresses the following research questions:

1) *To what extent does the elaboration of the strategy components lead to the intended effect: that students know 'what to do next, and why' when learning about macro-micro thinking using structure-property relations?*

2) *What is the formulation of an empirically underpinned sequence-principle?*

Method

Research approach

The research approach includes the elaboration of the strategy components of the sequence-principle into the design of the teaching-learning process, its classroom enactment, and subsequently the analysis of the enacted teaching-learning activities. This research is informed by design-based research approach with an empirically established design principle and the evidence-based understanding of the framework with learning phases as the twofold knowledge claim (cf. Van den Akker, Gravemeijer, McKenney & Nieveen, 2006; McKenney et al., 2006; Chapter 6) for which details and procedures are described in chapter 6 of this thesis. In the method we apply, the enacted teaching-learning process is compared with the designed teaching-learning process on the basis of specified expectations about the way each of the teaching-learning activities should function (Lijnse & Klaassen, 2004). The expectations are concrete descriptions of the intended pedagogical effect which is described in the design principle. Expectations can refer to written or oral answers, or to actions of students. The arguments for the design principle and the expectations should be based on the literature (T), empirical evidence from previous studies (E) and practical experiences (P) of the members of the design team (Figure 1). The evaluation of the teaching-learning process may give rise to a redesigned version of a teaching-learning process, and if necessary to the adaptation or refinement of the strategy components in the design principle including the arguments. In this chapter we describe two design cycles. The first cycle is focused on the verification of the initial design principle, especially the strategic components and the arguments. The second cycle should lead to a further understanding of the theoretical arguments and the establishment of the design principle with an empirical basis.

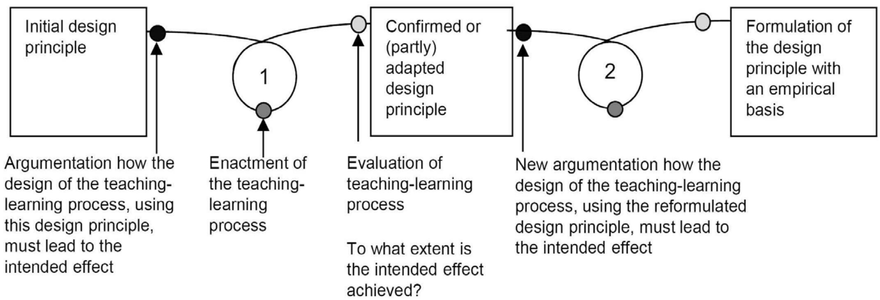

Figure 2 The development of a design principle within two cycles of design and evaluation of a teaching-learning process

Data collection and analysis

For the two cycles, the strategy components were elaborated into a teaching-learning process (Appendix A and B respectively). Connected to each of the strategy components, the intended effects for each cycle were described as concrete detailed expectations embedded within the teaching-learning process (see further for each cycle the Tables 2 and 6). These concrete expectations which embody the described intended effect of the design principle (Figure 1) were connected with the function of a teaching-learning activity (see Appendix A and B).

Data collection took place by multiple data sources.

A. Video and voice recordings were taken during enactment of teaching-learning process.

B. The first author took field notes during classroom observations.

C. Student questionnaires were administered before (pre questionnaires), during and after enactment (post questionnaires). The questionnaires during enactment were especially designed to verify after each of the separate learning phases (Appendix A and B) whether the students experience a motive to proceed from one activity to the next. Questions in these students' questionnaires were: a) How do you judge each teaching-learning activity on a five-point Likert scale, and provide an argumentation for your judgement; b) How do you judge this teaching-learning process with regard to difficulty, personal interest and information; and c) Can you formulate the purpose of this teaching-learning process and describe an outlook to the next teaching-learning activities?

D. Copies of student' work in terms of worksheets and reports were collected.

E. At the end of cycle 1, students were individually interviewed. A focus group interview is held at the end of cycle 2. As a preparation of that group interview, students filled in a short questionnaire about their role, about the experienced relevance of the community of practice, and the advantages and disadvantages of this type of education. These questions were to guide the focus group interview. The teacher interview was held after each teaching-learning phase. The purpose of the interview was to reflect on the previous phase and to prepare for the next one.

Analysis and interpretation of the data sources were performed according to the following procedure (Bulte, Westbroek, De Jong & Pilot, 2006).

- Fragments of video and voice recordings in relation to the formulated expectations were selected and transcribed verbatim when necessary (data source A). These fragments in combination with the related field notes (data source B) were used to analyse whether the elaboration of the strategy components into the teaching-leaning process proceeded according to the formulated expectations (cf. the Table 2 and 6 in the next sections). In this analysis, the discourse of the whole group of students and their teacher was the unit of analysis. The number of students who acted as intended was counted to determine their active involvement during classroom discussions.

- Additionally, to analyse whether each of the formulated expectations was achieved (Tables 1 and 4), at least two of the five data sources (A - E) were used.

This analysis resulted in a 'thick description' of the enactment (prepared by the first author, MM) with respect to each of the formulated expectations and was judged on a three-point scale ('not' – 'partly' –'fully'). We used the criterion 'fully' when 80 per cent of the students acted according to at least 80 per cent of the expectations (Juran, 1974). If none, one or two of the students acted according to the intended expectations, we used the term 'not achieved'. The term 'partly' refers to outcomes in between 'not achieved' and 'fully achieved'. This is considered sufficient for the purposes of this study.

The judgment on a three-point scale was performed by two researchers independently (first cycle: first and second author; second cycle: first and third author). We regarded 80% as lower limit for a substantial level of agreement (inter rater reliability; Miles and Huberman, 1994, p.64; Prins et al., 2009).The first qualitative judgement of the whole set of expectations was discussed among the two researchers until they had reached consensus about the findings. Subsequently, the whole set of 'thick descriptions' was discussed in the entire research team in a peer review process (all authors). We used three validation strategies: triangulation of data sources (see above A-E) for providing detailed thick descriptions, independent analysis of data by two raters and a peer review process, thus meeting the criteria required for a valid study (Creswell, 2009, p. 209).

Enactment of the teaching-learning process

In the first cycle, the enactment of the teaching-learning process took place during eight afternoons (two or three hours each) during the period February to March 2006. The second cycle was enacted within one week in July 2007 (25 hours in total). In both cycles the adapted authentic practice used as a context in the teaching-learning process was: the development of gluten-free bread based on corn for people with coeliac disease (Chapter 2; Meijer et al., 2009).

Participants

All students, from pre-university education, were recruited from one school in an urban area in the Netherlands. As volunteers they had positively responded to a letter distributed in their school. All these students within cycle 1 (numbered S1 to S8; average age ≈ 17.6 y) had chosen at least two of the subjects out of mathematics, physics and chemistry for their final exam. All students had gained marks between six and seven (on a scale from 1 to 10) for the science subjects (average = 7.0). The fourteen voluntary students of cycle 2 (numbered S9 to S22; average age ≈ 17.2 y) had gained marks for their science subjects between five and nine (average 6.7). The students in both cycles can be regarded as average students. By participating in this project, students gained a mark for their practical exam.

The teacher within cycle 1 (T1) has taught chemistry for seven years at all secondary school levels. T1 has been involved in the development of science education at secondary school. Furthermore, T1 participated in a developmental group of chemistry teachers who are designing, enacting and evaluating programmes for a new chemistry curriculum. The preparation of T1 was performed by conversations with the first author about the purpose, the content and pedagogy before and after each of the afternoons. The teacher in cycle 2 is the second author of this chapter (T2) and therefore well prepared with the content and pedagogy of the teaching-learning process. She had five years' experience as a chemistry teacher in secondary education and as an assistant professor she has been actively involved in curriculum development for chemistry education in secondary school.

The results of our design study are presented as follows (see also Figure 2). For each cycle we describe the following.

- 'The sequence-principle in the teaching-learning process'. This section describes the arguments (Figure 1) for the choices made in the design of the teaching-learning process.

- 'The elaboration of the two strategy components' (Figure 1): i. use an authentic procedure, and ii. Sequence students' motives. This section describes how these strategy components were elaborated into a sequence of teaching-learning activities. Connected to each of the strategy components, the detailed expectations were formulated. Together these expectations form the concretised intended effect (Figure 1).

- 'The evaluation of the strategy components' that were elaborated into the designed teaching-learning process, leading to reflection on the design principle.

- A reflection on the sequence-principle for the next cycle including new arguments, and so on.

Cycle 1: design, enactment and evaluation

The design principle in the teaching-learning process

First, a description of choices and arguments is presented, followed by a detailed elaboration of the strategy components: (i) Use a procedure and (ii) Sequence anticipated students' motives. These are described below with expectations as concrete descriptions of the intended pedagogical effects.

Strategy component i: Use a procedure which is built on intuitive notions of students

A general procedure for designing new food products within a corresponding authentic practice is as follows: a developer of (food) products starts by exploring the problem, subsequently finding an explanation for this problem, followed by the purposeful design and evaluation of the product in several cycles.

Within the designed teaching-learning process for students, the procedure differs from the typical procedure of the authentic practice. In relation to procedural steps of the related authentic practice (Chapter 2), we used six learning phases in the design of the teaching-learning sequence in cycle 1, based on Lijnse & Klaassen (2004): I. orientation, II. task definition, III. extension of knowledge, IV. applying the obtained knowledge, V. transfer and VI. reflection (Appendix A). The first two learning phases and the last two differ from the procedural steps experts in the corresponding authentic practice would apply. The starting phases I and II in a learning situation for students take longer than the exploration an expert would carry out within the related authentic practice. Experts do not need an extensive orientation on the issue of gluten in relation to the quality of the food product, because they are already familiar with this field. Besides, these experts already have a broad experience with procedures how to address such a task. Additionally, in the learning phases V and VI the students explicitly need to reflect on the procedure in a meta-cognitive way. This is different compared to the authentic practice, since professionals do not explicitly focus on the *learning* of procedural and conceptual knowledge, as is valid in a learning situation for students.

The argument for the designed sequence of the procedural steps with the six learning phases is as follows. In the learning phases III and IV, students should use their intuitive notion that properties of a material are related to micro structures within that material (Harré & Madden, 1975). Therefore, in the designed activities of phase III, students have to 'descend' from macro via meso to micro to find an explanation which is sufficient for careful selection of the necessary structures: Hydrogen-bridges, Sulphur-bridges and entwined molecular chains. This is followed by the selection of hydrocolloids with similar structures for the development of a new food product with the same properties of gluten, in order to develop a new food product in phase IV. In this phase, students ascend from micro via meso to macro.

In summary, the following procedural steps to develop food products can be related to the learning phases of the teaching-learning process (Table 1):

Table 1 Procedural steps related to the learning phases in cycle 1

Procedural steps (from authentic procedure)	Learning phase
Exploring the problem	I. Orientation II. Definition of the task
Finding an explanation	III. Extension of knowledge
Designing	IV. Using the obtained knowledge
Evaluating	V. Transfer VI. Reflection

Strategy component ii: Sequence motives

All teaching-learning activities are framed by the task which is to develop a gluten-free food product. Therefore the purpose of each of the teaching-learning activities is related to the overall task, and cannot be achieved without each of the teaching-learning activities. For sequencing the anticipated students' motives, the detailed alignment of all teaching-learning activities must be such that students experience a motive to proceed from one activity to the next for all learning phases. A part of the sequence of teaching-learning activities of cycle 1 is presented next as an example to illustrate the elaboration of this strategy component. A detailed description of the sequence of teaching-learning activities is presented in Appendix A.

An example of teaching-learning activities is as follows. In activity 5 (appendix A), students have concluded that the presence of gluten in bread is essential for the quality of bread. This should provide students with a motive to know more about the process of baking bread (activity 6). As a result of this activity, students identify the processes 'mixing of ingredients' and 'rising of the dough' as essential steps. This conclusion should lead to a motive to know more about the properties of gluten during the rising of the bread, which then is investigated in activity 7 for dough prepared from wheat and for dough prepared from corn with different content of additives. This experiment leads to conclusions about the quality of dough in relation to gluten content, and provides students with a motive to know more precisely what (meso) structures within the dough may be responsible for the property of the dough. The students are provided with an (adapted) authentic article about the elasticity of dough in relation to the rising of dough (activity 8). By using this information, the students can formulate hypotheses about the elasticity of dough in relation to gluten content in wheat dough, and in relation to corn dough containing certain additives as gluten replacers.

The sequence of the activities 5, 6, 7 and 8 is essential when the teaching-learning process is to be regulated by the students' own motives. For example, if we did not include activity 7, there would not be a motive to know more about the (meso) structures within the dough, and consequently the search for additives as replacers in corn dough would rely on trial and error experiments, without further knowledge about meso level structures in the food.

Elaboration of the strategy components

Both strategy components i: use a procedure based on intuitive notions of students and ii: sequence motives) are integrated into the designed phases of the teaching-learning process. For each phase the specific expectations are presented below and summarised in Table 2.

In phase I, we expected that students formulate notions about the necessary steps of the procedure: exploring the problem, finding an explanation, designing and evaluating, and that they would accept bread as a recognizable exemplary food product and use corn as a replacement for wheat (I-i). Furthermore, we expected that students would recognise the social importance of designing gluten-free food products, because this problem lies within their interest and is related to their daily life (I-ii). As a consequence, they were expected to formulate a proposal for a project based on given information sources.

Phase II started with baking bread with different wheat content. We expected that students would want to study only the first and second stages in the baking process. From the results of the baking experiment we expected that students wanted to know more about gluten to be able to argue for the selection of a particular replacement for gluten (II-i). Furthermore, we expected students to be able to formulate the problem: corn bread without gluten has low quality so an additive that replaces gluten in corn dough is necessary (II-ii).

In phase III, students were expected to gradually wanting to extend their knowledge of the molecular structure of gluten (III-ii), using the texts which were translated and modified versions of authentic research articles. It was expected that students wanted to take the step of 'finding an explanation' as necessary to design a gluten-free food product (III-i):

- to perform experiments to understand the rising of bread
- to know more about structure of the gluten network and the molecular structure of gluten.

Table 2 Overview of the detailed expectations of the two strategy components, the procedure based on intuitive notions of students and sequence motives within design cycle 1

Teaching-learning phase		Strategy component	Detailed expectation
I	Orientation	i. Procedure which is built on intuitive notions of students	Students mention the four steps of the procedure: exploring the problem, finding an explanation, designing, evaluating. Students zoom in from a range of food products to one example: bread.
		ii. Sequence motives	Students recognise the social need to develop a new food product and consequently formulate a project plan to accomplish the task.
II	Definition of the task	i. Procedure which is built on intuitive notions of students	Students intuitively know the plan of action to accomplish the task, that is, to focus on the first two stages of the baking process.
		ii. Sequence motives	Students have a motive to formulate the key aspects of the task: corn bread without gluten has low quality; an additive is necessary.
III	Extension of knowledge	i. Procedure which is built on intuitive notions of students	Students want to take the step of 'finding an explanation' as necessary to design a gluten-free food product: - to perform experiments to understand the rising of bread - to know about the molecular structure of gluten.
		ii. Sequence motives	For each activity, students have a motive to extend their knowledge about bread baking and micro structures within the bread.
IV	Application of knowledge	i. Procedure which is built on intuitive notions of students	Students experience that the step 'designing' is an application of their extended knowledge: based on this knowledge they select a replacement for gluten and evaluate the findings of their test.
		ii. Sequence motives	For each activity, students have a motive to apply their knowledge acquired in phase III to select a substitute within the development process.

V	Transfer	i.	Procedure which is built on intuitive notions of students	Students have the notion that the procedure can be used in other situations.
		ii.	Sequence motives	Students have a motive to use their knowledge, acquired during the step 'designing', in other situations.
VI	Reflection	i.	Procedure which is built on intuitive notions of students	Students write a report as an evaluation which is useful for further investigations.
		ii.	Sequence motives	Students have a motive to reflect on the procedural steps while they write their report.

In phase IV, students were expected to experience that the step 'designing' is an application of their extended knowledge: based on this knowledge they select a replacement for gluten (IV-i). They derive criteria for selecting hydrocolloids as replacements for gluten. Depending on their choice, corn bread with different hydrocolloids or variable content of hydrocolloids should be baked, tested and evaluated (IV-ii). Students should explain the obtained results and propose a new way to obtain corn bread of good quality.

The educational purpose of phase V was to evoke a motive for the planning of the development of another gluten-free food product using theoretical argumentation. Subsequently students had to use the procedural knowledge they acquired and to apply the conceptual schema of nested structures for another situation: the baking of gluten-free Dutch doughnuts (V-i).

In phase VI, the intention was that students should write a report for the further investigation of gluten-free bread within the community of practice (VI-i). Students should have a motive for writing their report (VI-ii).

Evaluation of the strategy components

Strategy component i: Use of a procedure which is built on intuitive notions of students

In phase I and II, we 'partly' achieved the expectations with regard to the use of the procedure (students' questionnaire after phase I; Table 3). Among the four procedural steps (expectation II-i; exploring the problem, finding an explanation, designing and evaluating), all students (seven out of eight, S1 was ill) were able to formulate the problem, and refined this for themselves in terms of the expected task, that is, to focus on the example of bread (expectation I-i). All students mentioned 'designing' as well. In the classroom discussion (video recordings and field notes), these two steps of the procedure (exploring the problem and designing) were present in the discourse. Their response, however, did not include the steps 'finding an explanation' and 'evaluating' (questionnaire, video recordings and field notes). Only two students (S2 and S3; Table 4) refer to 'explain everything theoretically' and 'obtain insight', as an indication that they experience a need to look into the theoretical background of the problem. As a result, it was unclear to most of students why they had to study about the behaviour of gluten in the next activity and why this theory was needed to design a food product.

Table 3 The purpose of the teaching-learning process after phase I as perceived by students in cycle 1 (students' questionnaire)

Student	Response
S2	Make the perfect bread, according to the aims, produce it and explain everything theoretically
S3	Make gluten-free bread. Obtain insight into the process of bread baking
S4	Develop the perfect bread with good properties which tastes and looks good
S6	To investigate properties of all varieties of bread and think of new products
S7	Design a gluten-free bread
S8	Design a bread with sufficient quality and with a low gluten content

In phase III, the expectation (III-i) about the necessary step of finding an explanation is 'partly' achieved because the students did not have clear motives for extending their knowledge in the expected direction. They understood that they had to know more about gluten (see Table 4). However, they hardly understood the purpose of most of the activities of phase III: why to find an explanation, that is, to find a relation between the elasticity of dough and its ability to capture the gas, CO_2 during the fermentation of the dough (voice recordings activity 8, cycle 1). Although the purpose of the step 'finding an explanation' is not clear to students, they performed most activities in phase III well, because as obedient students, they correctly executed the (teaching-learning) activities. As a result, the next procedural step in learning phase (IV), designing, did not proceed as a purposeful 'flow' after phase III. In the formulation and use of criteria for selecting a replacement for gluten (expectation IV-i), only two students acted as expected (S7 and S8; voice and video recordings, activity 12, cycle 1). Furthermore, the students lost the main leading thread from this point of the teaching-learning process, and as a result the teacher took over most of the initiatives to continue with the teaching-learning process (voice and video recording of the discourse during activities 11 and 12, cycle 1).

Table 4 The perceived purpose of the teaching-learning process after phase II in cycle 1 (students' questionnaire)

Students	Remarks
S2	*What is in the [gluten] fibres and how does it work?*
S3	*The formation and how does the network function?*
S4, S5, S7 and S8	*How will the network and fibres be formed and what is the influence of time on the process?*
S6	*How will fibres be formed?*

Strategy component ii: Sequence motives

In phase I and II, all expectations (I-ii and II-ii) were 'fully' achieved by seven out of eight students. The setting and task were relevant for the students (expectation I-ii; Chapter 3). During phase II, the problem became clear to the students (expectation II-ii): the link between the presence of gluten and large cavities in wheat bread (and consequently, without gluten the dough will not rise). S2 formulated (video recordings of classroom discourse in activity 5), '*what I wonder with respect to wheat…, why are the cavities really larger?'* and S7 reacts, '*[apparently] with wheat you have a very clear protein network'.*

In phase III, expectations were 'partly' achieved. The students indeed expressed a motive for extending their knowledge about micro structures in bread (expectation III-ii). In the beginning of phase III, students formulated questions in their student work, like (students' work): *'how can a close gluten network be formed out of gluten?'* (S2), *'how does gluten maintain the network?'* (S3), *'something must be added to corn that can make it possible to form a network'* (S6) and *'We do not know how gluten is able to capture the gasses*' (S8). In their plans (student work), students wrote remarks about what to do next in relation to the previous discussions (cf. Table 4).

Although students had a motive to extend their knowledge about micro structures in bread, the students did not have a motive to perform further practical investigations to explain the elasticity of gluten (expectation III-ii). Students' responses varied when they were asked to what extend the experiments were relevant (questionnaire after activity 8): '*little bit superficial' (S2), '[some of the] steps in between were already orally discussed' (S2), 'has no connection with the solution [of the problem]' (S5 and S8),'[doing] experiment[s] was nice' (S3), 'this activity can be done, and we observed the elasticity of wheat bread'(S4), 'interesting to observe the reaction of dough (S6 and S7), because you need the information to go further' (S7)*. These student responses can be interpreted as 'we did the experiment; however, we did not experience the purpose of it'. From the students' perspective, it was not necessary to formulate an explanation for the elastic property of gluten, that is, they did not have a motive to perform this experiment.

A clear connection to the activities of phase IV was not established from a student perspective: only one student (S8, video recordings of activity 12 and student work) formulated criteria for selecting hydrocolloids as replacements for gluten (expectation IV-ii). Despite the input of S8, the students did not express any motive to use these criteria, illustrated by the statement of S3 to the teacher: *'which hydrocolloid did you buy?'* As a result, students read and used the labels of the selected additives which were available in the lab; availability was used as selection criterion (field notes and video recordings of activity 12 and 13). The students lacked a clear motive for selecting hydrocolloids in phase IV (expectation IV-ii); only at the end of the teaching-learning process in phase IV, students realised that the baking tests of corn bread with hydrocolloids were necessary (see Table 5; questionnaire). All statements of students can be interpreted as that students saw the added value of testing the newly designed breads.

Table 5 Responses of students S1 to S6 about the activity 16 after testing the addition of gluten replacements (questionnaire after phase IV)

Important because the results of the baking process will be evaluated. (S1)
The attempt was without changes; the purpose [of testing] is clear to me. (S2)
Interesting to compare the results. (S4)
It becomes clear that it is impossible to find an acceptable replacement for gluten. (S5)
Bread baking is nice, gives insight in the effects of HPMC and alginate [examples of hydrocolloid] (S3 and S4)
It gives a clear overview of what we have done …. the effect of gluten is clear. (S6)

The last two activities (phase V and VI) were not performed in the classroom as planned because of organisational circumstances. The relevant expectations with regard to the strategy component procedure were processed in the final individual interview. In this situation it was not possible to evaluate expectations related to students' motives. In their final reports (students' work) students described the outcomes of their projects on a concrete level. They did not explain why they had carried out experiments, what was the purpose of their classroom discussions, nor did they mention why they used the specific information sources. The focus of students was on product development, not on the process and why they performed certain activities. This confirmed that students performed exactly what were told to do as in a traditional classroom setting without experiencing the purpose of each activity in relation to the goal of teaching-learning process.

In summary, the teaching-learning process in the first cycle was designed with strategy component i, the procedure, mainly with a focus on *understanding.* The procedural step of 'finding an explanation' was placed before 'designing', as an application of the previously acquired knowledge. However, from the start of the teaching-learning process in the phases I and II, *the students* directed their focus towards *developing* a gluten-free product for people with coeliac disease: a much more straightforward design procedure. This unintended implicit intermingling of a more *traditional research procedure* and a *straightforward design procedure* resulted in an unclear focus of the teaching-learning process, especially in the connection between the phases II and III, which came more prominent when phase IV started. Therefore, at a more detailed level with respect to the strategy component ii, 'sequencing of motives', the focus of students was deflected from the intended motives of the teaching-learning process in phase III: the need to have more knowledge of gluten and the cause of the properties of gluten for the development of gluten-free products. The intended motives were not evoked as expected, and as a result the teacher – and not the students – regulated the sequence of the teaching-learning process.

The conclusion with regard to the strategy component i 'use a procedure which is built on intuitive notions of students' is that the procedure was not focused well enough and caused problems for the anticipated sequence of motives (strategy component ii). First the procedure needs adaptation to influence the detailed design of the finely-tuned sequence of teaching-learning activities. Second, as a result of this adaptation, we argue that the sequence of motives could be realised as intended.

Both strategy components still have enough potential for designing a sequence of teaching-learning activities in which students experience motives to proceed from one activity to the next. This conclusion justifies stating that new strategy components are not needed, nor do we have to change the formulation of the components. The sequence-principle itself does not need adaptations.

Cycle 2: design, enactment and evaluation

Arguments: the procedural steps revisited

A more straightforward procedure aiming at the design of food products would be more easily recognised by students. Therefore, we used the following main steps of the design procedure: exploration of the task, finding an explanation, search for solutions and test these. In the start of the redesigned teaching-learning process, we assumed that students have the following intuitive notion how to design a (food) product:

- explore the problem,
- find a solution by making the food product,
- test, and
- evaluate.

Instead of implementing these procedural steps in a strict linear way, the design of the teaching-learning process in cycle 2 used this procedure in a series of cycles. At least two cycles of designing gluten-free bread were thought to be needed to obtain reasonable results. After an introductory experiment, students start with first 'design' as an exploration that can lead to a possible solution. The evaluation of the 'exploratory' design of loaves of gluten-free bread should lead to the need for more knowledge what causes the elastic property of gluten. Students apply the new knowledge they acquired when designing and testing a new food product. Because the focus of the project is more on the improvement of the design of a food product, it is possible to combine the learning phases III and IV of cycle 1 into one new learning phase III in cycle 2. The number of learning phases is reduced with one (see Appendix B).

The elaboration of strategy components

The expectations of the redesigned teaching-learning process are presented in Table 6.

In phase I, a university food scientist (Chapter 2) introduced the need to develop a new food product to the students in a video message. Subsequently, a task was given to the students: to design a class of gluten-free food products with the purpose of obtaining more knowledge about the design processes of this type of food products. Consequently, the purpose of the student task in cycle 2 differed from the one in cycle 1. The acquired knowledge during the project had to be useful for further investigations: students have intuitive notions about the design procedure as presented above (I-i). Students recognise that this kind of task is common in authentic practices of designers of food products (I-ii).

Table 6 Overview of the detailed expectations of the two strategy components, the procedure based on intuitive notions of students and motives within in each of the learning phases in the design of cycle 2

Phase	Phase description	Strategy component	Detailed expectation
I	Orientation	i. Procedure which is built on intuitive notions of students	Students are able to construct a plan of action based on their intuitive notions of the procedure: explore the problem, find a solution by making the food product, test and evaluate.
		ii. Sequence motives	Students find the task realistic and understand that professionals are working on such tasks. A motive is evoked in students to accomplish the task.
II	Definition of the task	i. Procedure which is built on intuitive notions of students	Given their intuitive notions about the procedure expressed in phase I and based on new information, students are able to adapt and improve their project plan.
		ii. Sequence motives	Students have a motive to extend their knowledge about what causes the properties of gluten and to execute their project plan to accomplish the given task.
III	Extension and use of knowledge	i. Procedure which is built on intuitive notions of students	Students extend their knowledge about the procedure to select an additive for replacement of gluten, to design a new/ adapted product, and to find an explanation through additional experiments.
		ii. Sequence motives	Students have a motive to find an explanation why the product is improved although it still has inferior quality caused by the absence of gluten and to use an explanation about the elasticity of gluten for the improvement of their designed food product.

IV	Reflection on the design and thinking processes	i.	Procedure which is built on intuitive notions of students	
		ii.	Sequence motives	Students have a motive to reflect on their activities and thinking process (macro-micro thinking) to obtain the knowledge claim of designing a gluten-free food product.
V	Reflection and transfer	i.	Procedure which is built on intuitive notions of students	Students are able to select a substitute and to use the procedure and macro-micro thinking in designing another food product.
		ii.	Sequence motives	Students have a motive to use the procedure and macro-micro thinking in another task to design a food product.

In phase II, the expectation was that students use their notions about the procedure to formulate an improved version of the project plan (II-i). Furthermore, with respect to the sequence of motives (II-ii), students would accept that for baking other loaves of bread, based on a mixture of corn and wheat, it was necessary to understand why it is difficult to bake a gluten-free corn bread. We expected this baking experiment to lead to the conclusion that the free quality of corn bread is related to the gluten content. As a result a motive is aroused in students to investigate which substance can be added to corn bread as a replacement for gluten. Students would have a motive to acquire more knowledge about the microstructures and the properties of gluten.

Within phase III, two cycles of designing, testing, and searching for an explanation (III-i) were implemented which should provide a sequence of motives (III-ii) for proceeding to a next activity. Students would select a potential replacement for gluten based on given information, and to use this selection to bake new corn breads with different additives. Because of the low quality of the new corn bread, we expected to evoke a motive by students to extend their knowledge of the cause of the elastic property of gluten. After acquiring this knowledge, students could formulate arguments for the selection of hydrocolloids to replace gluten in corn bread. This would result in a new test cycle of corn bread with other additives and/or improved composition of additives. In spite of the improved bread quality, an ideal combination of hydrocolloids was then still to be found.

In phase IV, we expected that students wanted to reflect on their design and thinking processes (IV-ii), because they had obtained an improved gluten-free corn bread. This should result in a desire to make this knowledge explicit, to use this in other situations to design gluten-free food products and to apply the knowledge for further investigations. This would evoke a motive in students to report all findings in a written and oral form (phase V-ii).

Evaluation of the strategy components

Strategy component i: Use a procedure which is built on intuitive notions of students

In cycle 2, we achieved the intended pedagogical effect at least in the phases I to III: to sequence teaching-learning activities in which students experience that the procedural steps formed a leading thread for the teaching-learning activities and provided them with a motive to proceed to the next one (see below for strategy component ii). In phase I, we 'fully' evoked their intuitive notions about the procedure (expectation I-i) as expected (video tapes and discourse, activity 1 of cycle 2). In phase II, the intuitive notions with respect to the procedural steps could be 'fully' used by all students and were extended to the step of 'finding a replacement for gluten' (expectation II-i; student' work and video and voice recordings of activity 1 of cycle 2, student work). In phase III the extension of the procedure was 'partly' achieved (expectation III-i). The step 'extension of knowledge of gluten' was insufficiently evoked: only at the beginning of phase III 'fully' by all students and later on only by four students (student work of S5, S6, S10, S14 and video and voice recordings, activity 4 of cycle 2). This step is described in more detail below because it differs from our expectations.

In phase III, a second information source was given to the students to extend their knowledge about detailed steps in the procedure. The expectation was that students would use the suggested experiments to acquire more knowledge about the cause of the elastic property of gluten and consequently what the effects of adding hydrocolloids to corn flour would be. At that moment the teacher took the lead and controlled the teaching-learning process, because the teacher anticipated that the students would not develop the conceptual understanding as was necessary (video and voice recordings of activity 7 in cycle 2). She experienced a lack of initiative of the students to use the appropriate information from the three articles provided in the teaching materials (interview teacher after phase IV). As a result, the regulation of the teaching-learning process was taken over by the teacher. When preparing the experiments, the teacher guided how variables should be distributed among the different groups of students (kinds of hydrocolloids and hydrocolloid concentration). Students did not experience the experiments as a logical subsequent step in the procedure (voice and video tape of activity 9 in cycle 2). However, to some extent, students were able to explain the purpose of the experiment to the school principal when he visited the research setting and interviewed the students (voice recording and field notes). Student S11 explained why they performed the experiments: '*First we have investigated which [hydrocolloid] is the best. Yesterday we baked some loaves of bread, each with one hydrocolloid...*'.We found the same with six students (S1, S3, S11 to S14) (voice recording of activity 12). The expectation (III-i) was thus 'partly' achieved because students selected an additive for replacement and used it to design a new/adapted product. However, they experienced not the purpose of these activities: to find an explanation through additional experiments.

In phase V, students only 'partly' used their acquired procedural knowledge for another situation (expectation V-i; student work and voice recordings of activity 16). According to the teacher (interview teacher after phase V), the switch from designing gluten-free bread to gluten-free pasta proceeded in a flow (video recordings). This switch took place when she referred to the main objective of the project. Students superficially used their acquired procedural knowledge to design gluten-free pasta. The use of this knowledge for another situation did not have the expected quality because it was not related to any content issue, but mainly to superficial procedural steps, as evidenced in students' statements: '*yes, maybe a more specific [additive as a] replacement, yes something changed, that becomes clear'* (S16, student work in activity 16) and '*with these tests you can observe specific properties of the substance. And then investigate what these substances will do, so you can determine what is suitable for the product or not'* (S15, student work in activity 16). Students formulated a new proposal to design gluten-free pasta, using their project proposal, by replacing the terms 'bread' with 'pasta'. Eight of fourteen students formulated a procedure. An example of their statements is: '*Yes, it is like: theory and then to bake, to test and then more theory'* (S15; students' work).

Strategy component ii: Sequence motives

In phases I and II the expectations with regard to the sequence of motives (I-ii and II-ii) were 'fully' achieved (voice and video recordings of activities 1 to 3). In phase III, motives could be evoked according to the expectations, until the moment when the teacher took too much control of the regulation of the teaching and learning process. Additionally, when she changed the sequence of teaching-learning activities (see Appendix B, numbers 10, 11 and 12), due to time constraints, the intended sequence of motives was disturbed: students did no longer experience a series of motives to proceed from one activity to the next.

Although students performed all teaching-learning activities of phase III as intended, they did not have the intended motives to think about an explanation for the elastic property of gluten (expectation III-ii). Several of their remarks could be indirectly related to a diversity of motives:

- *'How can we adapt it* [structure]*? How can we change the micro structure of bread?'*
  S14 formulated a motive to know more about micro structures during a discussion with S13 and the teacher (voice recording of activity 6 and field notes).
- *'The dough has to be firm to obtain a light [fluffy] structure, and then the elasticity is good.'* S9's written remark about the sub-goal after teaching-learning activity 8 (student questionnaire after phase III).
- *'It works well with wheat. Maybe it works with corn. We do not know that, so we have to do it [perform experiments].'*
  S14 has a reason to perform an experiment in teaching-learning activity 9 (voice recording of activity 8).

In the light of the analysis of the questionnaires the students filled in after each phase, a shift in the objective of the project can be observed after phase II: more focus on designing gluten-free bread instead of acquiring more knowledge about the design process when developing gluten-free food products:

- *'To try compositions'* (S10)
- *'To make gluten-free bread'* (S11, S12, S13, S14, S16, S18, S19, S20, S21)
- *'New bread with two hydrocolloids'* (S15)
- *'Find a substance with the same properties and functions as gluten'* (S9 and S17)
- *'To bake the best possible corn bread while learning chemistry'* (S22).

Thus, students only focused on the design of one food product. This could be a reason for the poor elicitation of a motive to find an acceptable explanation for the elasticity of the gluten network in phase III. A second reason was the reversion of two teaching-learning activities for organisational reasons. Just at this point, a third article (information source) with necessary information about gluten molecules and networks was to be used by students. Therefore, students formulated criteria using an incomplete knowledge base.

The motive to use their thinking process and procedure in another task to design a food product (expectation V-ii) could not be evoked at students as a result of the changed focus of the students: from obtaining knowledge of a design process for a food product to the design of a food product.

Summarising the evaluation of and reflection on cycle 2: the use of the procedure was mainly as expected. The use of a sequence of motives within cycle 2 was realised as expected only for the phases I and II and partly in phase III. Intuitive ideas of the procedure were evoked in students, and could be made productive in the teaching-learning process up to phases III. In the reflection phase V, the steps of the procedure were identified and subsequently used in another situation. In phase IV, however, the procedure did not guide to the motive to acquire more knowledge about the whole design and thinking process about macro-micro. From activity 10 in phase III, the intended sequence of motives could not be evoked at students.

Two reasons can be given for this finding. First, the focus of the students was directed towards the design of gluten-free bread as a final product they thought should be delivered at the end of the teaching-learning process. Second, the chosen design procedure did not necessarily imply the generation of new knowledge. The intuitive idea of students about the yield of a design procedure is a product (Lewis, 2006), not more understanding or knowledge.

We found three causes which might explain why the sequence of motives was only partly experienced by students. First, the sequence of motives was broken because the sequence of teaching-learning activities was changed for organisational reasons at a crucial moment when students should experience a motive to know more about the cause of the elastic property of gluten (see Appendix B, activity 10). Second, the situation half-way phase III was changed into a setting in which the teacher regulated the process too much, thereby no longer evoking students' motives. It was the teacher and not the students who formulated many of the motives to proceed to a next teaching-learning activity at the end of phase III, and in the phases IV and V as a result of her judgement about the insufficient concept development of students. The teacher felt insecure about the students' understanding. Therefore she shifted towards a teaching strategy of asking questions, and replying to correct, incomplete and/or poor student responses (Lemke, 1990, p.10). Third, although the objective of their task was to acquire knowledge, the focus of students was on the design of the product. The combination of these three elements probably led to the disruption of the intended chain of motives half-way of phase III.

Conclusion and discussion

This study had a two-fold aim: 1) to elaborate the strategy components to achieve that students know 'what to do next, and why' when learning about macro-micro thinking, and 2) to formulate an empirically underpinned design principle as heuristic guideline for sequencing teaching-learning activities in which students experience that they have motives to proceed from one activity to the next. In designing this sequence, we used two strategy components: (i) a procedure originating from an authentic practice which could build on intuitive notions of students and (ii) a sequence of anticipated students' motives. The research questions were:

1) To what extent does the elaboration of the strategy components lead to the intended effect: that students know 'what to do next, and why' when learning about macro-micro thinking using structure-property relations?

2) What is the formulation of an empirically underpinned sequence-principle?

To answer the first research question, we conclude that the elaboration of the first strategy component into the teaching-learning process largely had the expected effect, despite the fact that the procedure did not directly lead to students acquiring more knowledge about their way of thinking when achieving the task in phase V 'Transfer and Reflection' (Table 2; Appendix B). The intuitive notions of students with respect to the procedure could be evoked and students used this procedure productively to accomplish the task. The second strategy component, sequence anticipated students' motives, led to a well sequenced set of teaching-learning activities until the teacher took over the regulation of the activities and thereby the evoking of own motives of students stopped.

For answering the second research question, we first provide an overview of the main conclusions of the two design cycles. These conclusions with respect to both strategy components are summarised in Table 7.

Table 7 Conclusions from design cycles 1 and 2

Strategy component	Conclusion after enactment in cycle 1	Conclusion after enactment in cycle 2
i. Use a procedure which is based on intuitive notions of students	The intuitive notion of the intended procedure was partly evoked. The procedure was not clear for students. Product development was the goal for students instead of explicating the obtained knowledge.	The intuitive notion of the intended design procedure was fully evoked. The procedure was clear for students: the procedure was connected to the intuitive notions and useful for achieving the goal of the project from the perspective of students.
ii. Sequence anticipated students' motives in which the reflection on one activity is the orientation for the next	The sequence of motives were evoked as intended in the first two learning phases, however, the sequence of teaching-learning activities was no longer regulated by students' motives in phase III.	The intended motives were evoked in students as intended, until the teacher took the lead instead of guiding/coaching the students to formulate their own motives.

Both strategy components influence each other into a coherent whole (Arievitch & Haenen, 2005). We observed that if the procedure used as a leading thread in the teaching-learning process is not correctly designed or implemented, then the intended sequence of teaching-learning activities will not be realised. If the designed procedure is implemented, then the sequence of teaching-learning activities can in principle be realised indeed with the expected effect.

Although the elaboration of the strategy components largely resulted in the intended effect until half-way phase III, we must mention the following three problems. First, the focus of the students changed during the enactment of the teaching-learning process. Second, as a consequence of the first problem, the procedure did not lead to a motive to acquire more general knowledge about the whole design process and thinking process in the reflection phase (V). Additionally, the teacher is very important in the realisation of the design, especially for the sequence of teaching-learning activities. Therefore, the design principle and consequently the design of the teaching-learning process need to be changed to address these three problems.

To address the first and second problem, the goal of the teaching-learning process has to be clearer for students to keep their focus as intended until the reflection phase in which transfer to other tasks needs to take place. Therefore, the procedure has to change from a product design procedure towards a conceptual design procedure (Blessing, 1996). The purpose of a conceptual design procedure is to obtain the knowledge needed to build a concept of a product. Then students focus on the use of the knowledge also applicable for other situations, and the intended sequence of motives can be likely be evoked.

In this study the use of a procedure based on intuitive notions of students and the sequencing of motives suggest that there is a mutual influence of both strategy components. Together with an achievable goal from the students' perspective, the design principle has potential to build up a sequence of teaching-learning activities based on initial motivation (Westbroek et al., 2010) in which students know 'what to do next, and why'.

In addition to the three problems discussed, we did not evoke a motive in students to reflect on their procedural steps and way of macro-micro thinking and to use this in another context-based situation in phase V (reflection and transfer). Although, earlier disturbances in the sequence were determined by teacher behaviour (see above), we have reason to believe that the issue of transfer still needs further attention. For example, the division of the teaching-learning process into five learning phases is comparable to the four phases of ChiK units (Parchmann et al., 2006). The difference is mainly in the proposed phase IV in our sequence (Appendix B) which is not present in the ChiK learning phases. This phase (IV) relates to the 'need-to-know' for basic concepts and skills (cf. Parchmann et al., 2006; p. 1060). The presence of motivational dimensions and social significance is mentioned as important in sequences of teaching-learning activities (e.g. Meheut, 2004). Komorek & Duit. (2004) used a teaching-learning process in which the design of the first and second phase resembles to a large extent to the procedure of prediction, observation, and explaining (p. 625). The function of the third and fourth phase was generalisation and reflection. Again, a clear motive for students to go from one phase of teaching-learning activities to the next one was not reported by them. Kabapinar et al. (2004) used four phases: introduction, creating a need for a model, construction of the model and using the model. The design of these phases was teacher centred (p. 640), although the purpose was that students construct their own model. Kabapinar et al. (2004) draw the conclusion that they needed to pay more attention to students' ideas about science teaching in order to motivate them (p. 650).

All these studies indicate that the learning phases and/or functions to direct students' motives to reflection on the acquisition of knowledge remained implicit (cf. Kortland, 2001), Prins, 2010; Westbroek, 2005). We recommend that this aspect becomes an explicit part of the design of teaching-learning processes, especially because transfer is an important activity in education to consider. It is also needed but difficult to make explicit what should be learned in the teaching-learning process in such a way that it can be used in more or less related tasks (Gilbert, Bulte & Pilot, 2010). An adapted procedure taken from an authentic practice does not naturally include a phase in which transfer takes place. In this study, we intended to design activities which make the acquired knowledge explicit and which could be combined with the function of the transfer phase. We did not achieve this to the intended extent within one unit, so the design of effective activities for acquiring transfer is still a problem for further research.

To answer the second research question about the empirically underpinned sequence-principle, an adapted formulation of the sequence-principle could be formulated:

> If a procedure is used which is built on intuitive notions of students (strategy component i), and motives are sequenced in such a way that the reflection on one teaching-learning activity provides the orientation for the next (strategy component ii), then students experience a sequence of teaching-learning activities in which they know 'what to do next, and why' (intended pedagogic effect).

Additionally, it is recommended that strategy component i is adapted by adding a condition to the formulation of strategy component i (in italics): … a procedure is used which is built on intuitive notions of students and *aligned with the learning goal of the teaching-learning process* …. Furthermore, the issue of transfer needs attention, and should perhaps lead to the formulation of a separate design principle.

The conclusions are limited to the case of macro-micro thinking, and limited with regard to the other choices made in this study. As a consequence of the many unknown variables with regard to the way of macro-micro thinking with structure-property relations, and the use of an authentic practice as a context, an explorative set-up of this study was chosen. The two teachers, who both were well informed with new curriculum ideas, were not average teachers. So, our conclusions cannot be extended to teachers who are not familiar with the new context-based chemistry education with a specific focus on student-regulated learning. The teachers' expertise and beliefs (Anders Ericsson, 2006; p. 701) are important factors to effectively give shape to this type of education. Therefore, the results of this study are limited by the relative small group of students, the two teachers and the location of the research settings at one school. Additionally, this study is limited because of the heuristic, case specific nature of the design principle.

However, we have reason to believe that this design principle can be applicable to other situations. First, the students who participated in this study can be considered as rather average students in a common school in the Netherlands. For a new topic this design principle has to be elaborated again to some extent (Westbroek, 2005, Prins, 2010). In each of the newly designed teaching-learning process this involves some uncertainty regarding the interpretation and the decisions of the designers (Pintrich, 2003; McKenney et al., 2006). With respect to this design principle, sequencing teaching-learning activities which are relevant from a students' perspective, the main struggle for the designer is to find a balance between both strategy components while taking into consideration the mutual influence between the components. The further refinement of the design principle can lead to chemistry education that is more relevant from the students' perspective and is regulated by their own motives, as is illustrated in this study.

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Appendix A Sequence of teaching-learning activities in cycle 1

Phase	Activity	Teaching-learning activity
I Orientation	1	Given the notes of a senior food developer of food products, students are confronted with the problem of people with coeliac disease.
	2	Students become employees of a (virtual) food production company. Based on given information students have to write a proposal as an internal memo. This proposal contains a primary idea for a solution of the problem: the development of a gluten-free food product is necessary.
	3	In the light of additional information, students choose corn to replace wheat, and select bread as exemplary food product.
	4	Students have to write a plan how to develop a gluten-free corn bread.
II Definition of the task	5	A guiding experiment is proposed in which three different loaves of bread are baked: 100% of wheat, 100% of corn and half wheat/half corn. In this experiment, students relate the gluten content to the quality of the bread. This results in the conclusion that a replacement for gluten is necessary for corn dough to yield at least the same quality of bread. Students write a more detailed project plan to develop a gluten-free corn bread.
	6	To reduce the problem, the steps of the baking process, 'mixing' and 'rising' are considered essential for this project. Students will realise that they need to know more about the properties of gluten to choose a suitable replacement to be added to corn.
III Extension of knowledge	7	Based on an additional experiment, students investigate the rising of bread. Students relate the structure of a gluten network to the elastic property of walls of gas holes. They do not know enough to explain this relation.
	8	Students carry out an additional experiment that makes them to descend to meso levels at a lower scale within the structure of dough. Students have to write down an explanation which relates the structure of gluten chains to the ability to be lengthened of dough.
	9	The different explanations of students are discussed within the whole group. A motive is evoked in students to study a new scientific article about hypothetical explanations of the elastic property of the gluten network.
	10	In this information source three hypothetical models are proposed which can contribute to the understanding of the elastic property of the gluten network. Students have to choose one of these models, using scale models of ropes (gluten chains) with knots (Sulphur-bridges). Depending on their choices, they can formulate an adequate explanation.
	11	Students reflect on their own explanation, given their task to obtain more knowledge how to develop gluten-free food products. They formulate their conceptual understanding of macro-micro thinking with structure-property relations.

IV Using the obtained knowledge	12	Using the accepted explanation, students are able to derive argued criteria for the replacement of gluten to be selected out of a group of carbon hydrates.
	13	A new article is presented to the students. The article contains information about the structures, interactions and properties of hydrocolloids. Informed by this article, students can select potentially suitable hydrocolloids.
	14	Students have to formulate arguments for a choice and propose an experiment for testing.
	15	Students discuss their arguments in the group and agree upon the proposed experiments.
	16	Students test the hydrocolloids they selected by baking loaves of corn bread. The results are evaluated.
V Transfer	17	Students reflect on the procedure and on their thinking process. Students are asked to use the obtained knowledge for another situation: developing a gluten-free Dutch doughnut.
VI Reflection	18	Students have to write a report which can be used as a starting-point for further research.

Appendix B Sequence of teaching-learning activities in cycle 2

Phase	Activity	Teaching-learning activity
I Orientation	1	In a video-tape, a senior scientist introduces a problem with respect to food products containing gluten and formulates a task of this project. This leads to a discussion between teacher and students about the adaptation of the project proposal and the procedure how to proceed. Students formulate their intuitive notions about a design procedure. They bake loaves of corn bread. For a reference base, they bake several loaves of bread with a variable ration corn to wheat.
II Definition of the task	2	In the light of this experiment, students relate the gluten content to the quality of bread. They conclude that a replacement for gluten to add to corn dough is necessary to obtain at least the same quality of bread.
	3	During a group discussion, students adapt the project proposal for designing bread without gluten. For this, they need more knowledge about additives that can be used as replacements for gluten to improve the quality of bread.

III Extension and use of knowledge	4	Hydrocolloids are used as normal additives for all kinds of food products. Students make a selection of hydrocolloids using rather superficial arguments they distract from an article about hydrocolloids as improvers for wheat bread.
	5	Several loaves of corn bread with different hydrocolloids are baked. This is the first design of the food product by students. The loaves of bread the students bake do not have the desired quality. More knowledge about the gluten is necessary for an argued selection of hydrocolloids as additives.
	6	Students are provided with a second article with detailed information about the baking process of wheat bread. More knowledge about the elastic property of the gluten network is necessary for the argued selection of hydrocolloids.
	7	To understand this second article, in which the concepts 'structure' and 'property' are presented, students experience that the meaning of these core concepts is needed. A series of photos is presented and elaborated to evoke intuitive notions about these core concepts.
	8	A group discussion about the article leads to a next step: carry out experiments as presented in the article on the baking of bread. These experiments are necessary to understand what causes the elastic property of the gluten network and provide possible improvements when hydrocolloids are added to corn flour.
	9	Students perform two additional experiments with corn dough with various hydrocolloids with different concentrations of hydrocolloids. The obtained results do not directly lead to one single conclusion. As a result more knowledge is needed about gluten networks. This will be the basis for an argued selection of hydrocolloids in a next step.
	10	A third article is introduced with information about the chemistry behind gluten, i.e. entangled long polymers which can form an elastic network.
	11	Using this information, students can derive criteria for selecting hydrocolloids as a replacement for gluten. Examples of criteria are: long hydrophilic chains with a low number of interconnections and long side groups.
	12	The selected hydrocolloids are tested in a second design of corn bread. Students explain the results using the given information.
	13	Students give each other feedback on their explanations, realising that other scientists have to understand these.
IV Reflection on design and thinking process	14	During a group discussion, students reflect about the purpose of their project. As a result motives are evoked in students to reflect on their procedure and thinking process.
V Reflection and transfer	15	To reconstruct their thinking process, students have to (re)organise their use of structure – property relations as into a conceptual schema of structures and properties.
	16	Students apply the knowledge they acquired with respect to procedure and thinking process for the design of another gluten-free product (pasta); they do this by writing a new detailed project proposal.
	17	Students write their report to the senior scientist: about the procedure how to design corn bread without gluten, about the results they obtained and the explanations they have formulated.

Chapter 1:
Introduction and overview

Part I

Chapter 2:
Conceptual analysis of macro-micro thinking:
structure-property relations for chemistry education

Part II
Two cycles of design, enactment and evaluation

Chapter 3:
Establishing a context for learning macro-micro thinking

Chapter 4:
Sequencing teaching-learning activities to evoke students' motives for learning macro-micro thinking

Chapter 5:
Elaboration and evaluation of macro-meso-micro thinking using structure-property relations

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Part III

Chapter 6:
A method for design-based research focusing on design principles for science education

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Chapter 7:
Conclusions and reflection

Chapter 5

Elaboration and evaluation of macro-meso-micro thinking using structure-property relations for pre-university chemistry education

Abstract

Chemistry students have difficulties in learning to relate macroscopic phenomena to models at the submicroscopic level. Students find it difficult to link the world of concrete phenomena to abstract scientific models, and they perceive these abstract models insufficiently as relevant. In order to solve this dual problem, we used intermediate levels between the macroscopic and the submicroscopic level with structure-property relations in materials as connecting elements. A design-based research approach was applied to study students acquiring macro-micro thinking using structure-property relations by elaborating two strategy components as formulated in an initial design principle. As a first strategy component, we introduced systems thinking with intermediate meso levels. Second, we made use of students' intuitive notion that a property is caused by objects within the materials. Through two design cycles, the strategy components were evaluated, leading to the formulation of a third strategy component. This led to the refinement of the elaboration of the new set of strategy components into the teaching-learning process. The findings were that students (pre-university level) were indeed able to construct a conceptual schema consisting of representations at macro, meso and submicro levels while using structure-property relations. Students were able to relate properties others than the ones related to the macroscopic level to entities at meso or submicro level. However, our study also showed that scaling and the use of metaphors were issues that future studies need to address. Furthermore, there needs to be explicit attention for 'upwards' reasoning, using the sub structures for predicting properties.

Introduction

Macro-micro thinking is difficult for chemistry students in pre-university education for two reasons. Firstly, many students do not recognize the relevance of learning macro-micro thinking (Gilbert, 2006). Secondly, the models at a submicro level are abstract (Anderson, 1990; Penner, 2000; Taber & Coll, 2002; Wiser & Smith, 2008; Harrison & Treagust, 2002; Rappoport & Ashkenazi, 2008; Gilbert & Treagust, 2009). Students find it difficult to understand the relation between phenomena and their corresponding models and representations (Nahkleh, 2005; Harrison & Treagust, 2002; Justi, Gilbert & Ferreira, 2009). Most of the designed teaching-learning processes do not provide students with a link between their intuitive notions and the scientific models. As a result, students find it difficult to connect macroscopic phenomena to submicroscopic entities. Additionally, the step from the level of macroscopic phenomena to the level of submicroscopic representations is a huge one. When people are not trained to interpret the models at submicro level, it is usually beyond their capacity to understand such transitions (Tretter, Jones & Minogue, 2006). Often the transition from the macro to the submicro world implies a number of relations and steps that textbooks seldom describe explicitly (Han & Roth, 2006; Penner, 2000; Meijer, Bulte & Pilot, 2009).

Dividing the macro-micro transition into smaller steps using intermediate (meso) levels might be helpful in the teaching and learning of macro-micro thinking (Millar, 1990; Besson & Viennot, 2004; Meijer et al., 2009; Chapter 2). We propose that these meso levels should be embedded within the design of a teaching-learning process that is relevant to students (Meijer et al., 2009; Chapter 2). For such a design we use a context-based approach with an adapted authentic practice as context for learning (Bulte, Westbroek, De Jong & Pilot, 2006; Gilbert, 2006; Van Oers, 1998; Prins, Bulte, Van Driel & Pilot, 2009; Chapter 3). Such a teaching-learning process will enable students to recognize the relevance and purposefulness of submicroscopic representations when addressing tasks that involve macro-micro thinking (Chapters 3 and 4).

The meso levels become manifest when studying structures and properties of materials that are related to for instance food, clothes and designed everyday artefacts (Millar, 1990; Wilensky & Resnick, 1999). In teaching macro-micro thinking, we aim to use students' intuitive notion that an explanation of a certain property can be found within the material itself (Harré & Madden, 1975; Chapter 2). By building on this notion, we argue that students will be motivated 'to zoom' into the material, i.e. to proceed from the macro to the meso world.

This chapter presents a study with a twofold aim:

1. To enable students to acquire macro-micro thinking as an pedagogical effect when we explore a new teaching-learning process to learn and teach macro-micro thinking, based on our earlier analysis of macro-micro thinking in authentic tasks (Meijer et al., 2009; Chapter 2);

2. To develop by this exploration a design principle including the arguments with an empirical basis by two iterations of design, enactment and evaluation.

The developed design principle including the arguments contributes to the understanding how students can effectively learn about macro-micro thinking. Structure-property relations will be used as causal relations between phenomena and meso levels within the material or substance.

Addressing difficulties in macro-micro thinking: introduction of meso levels and explicit structure-property relations

In authentic practices, scientists use structure-property relations to explain a certain property, frequently in order to develop new products (Aguilera, 2006). To implement such authentic practices as a context for learning (Van Oers, 1998), we use our empirical conceptual analysis of document analysis and expert thinking to define macro-micro thinking as a domain specific case of systems thinking (Meijer et al., 2009; Chapter 2). Macro-micro thinking conceives a material as a system consisting of subsystems. Properties of these systems arise from interactions or processes between lower-level objects or sub systems (Penner, 2000; Wilensky et al., 1999). An emergent property is a property of a system that is not a direct sum of the properties of its sub systems (Rappoport et al., 2008; Wilensky et al., 1999). Properties are lost when the system breaks down into its sub systems and when a sub system is removed from the whole; the component itself will lose its property (Laszlo & Laszlo, 1997).

Materials are built up from smaller structural elements which themselves are built from lower-scale structural elements (Aguilera, 2006). This system of sub systems becomes manifest when studying structures and properties of macroscopic objects and materials (cf. Aguilera, 2006; Cussler & Moggridge, 2001; Walstra, 2003). An example is bread based on wheat. Bread can be defined as a final fixed form of dough. When scientists repeatedly 'zoom deeper' into dough, by using light or electron microscopes, they are able to distinguish certain structures, such as walls of gas holes, threads, granules imbedded in networks and entwined long molecules (Meijer et al., 2009; Chapter 2). These structures are examples of intermediate meso structures which are related to properties such as the elasticity of walls of gas holes, the strength of a thread, the flexibility of textile and the stiffness of cloths. Properties and structures can be attributed to the different scales within this system and represented in a conceptual schema (Figure 1). Within such a conceptual schema, the meso levels link macroscopic phenomena characterized by properties to microscopic models to facilitate a thinking process using the structure, the properties and their interrelations at the different levels.

'Structure' can be defined as the spatial distribution of the components in a system. Physical building blocks of such a system are regions which are bound by a closed surface (Walstra, 2003). At least some of the properties within such regions differ from those in the rest of the system. 'Properties' can be defined as physical or chemical characteristics of a system (material): e.g., the elasticity of walls of gas holes or the capacity of gluten to absorb water.

A 'structure-property relation' is a causal relation between a structure at meso or submicro level and a property. Structure-property relations usually have a qualitative character (causal relations in words) and can be expressed as if-then clauses: '*if* this is an existing property, *then* it is caused by this type of structure' or '*if* this is the existing structure, *then* this property can be expected'. These relations are links between two different (meso) levels and take a slanted diagonal direction (Meijer et al., 2009; Chapter 2). See Figure 1 for an example of this type of structure-property relation: if gluten chains are entwined and connected by Sulphur-bridges then it can be expected that walls of gas holes are elastic.

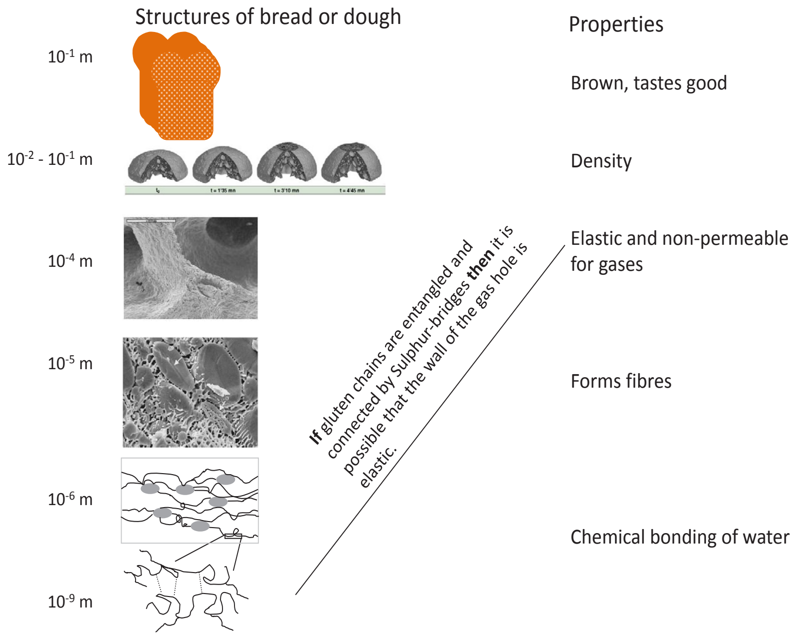


Figure 1 A conceptual schema of structures in bread connected with a scale and properties (Meijer et al., 2009). This figure contains one example of a structure-property relation

The macro level refers to the world in which visible, perceptible material and phenomena exist, e.g. gluten-free bread. The macro level also refers to objects or materials which are closely connected to the human scale (0.1-1 meter). The submicro level is related to models of molecules and/or atoms and is connected to a scale between 10^{-10} and 10^{-9} m. All different meso levels refer to structures with scales in between the macro and submicro level. The number of meso levels differs, depending on the specific tasks in macro-micro thinking (Chapter 2).

In the previous paragraphs, macro-micro thinking with structure-property relations is conceived as a domain-specific way of systems thinking. So, to consider a material as a system of sub systems can be conceived as a first strategy component to incorporate macro-micro thinking with meso levels into chemistry education in a for students relevant way. These sub systems can be related to structures within the material. Structure-property relations are causal relations between a property of a sub system and a structure from which the sub systems are built up. This first strategy component, the use of systems thinking, in this way accommodates the link between scientific models and students' daily life experiences.

For students to 'descent' from the macro to a meso level or from a (sub) system towards its building blocks by formulating structure-property relations, we use a second strategy component: intuitive notions of students about materials. Intuitive notions are based on everyday experiences (Nahkleh, Samarapungavan & Saglam, 2005) and stem from interacting with the material and social world (Linn, 2008, p. 698). These intuitive notions can subsequently be modified and developed upon their use in teaching and learning. In this strategy to incorporate macro-micro thinking with structure-property relations in chemistry education, we use the intuitive notion that a property of a material is caused by the nature of the material itself (Harré & Madden, 1975; Pinker, 2008; Talanquer, 2009). The property of an object or a material can be understood by its nature under certain conditions. Objects and materials have certain properties even when those properties are not directly observable or measurable. For this reason objects and materials differ from each other (Harré & Madden, 1975, p. 86). This difference constitutes their intrinsic nature. To explain or understand a property students have to identify the structure which causes this property. Structure-property relations connect a system (defined by a property) at macro, meso or submicro levels with a sub system at lower scales.

Design principle

Within the teaching-learning process, students need to learn macro-micro thinking using structure-property relations as a pedagogical goal. The initial starting point is that this goal or intended effect may be achieved by the two strategy components in the design of the teaching-learning process which we have taken from the review of the literature and arguments described in the previous sections:

i. Use systems thinking with structure-property relations by considering a material as a system consisting of subsystems, using intermediate meso levels.
ii. Use students' intuitive notion about the cause of a property, by stimulating them to find the cause of a property within the material or sub system.

The two strategy components are entwined and should be used in combination with macro-micro thinking with intermediate meso levels and structure-property relations. Therefore, we formulate a heuristic guideline in the form of an initial design principle for the content of the teaching-learning process. This study will focus on this content-principle:

If *students use systems thinking by conceiving a material as a system of subsystems (intermediate meso levels) (strategy component i)* ***and*** *use the intuitive notion of students that the cause of a property lies within a material (strategy component ii)* ***then*** *students acquire macro-micro thinking using structure-property relations (effect).*

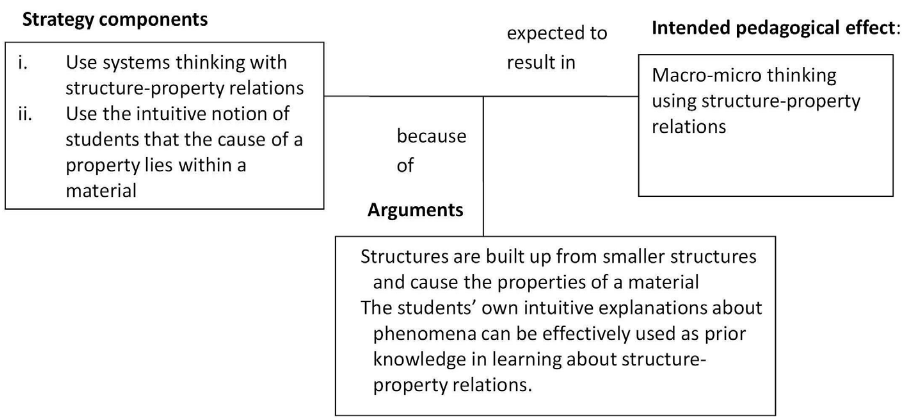
Figure 2 represents the initial design principle for this empirical study. The arguments for this content-principle and the expectations are based on the literature, empirical evidence from previous studies and practical experiences of the members of the design team. The strategy components should guide the design of the teaching-learning process. The intended pedagogical effect is that students acquire macro-micro thinking using structure-property relations for a variety of tasks, in a context that is related to materials science.

Based on the preceding argumentation the research questions in this study are:

1) *To what extent does the elaboration of the strategy components lead to the intended effect that students acquire macro-micro thinking using structure-property relations?*

2) *What is the formulation of the empirically underpinned content-principle?*

By answering these two questions, the formulation of the content-principle gets an empirical basis by designing a teaching-learning process which is studied in two cycles of designing, enactment, evaluating and redesigning (Figure 3). Two other design principles are used for the design of the teaching-learning process: a context-principle and a sequence-principle which are respectively related to the elaboration of strategy components to set up a context to make macro-micro thinking relevant for students and to design a sequence of teaching-learning activities. Both design principles are extensively described in the Chapters 3 and 4 and are beyond the scope of this Chapter.



Method

Research approach

The research approach includes the elaboration of the strategy components of the presented content-principle in the designing of a teaching-learning process. It also includes the classroom enactment of this teaching-learning process, and the subsequent analysis of teaching-learning activities and learning results with a reflection on the formulated design principle. This research approach is informed by a design-based research approach with an empirically established design principle as a knowledge claim (cf. Van den Akker et al., 2006; McKenney et al., 2006) for which details and procedures are described in Chapter 6 of this thesis. In the method we apply, the enacted teaching-learning process is compared to the designed teaching-learning process on the basis of specified expectations about the way each of the teaching-learning activities should function (Lijnse & Klaassen, 2004). The set of expectations is an operational detailed description of the intended pedagogical effect. Expectations can refer to written or verbal answers, or other products or actions of students. The arguments for the design principle and the expectations should be based on the literature, empirical evidence from previous studies and practical experiences of the design team members. The evaluation of the teaching-learning process may give rise to a redesigned version of a teaching-learning process, and if necessary to the adaptation or refinement of the strategy components in the design principle including the arguments. In this chapter two design cycles are described. The first cycle is intended to verify or adapt the elaboration of the strategy component and the formulation of the initial design principle (see Figure 2). The second cycle should lead to a further understanding of the theoretical arguments and the estabishment of the design principle with an empirical basis.

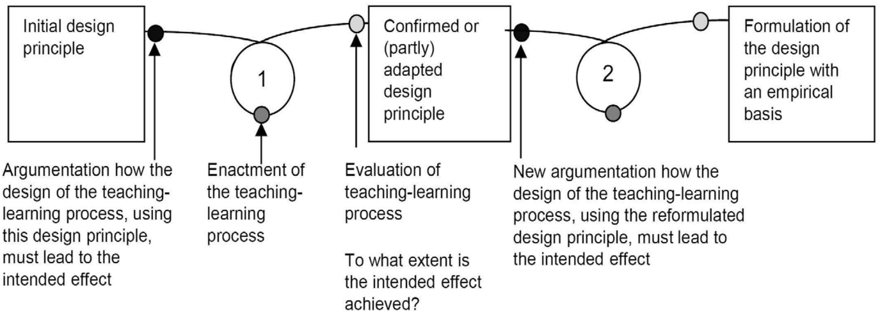


Figure 3 The development of the design principle in this study within two cycles of design and evaluation of a teaching-learning process

Data collection and analysis

For the two cycles, the strategy components were elaborated into a teaching-learning process (Appendix A and B respectively). Connected to each of the strategy components, the intended effects for each cycle were described as concrete detailed expectations embedded within the teaching-learning process (see further for each cycle in the Tables 1 and 2). These concrete expectations which embodies the described intended effect of the design principle (Figure 1) were connected with the function of a teaching-learning activity (see Appendix A and B).

Data collection took place by multiple data sources.

A. Video and voice recordings were taken during enactment of teaching-learning process.

B. The first author took field notes during classroom observations.

C. Student questionnaires were administered before (pre questionnaires), during and after enactment (post questionnaires). These questionnaires (cf. Table 1 and 2 in the next sections) were especially designed to verify whether the students had an outlook for the next teaching-learning activities. Questions in these students' questionnaires were: a) How do you judge each teaching-learning activity on a five-point Likert scale, and provide an argumentation for your judgement; b) How do you judge this teaching-learning process with regard to difficulty, personal interest and information; and c) Can you formulate the purpose of this teaching-learning process and describe an outlook to the next teaching-learning activities?

D. Copies of student work in terms of worksheets and reports were collected.

E. At the end of cycle 1, students were individually interviewed. A focus group interview is held at the end of cycle 2. As a preparation of that group interview, students filled in a short questionnaire about their role, about the experienced relevance of the community of practice, and the advantages and disadvantages of this type of education. These questions were to guide the focus group interview. The teacher interview was held after each teaching-learning phase. The purpose of the interview was to reflect on the previous phase and to prepare for the next one.

Analysis and interpretation of the data sources were performed according to the following procedure (Bulte, Westbroek, De Jong & Pilot, 2006).

- Fragments of video and voice recordings in relation to the formulated expectations were selected and transcribed verbatim when necessary (data source A). These fragments in combination with the related field notes (data source B) were used to analyse whether the elaboration of the strategy components into the teaching-leaning process proceeded according to the formulated expectations (cf. the Table 1 and 2 in the next sections). In this analysis, the discourse of the whole group of students and their teacher was the unit of analysis. The number of students who acted as intended was counted to determine their active involvement during classroom discussions.

- Additionally, to analyse whether each of the formulated expectations was achieved (Tables 1 and 2), at least two of the five data sources (A - E) were used.

This analysis resulted in a 'thick description' of the enactment (prepared by the first author, MM) with respect to each of the formulated expectations and was judged on a three-point scale ('not' – 'partly' –'fully'). We used the criterion 'fully' when 80 per cent of the students acted according to at least 80 per cent of the expectations (Juran, 1974). If only none, one or two of the students acted according to the intended expectations, we used the term 'not achieved'. The term 'partly' refers to outcomes in between 'not achieved' and 'fully achieved'. This categorization is considered sufficient for the purposes of this study.

The judgment on a three-point scale was performed by two researchers independently (first cycle: first and second author; second cycle: first and third author). We regarded 80% as the lower limit for a substantial level of agreement (inter rater reliability; Miles and Huberman, 1994, p.64; Prins et al., 2009). The first qualitative judgement of the whole set of expectations was discussed among the two researchers until they had reached consensus about the findings. Subsequently, the whole set of 'thick descriptions' was discussed in the entire research team in a peer review process (all authors). We used three validation strategies: triangulation of data sources (see above A- E) for providing detailed thick descriptions, independent analysis of data by two raters and a peer review process, thus meeting the criteria required for a valid study (Creswell, 2009, p. 209).

Participants

All students, pre-university level, were recruited from one school in an urban area in the Netherlands. All students within cycle 1 (numbered S1 to S8; average age ≈ 17.6 y) volunteered to participate. In their study, all students had chosen at least two of the three subjects mathematics, physics and chemistry for their final exam. All these students had gained marks between 6 and 7 (on a scale from 1 to 10) for the science subjects (average = 6.8). The 14 voluntary students of cycle 2 (numbered S9 to S22; average age ≈ 17.2 y) had gained marks for their science subjects between 5 and 9 (average 6.7). The students in both cycles can be regarded as average students. They were recruited by a letter. Students were able to gain a mark for their practical exam by participating in this research project.

The teacher within cycle 1 (T1) taught chemistry for seven years at all secondary school levels. T1 was involved in the development of science education at the school. Furthermore, T1 participated in a developmental group of chemistry teachers who are designing, testing and evaluating programmes for a new chemistry curriculum. The teacher in cycle 2 was the second author (T2). She was chemistry teacher in secondary education for five years and an assistant professor she has been actively involved in curriculum development for chemistry education in secondary school.

Enactment of the teaching-learning process

In the first cycle, the enactment of the teaching-learning process took place during eight afternoons (two to three hours each) during the period February-March 2006. The second cycle was enacted within one week in July 2007 (24 hours in total). In both studies the same adapted authentic practice was used as context in the teaching-learning process; the task was the development of gluten-free bread based on corn for people with coeliac disease (Meijer et al., 2009; Chapter 3). Translated and modified authentic research papers were used to introduce the chemistry concepts.

The results of our design study are presented as follows. For each cycle we describe the following.

- 'The content-principle in the teaching-learning process'. This section describes the arguments for the choices made in the design of the teaching-learning process.

- ‘The elaboration of the two strategy components’: i. Use systems thinking with structure-property relations, ii. Use students’ intuitive notion about the cause of a property. This section describes how these strategy components were elaborated into the designed teaching-learning process. Connected to each of the strategy components, the detailed expectations were formulated. Together these expectations form the concretised intended effect.

- ‘The evaluation of the strategy components’ that were elaborated into the designed teaching-learning process, leading to reflection on the design principle.

- ‘The (re)formulation of the context-principle’ in the next cycle including the (new) arguments’, and so on.

The findings of cycle 1 are more briefly described compared to the more extensive descriptions of the findings of cycle 2.

Cycle 1: design, enactment and evaluation

As a context for learning, this study refers to the authentic practice of food development with the development of gluten-free corn bread for people with coeliac disease as a (learning) task (Chapter 3). This practice brings the use of specific knowledge into focus: structure-property relations, and the meso and submicro levels within bread as a socio-scientific issue connecting this real-life issue to submicroscopic models by using intermediate (i.e. meso) levels (Meijer et. al., 2009). In this way, the specific task is about the designing of gluten-free bread based on corn. Corn does not contain gluten and can be used as a substitute for wheat bread for people with gluten intolerance. However, when corn is used a new problem occurs: corn dough does not rise due to the absence of substances which influence the quality of corn bread (the final fixed form of dough). In wheat dough, gluten is the substance which can be linked to the properties: to capture gasses and to elasticity of walls of gas holes. More specifically, the task can be described as: find a replacement for gluten which can be added to corn dough and leads to an acceptable quality of corn bread. To derive criteria for a replacement for gluten, one needs to understand which structures at which meso level cause the elastic property and capturing of gasses. The combination of these main properties results in an acceptable quality of bread. To understand the cause of these properties, it is necessary to distinguish the different meso levels and the submicro level related to gluten in dough.

The strategy components in the teaching-learning process

The arguments for the two strategy components of the content-principle (Figure 2) are as follows.

Strategy component i: use systems thinking with structure-property relations

In the designed teaching-learning process, students need to construct a conceptual schema (Figure 1) as a result of the task given to them. This schema must include the necessary structures, properties, relevant concepts and structure-property relations for a solution of the task (Chapter 2). When the essential structure-property relations are known, the teaching-learning activities can be constructed based on these relations. As a result, students should be enabled to construct the latter by linking presented structures to observations. In the planned subsequent teaching-learning activities students should descend to a level with a smaller scale using structure-property relations, and add new elements to their conceptual schema.

Wheat dough can be considered as a material of which the properties are caused by structures within the material (second column; Figure 1). When all its ingredients are mixed, dough can rise. The density of dough decreases, due to the increased volume of the cavities within the dough caused by the CO_2 production of yeast. The walls of the gas holes are elastic and able to capture the CO_2. The walls are formed by a gluten network consisting of many gluten chains in which grain and yeast are embedded. These chains are made by long gluten molecules with enormous side chains. So, dough (at a scale of: 10^{-1} m) consists of structures at different meso levels and scales, such as: holes (10^{-3} m), walls (10^{-4} m), gluten network (10^{-5} m), gluten chains (10^{-6} m) and molecules (10^{-9} m). Note that objects on a scale lower than 10^{-5} m cannot be observed by light microscopy.

Gluten is the largest natural protein, with a backbone of long chains of high molecular weight with different high and low molecular side chains, connected by a few Sulphur-bridges. When dough is lengthened, the stretch of a network built of gluten chains (consisting of bundles of gluten molecules) is caused by the possibility for the long gluten molecules to move along each other until entangled side chains or Sulphur-bridges hinder this movement.

For the teaching-learning process we selected the following structure-property relations (Chapter 2).

A. If the dough contains gluten, then the dough will rise, and consequently determines the quality of the (corn/wheat) bread.

B. If a gluten network is formed (10^{-5} m), then the walls of the dough are elastic (10^{-4} m), and consequently the dough can capture CO_2 gas.

C. If the structure consists of entangled long gluten chains (10^{-8} m), then there is an elastic gluten network (10^{-6} m).

There are three sets of arguments for using visible structures and phenomena as starting points for the teaching-learning process (Johnstone, 2000; Gilbert, 2006). First, the macro level is connected to students' daily life, it is easily recognizable and, therefore, relevant to students. Second, the way students think and explain in language how the world around them is rooted at the macro level. Students use concepts which have a meaning for them because they refer to objects and to phenomena around them. Language is tied to students' experiences of situated action in the social world (Gee, 2004). Third, as designers, we plan to extend students' knowledge by connecting new meso- and submicro level concepts to existing (macro) experiences and students' prior knowledge.

When defining a conceptual schema as presented in Figure 1, the submicro level has not always to be present in the explanations. In this case, the sequence of amino acids, which are the building blocks of protein (and so of gluten), is not relevant for an explanation of the elastic behaviour of the walls of gas holes. So, the amino acids and the way in which proteins are structured do not necessary form a part of the conceptual schema to be implemented in the teaching-learning process. The presence of concepts which are not needed, will only lead to students drifting away from the goal and subsequently to a decrease of relevancy for students. However, if the task is situated within another authentic social practice(e.g., the research chemist investigating the effect of salt on the formation of gluten network) the number of necessary levels, concepts and the starting point of the teaching-learning process may have to be changed.

Strategy component ii: use intuitive notions of students that the cause of a property lies within a material

When addressing the task situated within the authentic practice, it becomes necessary to design gluten-free corn bread by finding a replacement for gluten, based on argued criteria whilst avoiding a trial-and-error selection procedure. Then, it is necessary to 'descend' from the macro via meso to the submicro level for finding an explanation for two properties of dough: capturing gasses and decreasing density. Based on the conceptual schema, it is most likely to start the thinking process at the macro level.

For this reason at several moments in the design of a teaching-learning process students should be stimulated to use their intuitive notions to relate a meso level structure to a property, that is, to find an explanation for the properties of the structure of gluten molecules in order to make an argued selection for a substance which can form a network with similar properties as a gluten network.

Elaboration of the strategy components

The two strategy components are elaborated within the detailed design of a teaching-learning process with its subsequent teaching-learning activities. Appendix A provides an overview of the entire teaching-learning process. Below, we discuss the outline of the teaching-learning process by describing the activities which are related to the students' acquisition of macro-micro thinking. This is the conceptual development as intended by the described design principle and its strategy components (Figure 2). Table 1 provides an overview of the most important expectations related to macro-micro thinking with structure-property relations for design cycle 1. These expectations do not include phase I of the teaching-learning process, because this phase mainly relates to the setting of the context (context-principle; Chapter 3) and to the set-up of an appropriate sequence (sequence-principle; Chapter 4) which are beyond the scope of this chapter.

In most detailed expectations both strategy components are entwined. When formulating a causal structure-property relation (strategy component ii), systems thinking (strategy component i) is used implicitly.

Table 1 Overview of the most important expectations of the strategy components regarding macro-micro thinking in the relevant phases of the teaching-learning process in cycle 1

Teaching-learning phase	Strategy component	Detailed expectation
II Definition of the task	ii. use intuitive notions of students that the cause of a property lies within a material	IIa. Students refine the task to develop 'a qualitative good bread or dough with gluten which rises better then bread without gluten'. IIb. Students have the notion that a substance has to be added to cornbread which results in the same properties of bread as gluten.
III Extension of knowledge	both strategy components i & ii	IIIa. Students have the notion: If the dough contains gluten, then the dough will rise, and consequently determines the quality of the (corn/wheat) bread. IIIb. Students relate elasticity with the presence of fibres by elongation of dough. IIIc. Students are able to derive an explicit causal explanation for the elastic property of wall of gas holes including the notions: - If a gluten network is formed (10^{-5} m), then the walls of the dough are elastic (10^{-4} m), and consequently the dough can capture CO_2 gas. - If the structure consists of entangled long gluten chains (10^{-8} m), then there is an elastic gluten network (10^{-6} m). and construct a conceptual scheme which includes notions about a network, entanglement and movement of long molecules.
IV Using the obtained knowledge	i: use systems thinking with structure-property relations	IVa. On the basis of the conceptual scheme, students are able to derive criteria for the replacement of gluten: - Have not a toxic property - insoluble in water, otherwise it could not form a network - long molecules (high molecular weight - able to form hydrogen bridges - able to form a network which could capture gasses by forming intermolecular bonds.

V Transfer	both strategy components i & ii	Va. Students recognise 'systems thinking' and causal structure-property relations in the conceptual scheme. Vb. Students use the conceptual scheme to develop another food product. Vc. Students use structures, properties and structure-property relations to develop another food product.

Students start in phase I at the macro level and execute an exploratory experiment in which they bake three loaves of bread with different wheat / corn compositions. In this way they become motivated to relate gluten to the quality of bread. On the basis of this experiment, we expected students to be able to formulate the task as: corn bread without gluten has poor quality, due to the absence of gas holes or high density (expectation IIa; Table 1); so, an additive that replaces gluten in corn dough is necessary (expectation IIb). As a result, students want to know more about the cause of the ability of dough to rise (low density) and gluten (expectation IIIa; Table 1) in order to be able to select a replacement for gluten on an argued basis (expectation IVa; Table 1).

To investigate the cause of the elasticity of walls of gas holes, students have to study more precisely the function of the ingredients and structure of the dough that seems to be necessary to baking high quality bread. Bread is seen as a final fixed form of dough. In this part of the teaching-learning process, students are asked to take small steps from macro via meso to the nearby submicro level. Students subsequently zoom into the dough (expectations IIIa, IIIb, IIIc; Table 1) using structures as cavities with walls, gluten network, gluten chains and interconnections between protein chains, until their investigations lead towards a useful explanation of the quality of bread (expectation IIIc; Table 1). Students are given look-alike scientific articles as information sources and execute additional strain-stretch and dough development experiments. Students construct and extend a conceptual schema such as the one in Figure 1, based on their newly obtained information and experimental results (expectations IIIc; Table 1).

Based on their explanations, students are expected to derive explicit criteria for the selection of hydrocolloid(s) as replacement(s) for gluten (expectation IVa; Table 1). They use these criteria to investigate their hypotheses for the selection of a replacement for gluten and find an acceptable replacement for gluten in corn bread. Students bake, test and evaluate corn breads with different hydrocolloids or variable contents of hydrocolloids. In the transfer phase V, students use their own conceptual schema and understanding of it (expectation Va; Table 1) for a slightly different but related task: the baking of gluten-free Dutch doughnuts (expectation Vb and Vc; Table 1).

Evaluation of the strategy components

In this section, the main findings are presented in successive order: the evaluation of the expectations with regard to the entwined strategy components i and ii (Table 1) and new problems which came to the fore.

The intended process of macro-micro thinking was executed by all students (observations). Four arguments can be given for this. First, all students (voice and video recordings activity 5 and 6; students' work) had the intention to find the cause that the dough could rise (expectation IIa; strategy component i and ii). Second, the expectation IIIb (fibres will be formed by stretching of the dough: strategy component i and ii), is fully achieved. Seven out of eight students had mentioned this observation in their material. Third, in notes or questions notions about the existence of causal relations between structures and properties was found (students' works, voice recordings; 7out of 8 students; strategy component ii; expectation IIIc). In their constructed conceptual schema (students' work) and final reports students proved to be able to formulate their macro-micro thinking process (strategy component i and ii). Two representative statements are:

- *'The search for an explanation started at a scale of centimetres or even [the scale of] a whole bread. The final version of the explanation of the functions and properties of gluten was found at molecular level (meso level). Baking a bread of few molecules is not possible; therefore, if you want to understand the whole structure of bread you have to look into the bread. In this way we understood the function of gluten and we were able to find a replacement'* (S1 and S2: final report).
- *'With the conceptual schema, you have the feeling that you went deeper to a level, subsequently followed by a step towards a level with a lower scale'* (S7: post interview).

Fourth, students recognised 'systems thinking' and identified causal structure-property relations, thereby fulfilling expectation Va (student work, final reports). However, they were not able to use the way of thinking in another situation (expectations Vb and Vc; phase V). For organisational reasons, the last two activities of phase V were not performed in the classroom. The relevant expectations with regard to both strategy components were checked in the final individual interviews. The expectations Vb and Vc were not achieved because all students acted at a superficial procedural level without relating the macro-micro content (final interview). Three statements which can be related to the expectations Vb and Vc were found (final interviews):

- *'I will look deeper into it* [the Dutch doughnut]*' (S7)*
- '*from big to small' … 'all the times look at a smaller scale*' (S8)
- *'Look to small structures as gluten chains and structures of molecules, which you could add or remove to obtain the same results as at normal Dutch doughnuts'*(S2).

Students were able to describe the way of thinking in superficial terms like 'zooming in'. Although students struggled in phase III at the activities 7, 9, 10 and 11 (Appendix A) with the formulation of structure-property relations, all students were able to formulate *structure-property relations* (final reports; related to the expectations: IIIa and IIIc, Va). Examples of representative structure-property relations the students formulated in their final reports are:

- *'The freedom to move* [of gluten chains] *was important but also the amount of entanglement. The capture of gasses and possibility to blow up the matrix was possible with this structure* [the gluten network]. *The cause* [of the elasticity of wall of gas holes] *is rooted in structures that are invisible to the human eye and in the specific construction of gluten'*. (final reports : S1 and S2)
- *'Dough of wheat has a good gluten network* [structure] *which results in a good capability to capturing gasses* [property].' (final report: S3 and S4:)
- *'The experiment leads to the conclusion that after fermentation the gluten network* [structure] *is better than the dough which is only mixed, because it can be stretched more* [property].' (final reports: S5 and S6)

However, this analysis reveals the following three problems: 1) the formulation of structure-property relations without a relation to specific structures at a certain scale, and 2) consequently students did not often use structures with a scale below 10^{-5} m, and 3) the use of the term 'structure' without acknowledging this as an important 'concept'.

First, students did not attribute a scale to the meso levels; they did not show knowledge of the scale of the structures. The following utterances are exemplary (final report S3 and S4): *'The holes became too big, resulting in a break of the gluten structure. For this reason, the bread collapsed'*. S2 stated that when he looked at a given model of a gluten network which is able to capture gasses and is made of several threads connected by a certain amount of knots: *'is CO_2 a tennis ball or a basketball?'* (field notes and voice recordings of activity 10). However, students did know about the ordering of meso levels (student work of activity 10 of S8): '*We can be certain, because we can see the spheres and these are not present at molecular level. So it has to be a super molecule or ball of threads'*. The same student also wrote (student work of activity 11): *'Molecular level: This amino acid (cysteine) is able to form Sulphur-bridges. At a higher level there is interaction between glutenine particles' (*student work of activity 11 of S8). At the end of the teaching-learning process, *s*tudents found it difficult to distinguish between levels. It is not part of their discourse. This can be illustrated by the written statement of the students' work of activity 11: group: S2, S3 and S4): *'Meso level is about a lot of molecules and submicro level is about a few molecules'.* Second, as a consequence, students used general formulations (e.g., '*… rooted in structures that are …'*). This can be illustrated by the criteria for the replacement of gluten, formulated by the group at the initiative of one student: '*elastic, to form a 3D network, to capture gasses, to bind water'* (expectation: IVa). These criteria were not as expected. They were more related to the macro level and not to structures below 10^{-5}m, such as entangled gluten chains and Sulphur-bridges. Third, the use of the term 'structure' as a concept is problematic. This is illustrated by the following. Directly after a quantitative stretch-strain experiment to determine the elongation of different types of dough, T1 asked students about their observations (protocol 1).

Directly after this discourse, S1, S2 and S4 made the stretched dough into a ball, like clay (video recording of activity 8). To these students, the stretched dough and threads did not look like structures, due to their insufficient development of the meaning of the concept 'structure'. In the column 'structure' of their conceptual schema students noted the results of quantitative measurements. Most students described the concept ‘structure’ as restricted to ‘what you see’.

Protocol 1 Part of the discussion following a stretch-strain experiment with dough (video recording of activity 8)

Line	Who?	What is said?
1	S2	*Eh, it looks like a … eh … wigwam.*
2	T1	*No I meant structure.*
3	S2	*Threads are forming.*
4	S8	*Threads.*
5	S4	*Yes.*
6	S2	*Beautiful observation, isn’t it?*

In summary, the analysis of the enactment of the first design cycle showed that the strategy components i) use of systems thinking (expectations IIIa,b,c, IVa, Va,b,c) and ii) use of intuitive notions (expectations IIa, IIIa,b,c) could be generally incorporated into a chemistry teaching-learning process. Students were able to describe the way of thinking in general and superficial terms of ‘zooming into the material’ but they did not understand it well enough to use it in another situation. They could formulate structure-property relations for structures down to a scale of 10^{-5} m. They did not use these relations for levels below 10^{-5} m to find an explanation or to formulate criteria for the selection process, probably due to the increase of abstraction and the use of models of structures below 10^{-5} m. Students also had difficulties with the concept ‘structure’. The poor development of the concept ‘structure’ hindered students’ macro-micro thinking with scales and recognizing what the structure is at different levels before relating them to properties.

The elaboration of both strategy components showed potential, however new learning problems came to the fore which hindered a successfully elaboration of these components. For these reasons, the two argued strategy components did not lead in a sufficient extent to the intended effect. Therefore the content-principle had to be adapted regarding the development of the concept ‘structure’, since we identified this as most essential aspect and conditional for understanding that structures need to be attributed to scales, also at scale below sizes below 10^{-5} m.

Cycle 2: design, enactment and evaluation

Our findings with respect to the designed teaching-learning process in cycle 1 showed essential shortcomings in the students’ understanding of macro-micro thinking and students’ conceptual development. The design of the teaching-learning process needed adaptation. It appeared that the elaboration of the two strategy components i (Use systems thinking) and ii (Use intuitive notions of students that the cause of a property lies within a material) was not sufficient. In the enactment of the designed teaching-learning process the students did not adequately reach the intended conceptual development (pedagogical effect as described in the design principle; Figure 2). Therefore the design principle has to be reformulated by adding a third strategy component about the development of the concept ‘structure’, since students did not recognise the term as important. Furthermore, it is also likely that this is also the case for the term 'property'. This requires new arguments based on theoretical background to explain the 'why' and 'how' of designing a teaching-learning process that enables students an adequate concept development, in this case for the concepts 'structure' and 'property'.

With this new strategy component, we assume that the intended effect of strategy component i (Use systems thinking) will enhance understanding because students will understand better what is meant with structures or models of these structures. As a result the second strategy component will become more than 'zooming into the material' because now students will recognise more easily the systems and sub systems and relate them to the right scale. This will improve the quality of the structure-property relations.

The design principle revisited

After reflecting on the findings in the first cycle, we thus added a third strategy component to the content-principle: the use of the intuitive notions of 'structure' and 'property' in order to build on these notions for an adequate concept development. This requires new theoretical argumentation. According to Bakhurst (2007), intuitive concepts are formed in relation to concrete experiences by using criteria that sort entities into kinds. These criteria are formed by abstraction, a more general understanding, from the entities' surface characteristics. As described in Meijer et al. (2009), we have to pay attention to the developments of both 'structure' and 'property', because both are key concepts in the presented way of macro-micro thinking. When triggering intuitive notions of students with respect to the concepts 'structure' and 'property' (see Appendix C), students could be able to formulate their own definition of these concepts. Intuitive notions of structure could be: 'an ordering, arrangement', 'how things are connected with each other', and 'how things are build'. For property the intuitive notion could be: 'what something can or does', and 'a function'.

As a result of the students' own formulation of definition, the intuitive notions about 'structure' and 'property' can be used to categorize concrete structures and properties as a first step in concept development. As a result of this, the quality of the formulation of structure-property relations can improve and students can attribute a scale when referring to a specific structure at a meso- or submicro level. Therefore, the revised content-principle which is used in the design of the teaching-learning process of cycle 2, is formulated as (see Figure 4):

If *students use systems thinking by conceiving a material as a system of subsystems (intermediate meso levels) (strategy component i)* ***and*** *the intuitive notion is used that the cause of a property lies within a material (strategy component ii)* ***and*** the intuitive notions about 'structure' and 'property' are used (strategy component iii) ***then*** *students acquire macro-micro thinking using structure-property relations (effect).*

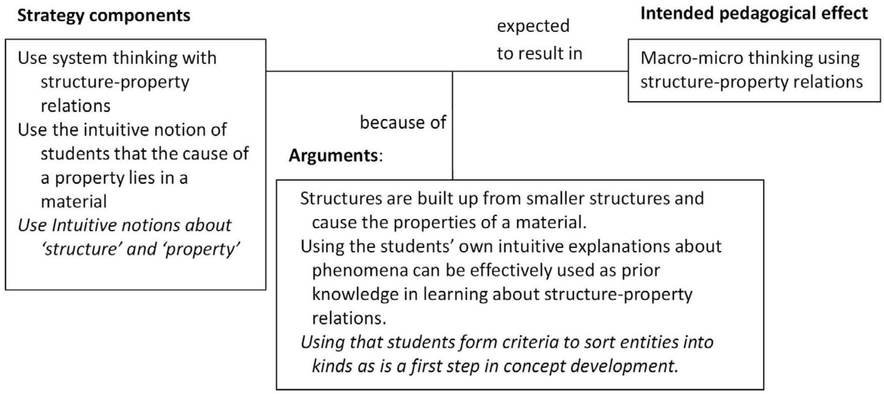


Figure 4 Revised content-principle and strategy components used in cycle 2. Additions to cycle 1 are presented in italics.

Elaboration of the strategy components

We focus on the description of the changes with respect to cycle 1 and therefore on the teaching-learning phases III and V. An overview of the teaching-learning process in cycle 2 is described in Appendix B. Table 2 presents only the most important detailed expectations regarding macro-micro thinking in cycle 2. These expectations do not include phase I, II and IV of the teaching-learning process, because these phases mainly relate to the setting of the context (I, II; Chapter 3 of this thesis) and to the set-up and performance of an appropriate sequence (phase I, II, IV; Chapter 4 of this thesis) which are beyond the scope of this chapter.

After starting the same exploratory experiment as in cycle 1, students investigate the properties of gluten-free corn bread, resulting in the conclusion that gluten is responsible for the quality of bread. A replacement for gluten has to be found based on information about hydrocolloids as potential additives to replace gluten. Students select hydrocolloids using superficial arguments in relation to water absorption and gelatination. Subsequently, they do experiments by adding these to corn dough and by baking new bread. The addition of hydrocolloids slightly increases the quality of the bread. Hence, students need to know more about the gluten to formulate more specific criteria for the selection of hydrocolloids. Students are given other information sources as well, i.e. an academic article, which results in the need to clarify the concepts 'structure' and 'property'. Modelled on our experience with a unit on ceramics (Pavlin, 2007; Meijer et al., 2009), a special teaching-learning activity is introduced (see Appendix C; activity 7) in which intuitive notions of students about these concepts are evoked and extended. Students are expected to use these intuitive notions (IIIb; Table 2) in the subsequent teaching-learning activities, when they execute additional strain-stretch experiments and dough experiments to develop gluten-free loaves of bread. During this process, experimental results and information from new sources guide the students into finding an acceptable

Table 2 Overview of the most important detailed expectations of the strategy components regarding macro-micro thinking in the relevant phases III and V of the teaching-learning process in cycle 2.

Teaching-learning phase	Strategy component	Detailed expectation
III Extension and use of Knowledge	i. Use systems thinking with structure-property relations ii. Use the intuitive notions of students that the cause of a property lies within a material	IIIa Students understand the thinking process using macro-micro thinking and structure-property relations.
	iii. Use intuitive notions about 'structure' and 'property'	IIIb Students are able - to formulate a meaning for the concepts 'structure' and 'property' in terms of ▪ Structure: a pattern, arrangement, construction, how things are built. ▪ Property: a characteristic, a function, something the material does. - to use these meanings in further teaching-learning activities.
	ii. Use the intuitive notions of students that the cause of a property lies within a material	IIIc Students search for an explanation for properties in the nature of the dough (structures at meso levels or system of structures).
	i. Use systems thinking with structure-property relations ii. Use the intuitive notions of students that the cause of a property lies within a material	IIId Students can formulate an explanation of the elastic property of wall of gas holes using their own formulations of structure-property relations by using the notions: - If there are walls around of gas holes (10^{-4} m) then the bite is good and the dough has a good resilience (10^{-1} m). - If the wall consists of a gluten network (10^{-6} m) then the wall is elastic (10^{-4} m). - If the entangled gluten chains (10^{-8} m) have some freedom to move then the gluten network is elastic (10^{-6} m). - If the polypeptide chains are connected by Sulphur-bridges (10^{-10} m) then gluten chains are flexible (10^{-8} m).
V Reflection and transfer	i. Use systems thinking with structure-property relations ii. Use the intuitive notions of students that the cause of a property lies within a material	Va Students are able to construct a conceptual schema. Vb Students are able to use this in a new task.

explanation of the elasticity of the wall of gas holes. The construction of a conceptual schema can now be designed as part of the reflection phase and used in reflecting on the thinking process.

As was the case in cycle 1, in cycle 2 most detailed expectations are related with the two strategy components, i and ii. When formulating a causal structure-property relation (strategy component ii), systems thinking (strategy component i) is used implicitly.

Evaluation of the strategy components

In protocol 2 (voice recordings and field notes), S19 and S20 achieved insight about the process they had gone through (line 1). They initiated a discussion because they wanted to find an answer to their own formulated question, 'how can you change meso structures by adding a gluten replacement to obtain more air into the corn dough?' When the last can be achieved, they had accomplished their task. Protocol 2 illustrates that students S19 and S20 recognised the relation between the cause of the elastic property of walls of gas holes and their task in the project. They described how to use this knowledge to achieve their goal (line 2). In fact, these students were able to relate a structure at a meso level with a desired property and therefore understand the intended way of thinking process (expectation IIIa, Table 2).

Protocol 2 Obtaining insight of S19 and S20 during an explanation in activity 12

Line	Who?	What is said?
1	S19	*So if the chains are more flexible … oh yes … then they can be stretched more and it becomes filled with air to a greater extent. You got it!*
2	S20	*So if the chains are flexible … what do we add to …then we can change the meso structure*
3	S18	*Yes, in my opinion*

The crucial expectation IIIb (Table 2) about the concept development of 'structure' and 'property' was 'fully' achieved (students' work and video recording of activity 7). Students were able to formulate explicitly what these concepts meant and to use their intuitive notions about these concepts as expected (student work, voice and video recording of activity 7 and 8). Their intuitive notions about both concepts appeared to be sufficient to understand the information in the (authentic scientific) documentation. In subsequent activities, their defining of these key concepts was good enough to enable them to arrange new scientific and technological terms in a coherent conceptual schema of 'structures and properties' (voice and video recordings, student work in activities 8 to 13 and 15).

The expectation IIIc (Table 2) about finding an explanation of the elastic property in the walls of the gas holes were both 'fully' achieved (voice and video recordings of activity 8 and 9; student work activity 13 and 15). Students were able to formulate structure-property relations as expected (IIId: Table 2) while they constructed the schema (voice and video recordings, student work of activity 15). The quality of their formulation was far more elaborate then in cycle 1: at this point they also did use structures below 10^{-5} m (student work in activity 15; Figure 5). In the reflection phase students formulated, for example, *'if glutenine molecules* (±10^{-9} m) *were not connected by Sulphur-bridges* (±10^{-9} m) *then it* [walls of gas holes] *will not be elastic'* (voice recording, conceptual schema activity 15; S22). Representative examples of these relations were:

- *If the glutenine molecule is connected by Sulphur-bridges, then a network can exist in which starch granules are imbedded(voice recording and students' work of S9, S10, S11),*

- *If there is no gluten network, then it is not elastic (voice recording S14, S20, S22),*

- *If glutenine molecules are connected by Sulphur-bridges, then it is elastic and it is possible to mould the dough (voice recording and students' work of S13, S14, S20, S22),*

- *If gluten chains are entwined, then the wall of the gas hole is firm enough to capture the gas bells (students' work of S9, S10, and S11).*

The presented examples of structure-property relations are not entirely scientifically correct because the students did not attribute structures to the correct scale in activity 9. The information offered by teaching-learning activity 6 and 10 did not present sufficient links between the models of structures and the scale of the corresponding representation in the materials. As a result, the students did not recognize which scale belonged to which representation. Furthermore, both the teacher and the information in the materials frequently used several metaphors. For this reason, concept development for the meaning of structures at a meso level was postponed or disrupted. As a result of an instructional dialogue held by the teacher in teaching-learning activity 10 (see further on; protocol 3 and Figure 6), this was sufficiently repaired in such way that students were able to independently construct an acceptable conceptual schema at teaching-learning activity 15. Students were able to relate properties connected with meso levels (elasticity, firm, 10^{-4} m) with structures at a level with a lower scale (glutenine molecules, entangled gluten chains, 10^{-9} m).

All students experienced to a large extent the intended way of thinking as necessary to accomplish the task. They could express the purpose of relating structures to properties. This reinforced the findings with respect to the expectation IIId. Exemplary is how S14 formulated this way of thinking in a conversation with the visiting headmaster (voice recordings during activity 12): '*Yes, if it stays together, then the dough can easily rise, because within the dough you find small bubbles with walls. If these walls break then the bread will not rise and the bread gets crumbled. So if the walls are firm, then bread will rise. … Gluten are long molecular chains and if they stay together, then it becomes elastic. And corn bread does not contain gluten,* *so we have to find a replacement'*. This is why S14 wanted to know why the walls of gas holes have an elastic property and so to achieve the task. He therefore wanted to understand what he had to do and why he had to do this. S14 was able to determine several structures at a meso level in the dough.

In phase V, reflection and transfer, students were able to present the macro, meso and submicro levels in a systematic way (student work): see the example in Figure 5 (expectation Va); other groups came up with similar schemas (student work). Together with the conceptual scheme, students had to formulate structure-property relations. However, during their subsequent task to design gluten free pasta, students were unable to make their way of thinking explicit (expectation Vb, Table 2; video and voice recordings, student work of activity 16). Hence, expectation Va (Table 2) was 'fully' achieved, and expectation Vb was 'not' achieved.

Although, many of the expectations were fulfilled, two new issues came to the fore during the teaching-learning process: 1) the use of metaphors, and 2) the difficulty with scaling.

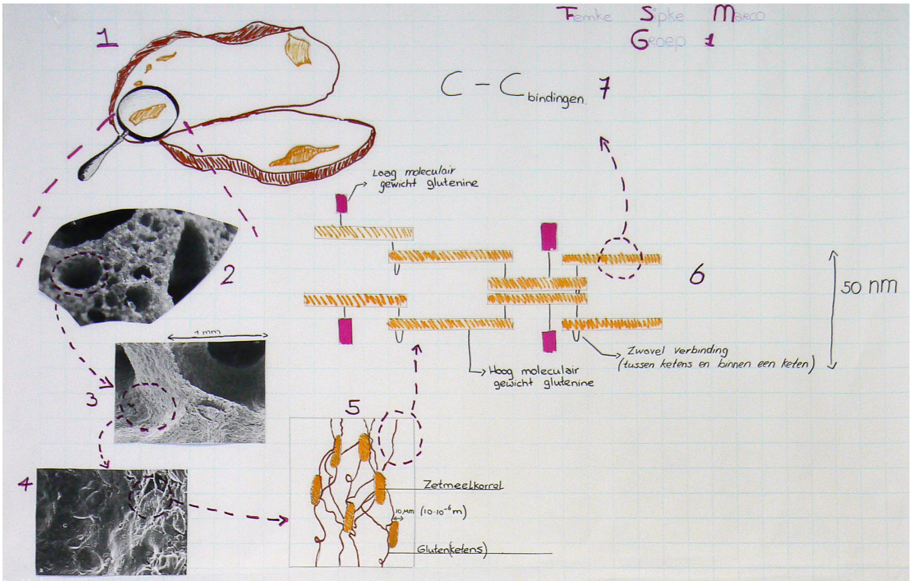


Figure 5 A conceptual schema constructed by students in phase V, Reflection and transfer. In the upper left corner is an illustration of a loaf of bread. The schema zooms counter clockwise into the meso levels down to a gluten molecule (6). Translated terms are (counter clockwise): low molecular weight glutenine, starch granule, chains of gluten, high molecular weight glutenine, Sulphur-bridges (between chains and within chains), C-C bonding.

In the greater part of the teaching-learning process, students used a language which was more related to the macro level (voice and video recordings, student work). In the design of the students' material, we used a balloon and a house of cards as metaphors for the growing gas hole in the dough and the weak construction of walls of gas holes within dough, respectively. Both students and teacher frequently used these metaphors at macro level for understanding the elastic property of walls of gas holes (voice and video recordings, student work in activities 13-17). For example, within the final explanation of their conceptual schema, students stated (video recordings and students work in activity 15), *'if the balloons cannot inflate, then* CO_2 *cannot be collected because the walls are too stiff'.* However, apart from the scientific incorrectness of this structure-property relation, the balloon-metaphor referred to a whole gas cavity, and did not refer to the cause of the impossibility to inflate. The use of the metaphor at macro level prevented a good understanding of the relations between structures and properties at the meso level.

We observed (again) that scaling was difficult for students (field notes, teacher interview and voice recordings) during phase III. For example, a discussion between the teacher and two students about the meaning of a picture in the information given to the students (picture on the left in Figure 6), is presented in protocol 3. The purpose of the discussion was to understand relations between different representations in the given sources.

Protocol 3 Discussion between students S9, S22 and teacher (T2), illustrating a scaling problem (voice and video recordings).

Line	Who?	What is said?
1	T2	*I want to zoom into the thread. Is the thread a link? What is the dimension of this link? What is the dimension of the granules? How do we know that?*
2	S22	*10 micrometre*
3	T2	*If you look at the pictures* [on the left in Figure 6] *and subsequently at the one of cellulose* [picture in the middle of Figure 6]*. You said that gluten chains are built up from molecules. What is the dimension of the molecules?*
4	S9	*Very small*
5	T2	*How small? …*
6	S9	*You cannot see it with your eyes.*
7	T2	*Yes. What is the distance between two carbon atoms? The atomic bond? …* [teacher gave the answer herself]
8	T2	… *So the threads in the figure* [left in Figure 6] *are these threads polymer chains? Is that possible?*
9	S9	*No*
10	T2	*So the question remains: what are these threads? Is there something in between?* [between the levels represented by the picture on the left and in the middle in Figure 6]
11	S22	*Maybe the wall of the figure in previous source?* [referring to the picture on the right in Figure 6]

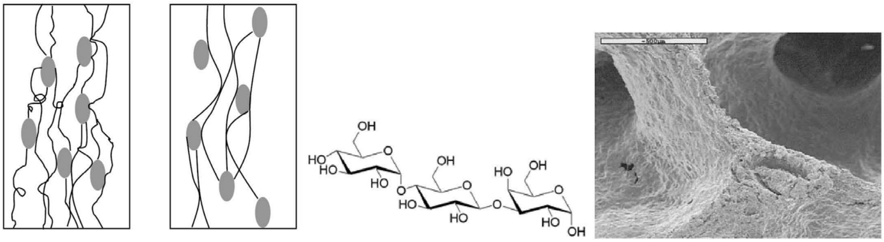


Figure 6 Three figures from information sources for students illustrate the scaling problem students had. On the left is a representation of a gluten network with gluten chains in rest and during dough stretching (10^{-6} m). The figure in the middle is a representation of cellulose (10^{-9} m). On the right is a scanning electron picture (Rojas et al., 2002) from a wall of a gas hole in dough ($500*10^{-6}$ m).

Students (noticed at least with S9, S10, S11, S13, S14, S20, S22; 7 of 14 students) were unable to make a correct scaling for the different representations in the information sources they were presented with (protocol 3: lines 7-8). Students did not have a notion of the size of a molecule or the length of covalent bonding (protocol 3: lines 3-6). At this point in the teaching-learning process, the ordering of the pictures on a length scale was difficult or impossible for students (protocol 3: line 11). However, the scaling problem was solved in an unplanned strong teacher-centred instruction at the end of the teaching-learning process and the students were able to construct their conceptual schema as expected. But even in the reflection phase scaling was still difficult for them (voice and video recording and student work of S13, S14, S20, S22). For example, students (S13, S14, S20, S22) formulated the structure-property relation (video recording of activity 15):*'If the gluten network is not entangled, then the bread will not be a firm whole and the threads within the gluten network will not be rearranged'*. This relation is not correct because 'gluten network' is used twice, referring to two different meso levels. The correct structure-property relation is: 'If the gluten ($\pm 10^{-8}$ m) within network (10^{-6} m) is not entangled then the bread will not be a firm whole' (dimensions given by us). This illustrates how difficult it is for students to relate meso levels to a specific scale.

In summary, the findings with respect to cycle 2 show that students were able to use macro-micro thinking by considering a material as a system which is built up from sub systems (strategy component i). Students use structure-property relations to explain the elongation of dough by 'descending' to meso levels at a lower scale (strategy component ii), although the scientific correctness of their relations could be improved. Students were able to construct a conceptual schema. The adapted content-principle (building development of abstract concepts on intuitive notions: strategy component iii) had the intended effect. Students appeared to be able to describe their intuitive notions and to use these in their learning (strategy components ii & iii). However, the issues of the use of metaphors and the problem of scaling still need attention.

Conclusions and discussion

In this chapter we have studied the pedagogical effects when exploring a new strategy to learn and teach macro-micro thinking with structure-property relations as causal relations between phenomena and meso levels within the material or substance. The strategy used included three strategy components: i) use systems thinking, (ii) use intuitive notions of students that the cause of a property lies within a material, and (iii) use intuitive notions about the concepts 'structure' and 'property'. The research questions were:

1) *To what extent does the elaboration of the strategy components lead to the intended effect that students acquire in macro-micro thinking using structure-property relations?*

2) *What is the formulation of the empirically underpinned content-principle?*

With regard to the first question, we achieved that students could determine structures and properties successfully and were able to relate phenomena and properties to structures at meso levels in the material or representations of these structures. Students were able to break up the system into smaller entities or sub systems as a way to bridge over the huge step between macro and submicro level (Millar, 1990). Students were also able to represent their way of thinking into a conceptual schema, together with the used structure-property relations. Finally, students were able to explain why and in what way the thinking process was intended. This refers to the reported difficulty for students with regard to macro-micro thinking to relate phenomena with corresponding models and representations (Justi, Gilbert & Ferreira, 2009). Beside this, students attributed other properties to sub systems when compared to the properties of the whole system. This indicates that students had a notion of the emergent character of properties which was also one of the reported difficulties (Penner, 2000; Harrison & Treagust, 2002).

To give an answer to the second question about the empirically underpinned content-principle, the formulation of the content-principle was (in the second cycle):

> '***If*** students use systems thinking by conceiving a material as a system of sub-systems (intermediate meso levels) (strategy component i) **and** the intuitive notion is used that the cause of a property lies within a material (strategy component ii) **and** the intuitive notions about 'structure' and 'property' are used (strategy component iii) **then** students acquire macro-micro thinking using structure-property relations (effect)**.**

This study has therefore enhanced our understanding of students' difficulties in bridging the gap between macro and submicro level, more specific in two aspects:

1) Students were able to distinguish different systems and sub systems and construct a hierarchy of these ontological entities into a conceptual scheme (Chi, 2005);

2) Students were able to descent from one level to another level at a lower scale by using the intuitive notion about the cause of a property when they were presented with information about these levels. Probably, this way of macro-micro thinking does prevent students to use macroscopic properties to describe the submicro world, a difficulty reported frequently in the literature (e.g. Wiser & Smith, 2008).

The results obtained in this study are subject to limitations. Firstly, only a small number of students (total: 22) and two different teachers were involved in testing and evaluating the design of the teaching-learning process, although both teachers had a long teacher experience and were familiar with recent curriculum developments. Secondly, the type of context for the intended way of macro-micro thinking using intermediate meso levels and structure-property relations is restricted to chemistry (materials science).

However, when working towards a new strategy for teaching and learning of macro-micro thinking, we were confronted with new challenges: 1) scaling was a problem for students and 2) the use of metaphors also hinders the intended conceptual development.

With regard to the first challenge, the intended conceptual development was hindered by difficulties students had in the scaling of meso and submicro levels (Tretter et al., 2006). In the enactment of the teaching-learning process in the first and the second cycle, we did not resolve the problem of scaling sufficiently. The students were able to come to an appropriate conceptual schema in the second cycle (Figure 5) because they could distinguish and categorize structures and properties. Students understood why they had to zoom in or out of the material, but they could not precisely describe the scale of the different levels. Still, during the enactment in cycle 2, students did not easily grasp the scales of meso levels below 10^{-5} m. People in general find it difficult to estimate a scale that largely transcends human proportions (Tretter et al., 2006).

The problem of scaling may be solved by a developmental trajectory from novice to expert (Jones et al., 2009; Tretter et al., 2006). This requires special attention within the curriculum development of science education. Scaling is related to intuitive knowledge, which becomes difficult when references to human sizes are not available. Human beings are unable to use language effectively when the size of an object (e.g., at the level of the molecules or the universe) is far removed from their usual perspective. This can be explained by the fact that spatial language is not only restricted to the size of objects but also to the way in which humans act (Pinker, 2008).

The second challenge is the use of metaphors. The apparent inappropriate use of macro level metaphors in students' material and the use of these metaphors by the teacher as a tool to increase understanding at submicro level in fact hindered their conceptual development. As a result, the students were hindered to describe relations between parts of the used metaphor and the elements of a structure at a specific meso level. In the teaching-learning process the use of metaphors was underestimated, more specifically the use of explicit structural relationships (Gentner & Wolff, 2000) between elements in metaphors and physical entities (similarities and differences). This challenge about metaphors might be approached by having students to describe in teaching-learning activities explicitly the relations between metaphors and physical entities (Gentner & Wolff, 2000; Treagust et al., 1998). However, this is complicated by the paradox that the acquisition of a new idea presumes the prior presence of the idea itself (Gentner & Wolff, 2000).

In retrospect, when comparing our empirical results with the findings and implications presented in Chapter 2, we have not paid enough attention to the prediction of properties or modelling by using the interactions between structures at meso or submicro level. In Chapter 2, this type of 'upwards reasoning' is frequently used by experts. However, the focus in the design task for students was too much on explaining the elastic property of gluten. To make full use of systems thinking with structure-property relations, both explaining and predicting of properties have to be incorporated in chemistry education. Therefore, we identify a new challenge about 'upwards reasoning' to predict a property.

With regard to this new third challenge, 'upwards reasoning', students should have the capacity to mentally 'translate' a model or representation of sub structures including their interactions at a level below 10^{-5} m towards a prediction of the behaviour of the whole (Justi, Gilbert & Ferreira, 2009). Students need knowledge about the interactions between sub systems and the plausible causal mechanisms behind these interactions (e.g. diffusion processes during sintering or the formation of a gluten network during the rising of dough) to build this model. The next step in upwards reasoning is to relate this (scientific) mental model to an emergent property of a structure at a higher level. In the design of a teaching-learning process, this needs attention. Students should become able to distinguish the mechanism of the interactions between the sub systems and summative outcome of all these interactions as property for the whole of the sub systems (Chi, 2005).

In the situation that students were able to recognize and use the interactions between sub systems, they could understand and describe (parts of) the whole system. The next thinking step for students is how these parts could interact under different circumstances, using the strategy components as recommended by this study for the design of other educational situations which demand macro-micro thinking, taking the limitations of this study into account. We illustrate this in an example, the task in which the students have to design a new material with a high elastic modulus for bullet-proof jackets (cf. Chapter 2). Students could derive criteria to obtain a new material with a high strength based on a study of the structures at meso levels using high strength materials Kevlar and Zylon B. Criteria could be related to the ordering of the molecules within both materials, necessary for a high alignment of molecular chains, and similarities and differences between both types of molecules and the type of intermolecular bonding which could lead to high crystalline structures within fibres and a high strength in longitudinal direction along the axes of the fibres. In this way, students could develop a more coherent mental model in line with the model for explaining and predicting properties of materials. Such steps might help to overcome the reported difficulty to connect models and representation with phenomena (Nakhleh et al., 2005).

When reflecting on the definition of the strategy components, we have to remark that for macro-micro thinking with structure-property relations, the strategy component 'systems thinking' requires at least three entwined parts, 1) use the notion that is a system is built up by sub systems, 2) use the notion that the cause of a property is found in the nature of a material and 3) use the notion that interactions between sub systems are used to predict a property. Therefore, from a designer perspective, we recommend that it is necessary to elaborate the entwined strategy component 'systems thinking' with the three parts mentioned above to achieve that students acquire macro-micro thinking using structure-property relations. Depending on the task given to students, different combinations of the three parts could be used, resulting in different alternative elaborations into the teaching-learning process.

The content-principle provides a useful guideline for incorporating macro-micro thinking with structure-property relations into a teaching-learning process. The results of cycle 2 show that the use of intuitive notions of the key concepts 'structure' and 'property' is a necessary condition to achieve that the elaboration of strategy components i and ii can lead to the intended pedagogical effect. However, two adaptations are necessary 1) the formulation of a strategy component with regard to explain or predict a property by using systems thinking and 2) at least two more strategy components should be added with respect to the scaling of structures and the use of metaphors to achieve the intended quality of structure-property relations. It should be remarked that a design principle has a heuristic nature (McKenney et al., 2006). The heuristic nature of the design principle is related to the complexity of the design of teaching-learning process, with variables such as the type of context, concept development, prior knowledge, and students' and teachers' competences. Therefore, there always needs to be a new cycle of design and evaluation to give the design principle its necessary empirical basis.

In this study we presented a content-principle for designing learning and teaching of macro-meso-micro thinking using structure-property relations and the introduction of abstract scientific concepts in an argued way. Its use can enhance the quality of chemistry education, but may be also useful in education in material technology, food technology and life sciences (Gilbert, 2009; p. 346). It provides challenging opportunities to address major problems in macro-micro thinking in chemistry education. Future work needs to include new challenges we identified to further enhance the quality and explicit use of macro-micro thinking by students.

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Appendix A Sequence of teaching-learning activities in cycle 1

Phase	Activity	Teaching-learning activity
I Orientation	1	Given the notes of a senior food developer of food products, students are confronted with the problem of people with coeliac disease.
	2	Students become employees of a (virtual) food production company. Based on given information students have to write a proposal as an internal memo. This proposal contains a primary idea for a solution of the problem: the development of a gluten-free food product is necessary.
	3	In the light of additional information, students choose corn to replace wheat, and select bread as exemplary food product.
	4	Students have to write a plan how to develop a gluten-free corn bread.
II Definition of the task	5	A guiding experiment is proposed in which three different loaves of bread are baked: 100% of wheat, 100% of corn and half wheat/half corn. In this experiment, students relate the gluten content to the quality of the bread. This results in the conclusion that a replacement for gluten is necessary for corn dough to yield at least the same quality of bread. Students write a more detailed project plan to develop a gluten-free corn bread.
	6	To reduce the problem, the steps of the baking process, 'mixing' and 'rising' are considered essential for this project. Students will realise that they need to know more about the properties of gluten to choose a suitable replacement to be added to corn.
III Extension of knowledge	7	Based on an additional experiment, students investigate the rising of bread. Students relate the structure of a gluten network to the elastic property of walls of gas holes. They do not know enough to explain this relation.
	8	Students carry out an additional experiment that makes them to descend to meso levels at a lower scale within the structure of dough. Students have to write down an explanation which relates the structure of gluten chains to the ability to be lengthened of dough.
	9	The different explanations of students are discussed within the whole group. A motive is evoked in students to study a new scientific article about hypothetical explanations of the elastic property of the gluten network.
	10	In this information source three hypothetical models are proposed which can contribute to the understanding of the elastic property of the gluten network. Students have to choose one of these models, using scale models of ropes (gluten chains) with knots (Sulphur-bridges). Depending on their choices, they can formulate an adequate explanation.
	11	Students reflect on their own explanation, given their task to obtain more knowledge how to develop gluten-free food products. They formulate their conceptual understanding of macro-micro thinking with structure-property relations.

IV Using the obtained knowledge	12	Using the accepted explanation, students are able to derive argued criteria for the replacement of gluten to be selected out of a group of carbon hydrates.
	13	A new article is presented to the students. The article contains information about the structures, interactions and properties of hydrocolloids. Informed by this article, students can select potentially suitable hydrocolloids.
	14	Students have to formulate arguments for a choice and propose an experiment for testing.
	15	Students discuss their arguments in the group and agree upon the proposed experiments.
	16	Students test the hydrocolloids they selected by baking loaves of corn bread. The results are evaluated.
V Transfer	17	Students reflect on the procedure and on their thinking process. Students are asked to use the obtained knowledge for another situation: developing a gluten-free Dutch doughnut.
VI Reflection	18	Students have to write a report which can be used as a starting-point for further research.

Appendix B Sequence of teaching-learning activities in cycle 2

Phase	Activity	Teaching-learning activity
I Orientation	1	In a video-tape, a senior scientist introduces a problem with respect to food products containing gluten and formulates a task of this project. This leads to a discussion between teacher and students about the adaptation of the project proposal and the procedure how to proceed. Students formulate their intuitive notions about a design procedure. They bake loaves of corn bread. For a reference base, they bake several loaves of bread with a variable ration corn to wheat.
II Definition of the task	2	In the light of this experiment, students relate the gluten content to the quality of bread. They conclude that a replacement for gluten to add to corn dough is necessary to obtain at least the same quality of bread.
	3	During a group discussion, students adapt the project proposal for designing bread without gluten. For this, they need more knowledge about additives that can be used as replacements for gluten to improve the quality of bread.

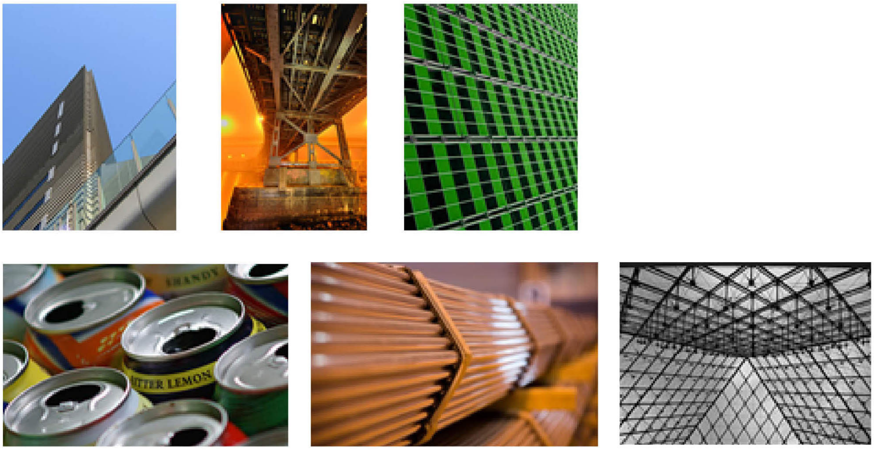
III Extension and use of knowledge	4	Hydrocolloids are used as normal additives for all kinds of food products. Students make a selection of hydrocolloids using rather superficial arguments they distract from an article about hydrocolloids as improvers for wheat bread.
	5	Several loaves of corn bread with different hydrocolloids are baked. This is the first design of the food product by students. The loaves of bread the students bake do not have the desired quality. More knowledge about the gluten is necessary for an argued selection of hydrocolloids as additives.
	6	Students are provided with a second article with detailed information about the baking process of wheat bread. More knowledge about the elastic property of the gluten network is necessary for the argued selection of hydrocolloids.
	7	To understand this second article, in which the concepts 'structure' and 'property' are presented, students experience that the meaning of these core concepts is needed. A series of photos is presented and elaborated to evoke intuitive notions about these core concepts.
	8	A group discussion about the article leads to a next step: carry out experiments as presented in the article on the baking of bread. These experiments are necessary to understand what causes the elastic property of the gluten network and provide possible improvements when hydrocolloids are added to corn flour.
	9	Students perform two additional experiments with corn dough with various hydrocolloids with different concentrations of hydrocolloids. The obtained results do not directly lead to one single conclusion. As a result more knowledge is needed about gluten networks. This will be the basis for an argued selection of hydrocolloids in a next step.
	10	A third article is introduced with information about the chemistry behind gluten, i.e. entangled long polymers which can form an elastic network.
	11	Using this information, students can derive criteria for selecting hydrocolloids as a replacement for gluten. Examples of criteria are: long hydrophilic chains with a low number of interconnections and long side groups.
	12	The selected hydrocolloids are tested in a second design of corn bread. Students explain the results using the given information.
	13	Students give each other feedback on their explanations, realising that other scientists have to understand these.
IV Reflection on design and thinking process	14	During a group discussion, students reflect about the purpose of their project. As a result motives are evoked in students to reflect on their procedure and thinking process.
V Reflection and transfer	15	To reconstruct their thinking process, students have to (re)organise their use of structure – property relations as into a conceptual schema of structures and properties.
	16	Students apply the knowledge they acquired with respect to procedure and thinking process for the design of another gluten-free product (pasta); they do this by writing a new detailed project proposal.
	17	Students write their report to the senior scientist: about the procedure how to design corn bread without gluten, about the results they obtained and the explanations they have formulated.

Appendix C Teaching-learning activity to evoke intuitive notions about 'structure' and 'property'

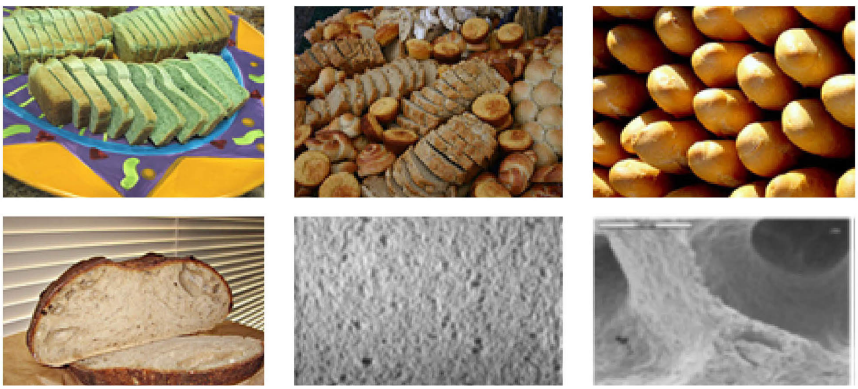
Pictures, adapted from www.flickr.com at May 2007, used to evoke intuitive notions. Within this teaching-learning activity, the students were asked the following questions:

- Can you describe why people have given each of the photographs the keyword 'structure'?
- Can you describe the properties of the objects in the last six photographs?
- What do these descriptions of structure have in common?
- What do these descriptions of property have in common?

Photo's obtained using the keyword: 'Structure'



Photographs obtained using the keywords: 'strucutre' and 'bread'.



Chapter 1:
Introduction and overview

Part I

Chapter 2:
Conceptual analysis of macro-micro thinking: structure-property relations for chemistry education

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Part II
Two cycles of design, enactment and evaluation

Chapter 3:
Establishing a context for learning macro-micro thinking

Chapter 4:
Sequencing teaching-learning activities to evoke students' motives for learning macro-micro thinking

Chapter 5:
Elaboration and evaluation of macro-meso-micro thinking using structure-property relations

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Part III

**Chapter 6:
A method for design-based research focusing on design principles for science education**

Chapter 7:
Conclusions and reflection

Chapter 6

A method for design-based research focusing on design principles for science education: a case study on a context for macro-micro thinking

Abstract

Design-based research is developing into a series of approaches that are frequently used in research on science education. Although agreement exists on general methods for design-based research, such methods are seldom described in a reflective way. In this chapter we describe how we focused design-based research on design principles including the arguments, strategies and the intended pedagogical effects for the case of context-based chemistry education for pre-university students. In a teaching-learning process about macro-micro thinking, students have to link daily life phenomena to the learning of (formal) relations between structures and properties in chemistry. Procedural stages for design-based research method and data from two empirical cycles are used to illustrate how the elaboration of the argued strategy components we started with was refined to obtain a valid insight and knowledge claim in terms of a design principle and an evidence-based framework of teaching-learning phases. We present how we linked theories on design of learning and teaching with design principles to obtain a contribution to this specific body of knowledge through design-based research. This is followed with a reflection on the presented method, the design principles and the validity of the method.

Introduction

Design-based research (DBR) is a rather new research approach (Brown, 1992; Collins et al., 2004) or series of approaches (Barab & Squire, 2004). It is an approach to design and develop an intervention (e.g. teaching-learning processes), especially to solve a complex educational problem with many variables for which a conclusive solution does not exist yet (Nieveen, 2009). DBR has two types of outcomes 1) development of the knowledge to support the processes to designing and developing education (Blessing & Chakrabarti, 2009; Nieveen, 2009), and 2) development of understanding, to advance knowledge about the characteristics of teaching and learning materials and processes.

In the design-based research community on education, there is a general agreement about what design-based research (or so called design studies or design experiments) is: it is iterative, situated, and theory-based research, aiming at understanding and improving educational processes (diSessa & Cobb, 2004), and it is evidence based and justified, improved or refined; it must explain why and how the elements from the theoretical base can be incorporated to achieve the intended effect (Barab & Squire, 2004; Burkhardt, 2006; diSessa & Cobb, 2004; Lijnse & Klaassen, 2004; Walker, 2006).

Although a certain consensus exists about when to apply a design-based research approach with its typical procedural stages: design, systematic development and evaluation, these stages are seldom described in a reflective and systematic way (Blessing & Chakrabarti, 2009). A reflective and systematic description should give a fellow designer of teaching-learning processes insight to decide how to generate, to select and to validate design alternatives at a level at which they have consequences for learning (diSessa & Cobb, 2004). It should also link existing theories about learning and psychological processes to the outcomes of design experiments (Nieveen et al., 2006). Furthermore, from the design-based researcher it is required to provide for a description how this insight developed into a knowledge claim.

The purpose of this study is to explicitly describe the procedural stages we followed and to reflect on our method and to illustrate our method for the case for context-based chemistry education in which students learn macro-micro thinking. We report about the procedural stages we applied, e.g. the type of (research) problems to be addressed, the type of knowledge base to be defined, the degree to which the design should be specified, and the way the intended effects should be achieved. By making the procedural stages explicit, we aim to present how we did come to the formulation of design principles as a knowledge claim.

The chapter is structured in the following way: first, we describe our method at a general level in terms of a process in four procedural stages, defining and elaborating design principles as a knowledge base. Then, for each of these stages, the main activities and products in the case study are presented. The final part of this chapter presents a reflection on the method and outcomes of each of these procedural stages.

The method for design-based research used in this study

In our method we distinguish four stages, which we have specified for the domain of education (Blessing & Chakrabarti, 2009; Brazer & Keller, 2008; Reeves, 2006).

1. A *Research clarification stage* leading to an analysis of an unsolved educational problem and a sketch how to solve this problem.

2. A *Descriptive stage* leading to a selection of relevant theories describing the assumptions necessary for a sketch to solve the problem, e.g. by identification of crucial factors or variables, resulting from available literature, earlier empirical explorations and/or practical experience of the members of the research team.

3. *A Prescriptive stage* concretising the sketch to a solution by combining it with the theoretical assumptions. It is described how and why the crucial factors or variables are used in the intervention and/or designed teaching-learning process, including a detailed description of the arguments why and how a designed teaching-learning process is expected to function as a plan for evaluation.

4. *An Evaluative stage* includes an empirical study in which a teaching-learning process is enacted and evaluated. The description includes an analysis of the enacted teaching-learning process in the classroom and the extent to which the intended teaching-learning process is realized. This stage is to draw conclusions about the usefulness of (the strategies included within) the teaching-learning process and how it has functioned. It describes which further investigations or improvements are necessary. The conclusions provide input for a reflection on the effectiveness of the design principles.

These four stages are in fact one cycle in an iterative research method. After the evaluative stage, a new cycle of description, prescription and evaluation takes place (see Figure 1, indicated by a redesign step: either step Y or step Z). We describe each stage to address the purpose of our study: to report about the method we have applied for our case leading to the formulation of design principles as an explicit outcome of our research method.

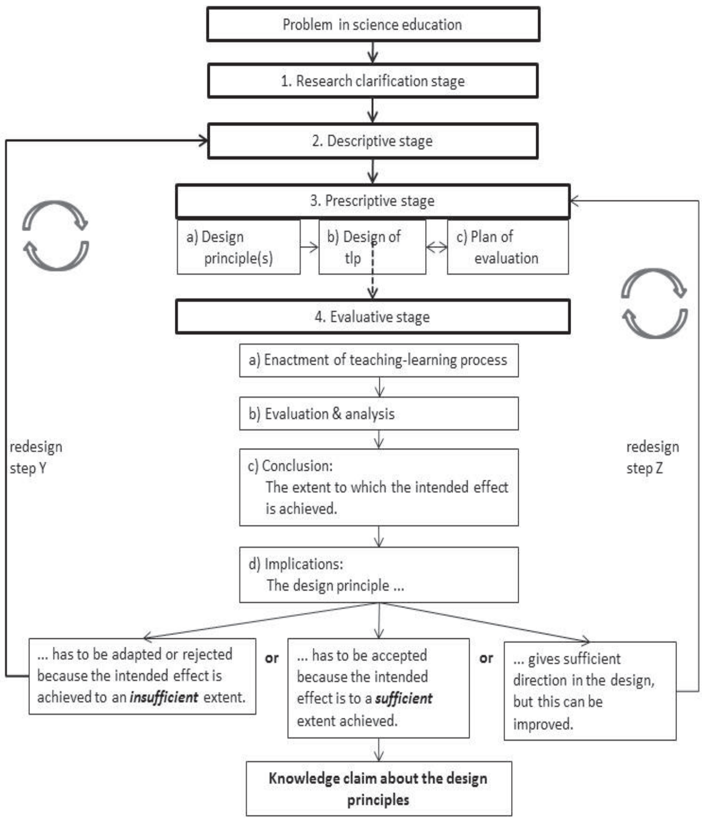

Figure 1 The method for DBR presented in this study

Design principles (Figure 2) form the core of our method and describe how strategy components can be used to design a teaching-learning process to achieve an intended pedagogical effect (Edelson, 2001; Hofstein et al., 2006; Swan, 2008; McKenney, Nieveen, & Van den Akker, 2006; Van den Akker, 1999). We consider empirically underpinned design principles as a knowledge claim. These design principles can be described as the result of the application of a design-based research method. Pedagogical effect refers to learning aims (e.g. macro-micro thinking, modelling) and/or (affective) educational aims (e.g. relevance, evoking motives) of the teaching-learning process.

A design principle is described with underlying *arguments* that relate the chosen *strategy* to the intended pedagogical *effects* as is schematically depicted in Figure 2. A strategy can contain one or more strategy components. The term *strategy component* refers to a potential process or sequence of student' activities to be planned or executed within a teaching-learning process to achieve certain intended pedagogical effects. A strategy component is an answer to the question: *'what strategy, based on a theory or experience is expected to be effective in the teaching-learning process?'* The strategy components are derived from potential solutions, formulated in the descriptive stage, related to the problems which are mentioned in the stage of research clarification.

The term *arguments* refers to the relevant literature, to empirical evidence of previous research cycles and to practical experience of the designer and/or teachers which are necessary to justify and to underpin the chosen strategy components. In fact the arguments contain one or more hypothetical mechanisms which explain why it can be expected that the use of the strategy component or combination of simultaneous use of strategy components leads to the intended effects. The term *mechanism* refers to a hypothetical or proven functional relation (between an aim and means) or correlative relation (between an effect and a cause).

Design principles can be both descriptive and predictive in nature and are considered to be hypothetical; they need to be confirmed or refined. They can be adapted or replaced based on findings of the evaluation of a design cycle. A design principle has a heuristic nature (Plomp, 2009). It is an argued but heuristic guideline for the designer of teaching-learning processes about how and why a strategy component is expected to function and can lead to the intended pedagogical effects. Due to the intrinsic incompleteness of a design (Petroski, 2006), design principles are developed or refined during the multiple cycles of design, enactment, analysis and redesign.

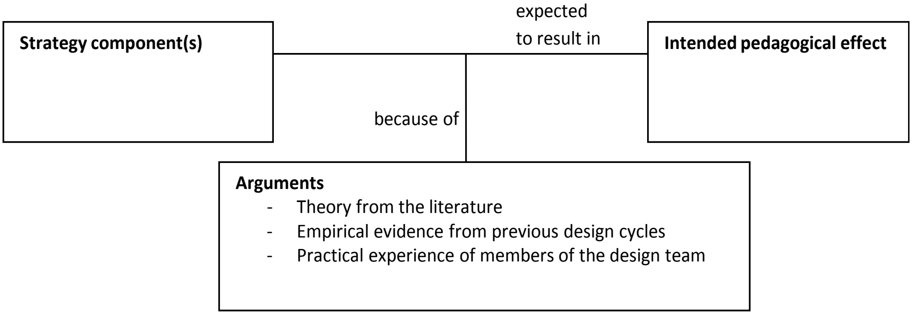

Figure 2 General presentation of a design principle

In the next sections, each of the procedural stages 1-4 is further explained and illustrated with the exemplary case with two cycles of description, prescription and evaluation.

Research clarification stage

Analysis of an unsolved educational problem and a sketch how to solve this problem.

In our case study *three problems* are important. First, students do not experience a connection between the phenomena in their lives and the chemistry theories, models and concepts they learn in school (Gilbert, 2006; Erduran & Duschl, 2004; Osborn & Collins, 2001). Second, students do not experience during their study why a preceding activity is followed by a next one. They do their work as a result of the top-down guidelines as being presented to them by the teacher and/or the textbooks (Boekaerts, De Koning & Vedder, 2006; Westbroek, Klaassen, Bulte & Pilot, 2010). Third, at this moment chemistry education has not found a strategy to bridge the huge gap between the experienced phenomena in the real world, and the abstract model descriptions of atoms and molecules which students experience as difficult to learn (Gilbert & Treagust, 2009; Millar, 1990). The step from observed phenomena (macro level) to the invisible entities at a scale of 10^{-9}-10^{-10} m (submicro level) is huge, and leads to cognitive confusion, such that students may give the sub microscopic entities the same properties as materials (e.g. Harisson & Treagust, 2002). The learning of this specific content is still problematic and unsolved in chemical education.

The *sketch of a solution* is as follows. To address the three problems, we chose to use adapted authentic practices as contexts (Bulte, Westbroek, de Jong & Pilot, 2006) for making the learning of chemistry relevant for the students (Chapter 3 of this thesis). From the vision that the content (i.e. chemistry) should be considered as a human activity, scientific and technological developments are interrelated with issues in society and part of our cultures. When positioning the specific content within relevant authentic practices, we use expert reasoning when they are addressing authentic tasks (Chapter 2 of this thesis). In this way, we anticipate that this sketch of a solution leads to a redefinition of chemistry content enabling an alternative, possibly more effective, sketch for the learning of macro-micro thinking.

Descriptive stage (cycle 1)

Selection of relevant theories describing and underpinning the assumptions necessary for a sketch to solve the problem, e.g. by identification of crucial factors or variables, resulting from available literature, previous empirical explorations and/or practical experience of the members of the research team.

The selection of key strategy components needs two theoretical perspectives: a) the selection of a teaching-learning theory to address the first and the second problem b) a process to analyse and redefine the content for addressing the third problem.

a. The selection of a theory for teaching and learning

With respect to the first problem, we select the cultural historical approach as a theoretical starting point. Consequently, we chose to position teaching and learning within an authentic social practice as context (Bulte, Westbroek, de Jong & Pilot, 2006; Westbroek et al., 2010; Van Oers, 1998). We argue that students will be enabled to construct meaning in connection to the concepts they learn, when they can connect their learning of the concepts to relevant social practices, for example related to foods, medicines, material science.

The second problem, the lack of motives with students to perform teaching-learning activities in a certain sequence, is connected to the first problem. We argue that through a relevant outline of a sequence of teaching-learning activities within a relevant context, students come to see why to proceed to a next activity. If students are provided with a specific (learning) task which is adapted from the social practice to make it relevant from the students' perspectives, students see intuitively what, why and how to do to achieve this task (Van Oers, 1998). In this way, students have a motive to perform each of the teaching-learning activities because they experience each of them as necessary. The incorporation of this strategy requires some freedom for students and another role of the teacher. Influence and self-regulation of students have to be part of the teaching-learning process.

In educational research, specific causal or functional relations between strategies and effects (mechanisms) which are needed for design decisions are frequently not available because the theories of learning and teaching are incomplete or underdeveloped. For example relevant variables without clear causal relations with intended effects are: the motives of students, the productive use of their intuitive notions, the selection of (learning) tasks and the procedural steps to accomplish such tasks, and a balance between students' freedom and teacher guidance. Within the chosen theoretical perspective, in the design of the teaching-learning process students and teacher are considered as a community of practice in which students perform one task. It requires a teaching-learning process with a subdivision into several (teaching-learning) phases which are derived from an adapted procedure of an authentic practice. We argue that in such a way students can address the selected (learning) task.

b. A process to analyse and redefine the content

The theoretical perspective of authentic social practices as contexts for learning requires a *new conceptual analysis of the content* with regard to the content problem, such that the reconstructed and/or redefined content can be incorporated into a teaching-learning process in the classroom (Bulte et al., 2006). As is the case in the model of educational reconstruction (Komerek & Duit, 2004), a new conceptual analysis is an integral part of our research method, as it will be in many domain specific design-based research studies. In the case we present, the re-orientation on the chemistry content is focused on the specific content of macro-micro thinking. However, in other studies such a re-orientation also forms an essential part of a design-based research approach, e.g. for the case of modelling in science (Prins, Bulte, Van Driel & Pilot, 2009).

In traditional chemical education, macro-micro thinking focuses on the particulate nature of substances in terms of molecules and atoms. In this way, macroscopic phenomena such as the different properties between gases, liquids and solids, can be explained. However, the proposed models are not suitable to explain or understand many of the daily life properties such as the elasticity of an elastic band, the strength of a wall, the deformation of dough, elongation, fracture, and so on. Nor are the models suitable to address real authentic tasks positioned within authentic practices. With a traditionally defined content, students do not come to know that properties emerge from structures within a material that are not directly related to molecules and atoms. The contents lack models that relate properties to structures at intermediate (size) level. For example structures such as treads of polymer fibres in coats, small ice crystals, micelles in food products such as milk, are respectively related to properties as the waterproof protection of gore tex, taste of ice cream, and transparent milky products. This focus on the content has not been explored yet in the domain of science education. Because the research for this important problem in science education does not provide new solutions during the past years, we do search for a solution within authentic practices related to the specific science domain. For a detailed description see Chapter 2.

Prescriptive stage (cycle 1)

Concretising the sketch to a solution by combining it with the theoretical assumptions, it is described how and why the crucial factors or variables are used in the intervention and/or designed teaching-learning process, including a detailed description of the arguments why and how a designed teaching-learning process is expected to function as a plan for evaluation.

In this stage, there are three main activities: a) The formulation of initial design principles and research questions. b) The design of the teaching-learning process by elaboration of the strategy components. The teaching-learning process is divided into teaching-learning phases containing one or more teaching-learning activities which are accompanied by expectations as concretized versions of the intended effects. c) The formulation of a plan of evaluation with the planned details for enactment, data collection and analysis.

a. The formulation of initial design principles and research questions

First, to formulate the design principles, key strategy components, underlying theoretical arguments and the intended pedagogical effects are described. These three elements form together a design principle (Figure 2; McKenney, Nieveen & Van den Akker, 2006). This activity also involves the formulation of the research questions.

In our method, the formulation and evaluation of design principles are used to develop a model for a specific teaching-learning process, and to reveal the underlying vision and assumptions (the 'why') and the use of design principles (the 'how'). The list of strategy components may be longer, however only necessary conditions for the elaboration of a strategy component in the instructional designs should be incorporated. In this way, the choice for the strongest relation to the intended effect should be highlighted. Examples of such design principles can be found in Merril (2002) and the database of design principles (Kali, 2008). In order to obtain a clear and simple model which can be handled by the designer, the number of strategies components should therefore be restricted.

We develop three design principles related to 'context', 'sequence' and 'content', which are addressing the three-fold problem described in the research clarification stage. The context-principle deals with the strategy to set up of a social practice as a context to increase the relevance of learning macro-micro thinking for students. The sequence-principle focuses on strategies to realise a sequence in which students have a motive to perform every teaching-learning activity to achieve the goal of the learning task (second problem). The content-principle is related to strategies on how the content-related part of macro-micro thinking can be incorporated into the teaching-learning process (third problem).

Context-principle

The *arguments* for the development of the context-principle are based on theories on social practices (Vygotsky, 1978; Wenger, 1998). Using these theories, we focus on an authentic practice which is defined as a homogeneous group of people in society working on real-world chemistry problems and societal issues in a 'community' connected by three characteristic features: common motives and purposes, working according to a similar characteristic procedure and using similar background knowledge about the issue they work on (Bulte et al., 2006; Prins et al., 2008). In an authentic practice, activities and conceptual knowledge do form a coherent whole (Gilbert, 2006; Bulte et al., 2006; Prins et al., 2008). According to Van Oers (1998), the context emerges into the existence in the interactions of students when it becomes clear what kind of task is to be accomplished (strategy component i). The procedural steps, how to accomplish the activity should be based on the intuitive notions of students (strategy component ii). In that case, the procedural steps can be seen as relevant from the perspective of the students. Students will become members of a community by involving engagement to the task (Wenger, 1998). To improve the engagement, productive interaction is needed which means that students have to share personal experiences, references and memories with others (strategy component iii) which also increases the forming of a community (Ryan & Deci, 2000). There is a need to pay attention to the students' input (Westbroek, 2005) and self-regulation (Pintrich, 2003; Ryan & Deci, 2000). This initial context-principle to design a context as an address to the first problem is formulated as (see further Chapter 3):

> **If** students as participants of a community of practice within the classroom are provided with a practice-related task *(strategy component i)* **and** have their own plan of action based on intuitive notions *(strategy component ii)* **and** productive interaction is enabled *(strategy component iii)* **then** a context is established at the start of the teaching-learning process as a condition to make the learning of chemical concepts relevant to students (*intended pedagogical effect*).

Sequence-principle

The sequencing of the teaching-learning activities should be such that students recognize the steps in the characteristic procedure which is necessary to accomplish their task in the authentic practice. For educational purposes, the activities within the authentic practice need to be adapted, because students do not have the experience of experts and the students are involved in learning activities towards a specific learning goal and assessment. The design of the teaching-learning process involves the adaptation of the characteristic procedure consisting of adding specific steps to introduce new information, experiments and reflection activities to achieve the learning goal (strategy component iv).

The *intended effect* of this design principle is to realize a teaching-learning process in which students know 'why what to do next' when proceeding from one activity to the next (mentioned as the second problem of this case study). Therefore, the designer should sequence the anticipated students' motives to enable students to proceed from one activity to a next one (strategy component v). So they know at every moment within the teaching-learning process why they have to perform a teaching-learning activity in order to accomplish their task (Lijnse & Klaassen, 2004). Based on these arguments, we formulated the sequence-principle as (for a more detailed description see Chapter 4):

> **If** a procedure is used which is built on intuitive notions of students *(strategy component iv)*, **and** motives are sequenced in such a way that the reflection on one teaching-learning activity provides the orientation for the next *(strategy component v)*, **then** students experience a sequence of teaching-learning activities in which they know 'what to do next, and why' *(intended pedagogic effect)*.

This design principle gives directions for the sequence of activities in a designed teaching-learning process. However, it does not include the specific conceptual domain, or conceptual area of the teaching-learning process (or in terms of activity theory, the 'tools' of the social practice). In chemistry education, these 'tools' are provided by a specific conceptual area within the domain of chemistry, and prescribed by the content-principle that is discussed next.

Content-principle

Following the newly reconstructed conceptual organisation as an outcome of the descriptive stage, we describe macro-micro thinking using systems thinking (strategy component vi) as presented in Figure A1 in the Appendix. In the case that a cause of a property should be explained, students need to search this in the nature of the material itself (strategy component vii). This intuitive notion about a cause of a property is used as an explanatory framework of the natural world (Harré et al., 1975). So, to explain or to understand a certain property, students have to identify the structure which causes this property. In this way, structure-property relations are the connections between the macro, meso levels and if necessary to the sub-micro level. A detailed description can be found in Chapter 2. To design a teaching-learning process to realize the intended pedagogical effect, the content-principle can be defined (see also Chapter 5):

If it is assumed that materials are a system of subsystems (with intermediate meso levels) *(strategy component vi)* **and** the intuitive notion is used that a cause of a property lies within a material *(strategy component vii)* **then** students acquire macro-micro thinking using structure-property relations *(intended pedagogical effect)*.

The design principles constitute an important part of the knowledge claim of our study. At this meta level, it seems that the design principles are not entwined. However, when the strategy components of the design principles are elaborated at the level of teaching-learning activities, design principles form an interrelated system, incorporated within a teaching-learning process with specific learning phases. E.g., in cycle 1 of this study, seven strategy components divided over three design principles 'context', 'sequence' and 'content' are used. At least, two strategy components will be necessary to obtain the intended effect, since very rarely there is relation between a single strategy component and a single effect. The design principles form a nested system; e.g. the context-principle is conditional for both sequence and content-principle. The context-principle is connected with the chosen (learning) task given to the students in which motives, goals and procedural steps are necessary to accomplish this task. However, these factors are also part of the sequence-principle and the content-principle since the task should be accomplished using tools such as chemical concepts and steps in their thinking.

Because the context-principle is conditional for the both sequence and content-principle, we illustrate the research method with the first strategy component of the context-principle only.

Research questions

Connected to a concretized teaching-learning process as an elaboration of the design principles, the research questions have the form: '*To what extent does the elaboration of the strategy components lead to the intended effect?'* and *'What is the empirically underpinned design principle?'* For illustrating our case, the specific research questions for the context-principle are:

1. *To what extent does the elaboration of the strategy components lead to the intended effect: the establishment of a context as a condition to make the learning of macro-micro thinking relevant for students?*

2. *What is the empirically underpinned context-principle?*

For the formulation of the other research questions in relation to the sequence and content-principle, we refer to respectively the Chapters 4 and 5.

b. The design process of the teaching-learning process; elaborating the strategy components

The design of the teaching-learning process starts by using a framework of teaching-learning phases, with functions of each learning phase, together with general expectations about how the learning phase will function in relation to the main goal of the learning process (second column in Table 1). The functions of the learning phases (see further, the second column appendix B) are a direct consequence of the chosen theory for teaching and learning, that is, an orientation of the practice-related task of the authentic practice is a necessary first step. In our case the teaching-learning process of cycle 1 consists of six teaching-learning phases: orientation, definition of the task, extension of knowledge, use of knowledge, reflection on design and thinking process, and reflection and transfer (see further Chapter 4 of this thesis).

Next, the learning phases are made concrete into a detailed outline of teaching-learning activities, accompanied with the theoretical or experiential arguments about why and how the teaching-learning activity will function as described by a detailed set of expectations. The whole set of expectations together describe the intended effects. The concrete expectations result from the elaboration of the strategy components; they may be connected to one or more strategy components (Table 1 and Appendix B). Designing is an iterative and creative process in which the designer(s) regularly switches between the design of teaching-learning activities, the underlying arguments and the intermediate activities to optimize the sequence of teaching-learning activities.

The framework of teaching-learning phases (Appendix B) is a 'model' for the teaching-learning process. Each of the phases consists of one or more teaching-learning activities together with the general expectations for the phases and the detailed expectations for each activity based on arguments.

In our case, the context-principle demands that specific choices are made for the type of authentic practice, the specific exemplary task, and the focus with which the task is addressed. We chose the following task for students: to acquire more knowledge about the development of gluten-free food products. There are two arguments for this choice. First, the relatedness with disease, people and food are close the students' daily life. Second, students need the specific content of macro-micro thinking with structure-property relations to achieve their task. Therefore, the context has to be the practice of developer of food products. In that practice, the task, the procedure to accomplish the task, and chemistry concepts and macro-micro thinking are relevant. The concretized outline of the designed teaching-learning process in cycle 1 is described below: the elaboration of the strategy component i of the context-principle 'select a task' (see Table 1).

In the orientation phase of the teaching-learning process, the task includes the presentation of the fact that about 15% of the human population has gluten intolerance. The initial setting is elaborated as a possible business idea of a virtual senior co-worker of a food company intending to develop gluten-free food products for the target group. This introduction is modelled on a realistic authentic practice. As participants in such an authentic practice, the students as junior developers of food products have to formulate their own proposal for a new project for the company to develop one of the gluten-free products as an example: bread based on corn instead of wheat.

For the development of gluten-free food products, the removal of gluten from wheat is far too complicated to perform in secondary education, so corn is presented to students as a useful replacement for wheat. The use of corn, however, leads to low-quality bread. Gluten consists of proteins which form an elastic network (structure) which can capture the carbon dioxide gas (property) that is formed during fermentation of the yeast. Due to this property of the gluten network, the dough will rise, eventually producing an acceptable quality of bread. Therefore, students have to find a replacement for gluten to add to the corn dough. For understanding this relationship, the students have to notify that they need to know more about the ability of wheat dough to capture gasses at the start of the teaching-learning process.

On the basis of the arguments for the design, the detailed expectations can be described as concrete realisations of the intended pedagogical effect (see Table 1). Connected to the elaboration of strategy component i of the context-principle, these detailed expectations are as follows. Students recognise the socio-scientific issue, which becomes relevant for them (expectation i-a). Students recognise that the practice-related task exists within an authentic practice; they develop a shared motive to accomplish this task (expectation i-b). As a consequence, the plan of evaluation contains these concrete descriptions of the expectations.

c. Formulation of the plan of evaluation, the planned enactment, and data collection and analysis

In the evaluation plan, the expectations are written in concrete observable behaviour of students or formulations of students' answers, statements or other outcomes (see examples in Table 1). For each learning phase, the expectations are related to the strategy components (see Appendix B). The expectation about a shared motive to accomplish the task is formulated as concrete observable behaviour, e.g. as enthusiastic reactions of students and focused actions of students to complete the task. Besides the complete set of expectations related to the elaboration of the three strategy components, the *plan of evaluation* is completed with appropriate instruments for data collection and protocols for data analysis.

Table 1 The context-principle with strategy components and intended effects concretized into detailed expectations embedded within the teaching-learning phase 'orientation' for cycle 1.

Learning phase	Expectation of phase	Context-principle Strategy component	Detailed expectation
I Orientation	Students experience the relevance of the task to design gluten-free corn bread as exemplarily of a class of food products because people have coeliac disease.	i. Select a task	a) Students recognise the socio-scientific task, which becomes relevant for them. b) Students recognise that the practice-related task exists within an authentic practice; students develop a shared motive to accomplish the task.
		ii. Use intuitive notions of students with regard to procedural steps	a) Students restrict the task by zooming from a range of food products into one product (bread) and use corn instead of wheat. b) Students have a notion about the main procedural steps of the development process: exploring the problem, finding an explanation, designing and evaluating. c) Students are able to extend their notions about the procedure with the use of a replacement for gluten and knowledge about baking bread.
		iii. Enable productive interaction between participants	a) Students experience being able to influence the task and the process to accomplish the task. b) Students become participants in the community of practice by accepting their role as junior designers of food products.

Evaluative stage (cycle 1)

An evaluative stage in which a teaching-learning process is enacted and evaluated. The description includes an analysis of the enacted teaching-learning process in the classroom and the extent to which the intended teaching-learning process is realized. This stage is to draw conclusions about the usefulness of (the strategies included within) the teaching-learning process, how it has functioned and which further investigations or improvements are necessary. The conclusions provide input for a reflection on the effectiveness of the design principles.

The product of this phase is a thick description in which the findings are presented as the evaluation of all concrete expectations, whether these are achieved or not achieved; subsequently, the conclusions are formulated. As an implication, the designed teaching-learning process as elaboration of the strategy components and the formulation of the design principles need to be part of discussion when the intended pedagogical effects are not fully achieved. If necessary the formulation of the strategy components and consequently the design principles, as a contribution to the body of knowledge, together with the designed teaching-learning process needs to be adapted or refined.

a) The enactment of the teaching-learning process in the classroom and collection of data

Enactment of the teaching-learning process in the classroom takes place by a well prepared teacher. In the first cycle, the teaching-learning process is enacted with a small number of representative students in a small scale setting, because this case study has an explorative character. In this case we used 8 students (17 y, pre-university level, grade 12) and one teacher.

During the enactment, the researcher needs to collect the data by using multiple sources and observes what actually happens in the classroom while the teaching-learning process is enacted. The data sources to be used are video and voice recordings, observations and field notes, questionnaires before (pre-questionnaires) during and after enactment (post-questionnaires), students' work, and interviews with students and the teacher. Pre-questionnaires are used to collect the prior knowledge of individual students.

b) Data analysis, including validation strategies

A valid process of in-depth analysis of the collected data is set up. This process makes high demands upon the method, the protocols for analysis and coding, and the validation strategies to address the issues of objectivity, subjectivity, reliability and validity. The purpose is to obtain a 'version of reality' of what has happened in the classroom during the enactment. The whole research team has to reach agreement about this.

Data collection and analysis are mainly qualitative, although also quantitative methods may and can be used where appropriate. Criteria for valid qualitative methods can be found in e.g. Miles and Huberman (1994). For example, McKenney et al. (2006) mention 'the extent to which causal relationships can be based on the findings'. Creswell (2007, p. 207) considers 'validation' as an attempt to assess the 'accuracy' of the findings. This accuracy improves when researchers know the culture of the research field to interpret the observations in the right way (issue of subjectivity), by triangulation of multiple data sources, independent analysis by two researchers (issue of reliability) and, by using a thick description to enable readers to transfer the information into other settings. For a valid study at least two validation strategies are necessary (Creswell, 2007, p. 209).

In this case, we determine to what extent the intended pedagogical effect is achieved by using the set of the detailed expectations as a framework for analysis. The data are analysed by comparing the actual activities and effects with the set of detailed expectations by two researchers independently. Triangulation of data sources takes place to increase the validity of the findings. Video and voice recordings together with the field notes of the researcher provide a first analysis of the enacted teaching and learning activities and a detailed description of what takes place in the classroom. The whole group of students is taken as the unit of analysis. The number of students who act as intended, is counted to determine their active involvement during classroom discussions. A further 'thick description' is obtained by using copies of the work of the students, post-interviews, pre and post questionnaires, and questionnaires during and after the orientation phase. These in-between-questionnaires are especially designed to verify whether the students have an outlook for the next teaching-learning activities. Questions in these students' questionnaires were a) 'How do you judge each teaching-learning activity on a five-point Likert scale?', and 'Provide arguments for your judgement'; b) 'How do you judge this teaching-learning process with regard to difficulty, personal interest and information?', and c) 'Can you formulate the purpose of this teaching-learning process and describe an outlook to the next teaching-learning activities?' This 'thick description' is compared with the intended teaching-learning processes, described in detail by the set of expectations (fourth column in Table 1).

The extent to which the expectations are realised are reported on a three-point scale using the terms 'not', 'partly' or 'fully' achieved. If only one or two of the students act according to the intended expectations, we use the term 'not achieved'. 'Fully achieved' means that at least 80 per cent of students acted according to at least 80 per cent of the expectations (Juran, 1974). This is considered sufficient for the explorative purposes of the case study. The term 'partly' refers to outcomes in between 'not achieved' and 'fully achieved'. For each detailed expectation, the extent of achievement is determined.

The judgment on a three-point scale is performed by two researchers independently. We regard 80% as the lower limit for a substantial level of agreement (inter rater reliability; Miles and Huberman, 1994, p. 64; Prins et al., 2009). The qualitative judgements are discussed among the two raters until they reach consensus about the findings. Subsequently, the whole set of 'thick descriptions' is discussed in the entire research team in a peer review process.

To formulate the findings, the researchers zoom out from detailed expectations of each teaching-learning activity to overall expectations of the teaching-learning phases focusing on the teaching-learning process at the level of the strategy components and the design principles. Then, a conclusion can be draw about the effect of each strategy component. In this way, the research questions can be answered.

c) Findings and conclusions

Conclusions are drawn about the usefulness of the strategies included within the teaching-learning process, how this process has functioned and which further investigations or improvements are necessary. The conclusions provide input for a reflection on the effectiveness of the design principles and the precise answering of the research questions.

This part of the method is illustrated by a description of the findings and conclusions of our case with respect to the first strategy component (select a task) of the context-principle, here for the first cycle. The expectations, as concretized intended effects, were: (i-a) students recognise the socio-scientific task, which becomes relevant for them, and (i-b) students recognise that the practice-related task exists within an authentic practice; students develop a shared motive to accomplish this task (Table 1).

We found that expectation i-a was 'fully' achieved. Students recognised the socio-scientific task and it was relevant for them (voice and video recording activity 1, cycle 1). The motivation of students to participate in this project came to the fore in the first group discussion at the beginning of the teaching-learning process (voice and video recording activity 1, cycle 1). The coeliac disease problem was important for three students (S1, S3, S4). Two students (S4 and S5) had family members who suffered from the disease. Two others (S7 and S8) knew that gluten-free products are sold because they work at a bakery. During the group discussion, all students displayed the insight that coeliac disease is a problem for people (voice and video recording of activity 1, cycle 1).

Although, students recognised the task of developing gluten-free bread, this only 'partly' evoked a shared motive to accomplish the task (expectation i-b; voice and video recording of activity 3 and questionnaire after activity 4). First, only two students showed the intended motive to accomplish the task: a formulation that can be considered as a motive was expressed by students (S2 and S8) in wording such as (voice and video recording of activity 3, cycle 1) *'we have to develop something'* and *'if we develop a new product'* and *'we also want people to buy our product'*. This was interpreted as a sense of ownership of the task. Second, a clear focus of the task was lacking in all descriptions formulated by the students (questionnaire after activity 4). A summary of those formulations is presented in Table 2. The task we selected was relevant from students' perspectives; however, we did not manage to evoke a shared motive due to the diverse interpretations (development, set-up, production, investigate, produce) of students about the task.

Table 2 Formulation of the task as recognised by students (questionnaire after activity 4)

The development of a gluten-free bread (S1 and S2),
Set up a project for the development of gluten-free bread (S3)
The production of different breads and experiments, learning from errors, with an excellent bread as outcome (S4)
To investigate the finest method of production of an innovative product (S5)
To produce a perfect gluten-free bread that addresses the following aims …(S6)
Using chemistry to find a solution for the hypersensitivity related to these proteins (S7)
Development of something innovative (S8)

With respect to the strategy component i, 'Select a task' (Table 1), we concluded that it was partly effective. As designers we did not manage to develop a shared motive for the accomplishment of the task (i-b), although the students experienced the task as relevant (i-a). As we conclude, the task in cycle 1 did not have a clear *focus*. Therefore it was not well defined for students what exactly they had to accomplish (Van Oers, 1998, p. 480).

d) Implications

When it appears necessary from the findings and conclusions, the formulation of the strategy components and consequently the design principles and the teaching-learning process need to be adapted or refined. This should provide a further contribution to the body of knowledge.

This part of the method is also illustrated by a description of the implications in our case with respect to the first strategy component (select a task) of the context-principle, here for the first cycle. An implication resulting from the given conclusion was that the task has to be clearly *focused* on the *design process* of a class of gluten-free food products to gain knowledge about the properties of gluten for designing food products. In this way, the task should evoke a broad motive to start with. As a consequence of the *focused* practice-related task, we argue that the necessary steps to accomplish the task are more easily evoked in students in an intuitive way. Secondly, the use of an external motivational aspect, an external supervisor as a member of the authentic practice, should introduce the issue to the students and can thus keep the students more *focused* on the goal of their task. Both students and teacher are then framed by the goal of their task (Sadler, 2009, p. 4).

Summarizing, the effect obtained in design cycle 1 was not as intended. The strategy components showed potential to achieve the intended effect; however, the elaboration into the designed teaching-learning process did not lead to the intended effect to a sufficient degree. The implication was that the formulation of the strategy components needed improvement although we did not have to add one or more strategy components in the design principle. As a result, the context-principle had to be refined. This illustrates the feedback loop from the evaluative stage to the descriptive stage (Figure 1: redesign step Y).

Descriptive and prescriptive stage (cycle 2)

The further description of the stages in the second cycle is also illustrated by a description of our case with respect to the first strategy component (select a task) of the context-principle. Based on the results from cycle 1, increased understanding of the design problem and additional literature, the teaching-learning process was redesigned. The new context-principle was formulated as (the new element 'focused' in italics): **If** students as participants of a community of practice within the classroom are provided with a *focused* practice-related task (strategy component i) **and** have their own plan of action based on intuitive notions (strategy component ii) **and** productive interaction is enabled (strategy component iii), **then** a context is established as a condition to make the learning of chemical concepts relevant to students (intended pedagogical effect).

Table 3 The context-principle with strategy components and intended effects concretized into detailed expectations embedded within the teaching-learning phase 'orientation' for cycle 2

Learning phase	Expectation of phase	Context-principle	
		Strategy component	Detailed expectation
I Orientation	Students experience the relevance of the task to design gluten-free corn bread as exemplarily of a class of food products because people have coeliac disease.	i. Select a *focused* task	(a) *Students accept the task of designing a class of gluten-free food products as realistic and understand that it is necessary to accomplish the task for people with coeliac disease.* (b) *Students have the opportunity to participate by developing a shared motive to accomplish the task.*
		ii. Use intuitive notions of students with regard to procedural steps	(a) Intuitive notions about the *design procedure are evoked by students: exploring the problem, finding solutions, testing, improving design and reporting the findings*. (b) Students are able to extend their notions about the procedure with the use of a replacement for gluten and knowledge about baking bread.
		iii. Enable productive interaction between participants	(a) Students *have the feeling that they can influence* the task and the process to accomplish the task. (b) Students become participants in the community of practice by accepting their role as junior designers of food products.

The (second) prescriptive stage is illustrated for strategy component i only. The adaptation of strategy component i led to a reformulation of the detailed expectations (see italics in right column in Table 3; see Table 1 for the formulation in cycle 1).

Evaluative stage (cycle 2)

The teaching-learning process of cycle 2 was enacted with 14 students (17 y, pre-university level, grade 12) and another teacher.

The expectation about the relevance of task (i-a) was fully achieved. To the question of why they volunteered in the pre-questionnaire four students (S15, S17, S18, S22) answered that the given task to find a recipe for a gluten-free food product was interesting. Two students (S11, S18) mentioned 'designing' and two (S9, S11) mentioned 'gluten intolerance' as the main reason to participate. According to the pre-questionnaire, seven out of fourteen students (S9, S10, S11, S15, S17, S18, S22) participated in the activity out of interest. All students performed equally well in terms of this expectation (video recordings).

Expectation i-b about students' development of a shared motive was 'fully' achieved. The goal of the task was clear to students. This became clear at the beginning of the teaching-learning process. After the video in which the senior scientist gave the task to the students, the teacher (T2) started together with the students to summarise the message of the senior scientist. The acceptance of the task was found in the statements of students during the focus group interview at the end of cycle 2 (S15): *'the task is necessary because there are people who suffer … and not that there is a company which …'*. From the statement like the one of student S13 it could be concluded that the students liked to be challenged when we pointed out that no research team has solved the task: '*That has to be said at the beginning. Then it would be much nicer, because you can find something, you have a goal. Maybe you obtain no acceptable results but even big scientists have the same experience*' (S13).

With regard to strategy component i it could be concluded that the task was perceived as relevant by students. The task could be stated more as a challenge *'You will be the first one to achieve this'*. For students at this level it was sufficient to understand why it is a problem and that people in society are working on the same problem. From the analysis with regard to the expectations related to all three strategy components, it was concluded that the task alone and not the use of a fictive company were sufficient to make the learning relevant for students. All the attributes as a role within a fictive company, were not necessary to start with the task. The chosen design procedure could be evoked intuitively by students. However, the chosen procedure did not lead to the intended goal to gain knowledge about the study of designing a product as was intended.

The elaboration of all strategy components led to a sufficient degree to the intended pedagogical effect: for students the context of an authentic practice for learning chemistry is relevant. For a third cycle, the elaboration of the strategy components has to be adapted with regard to the chosen procedure and the fictive company has to be left out the design. We concluded that we had come to the formulation of an empirically underpinned context-principle. More details about the three design principles are described in the Chapters 3, 4 and 5.

In retrospect

The purpose of this study is to describe a method to structure and plan design-based research in science education that provides outcomes in the form of design principles. We have illustrated this description with a case study in which we apply this method. We now present a reflection on the method, the design principles, the validity of the presented method and a general discussion.

Method

In our case study, the presented DBR method is used as a method to understand 'why' and 'how' design principles are successful instruments to guide possible solutions for a certain educational problem, by explicitly presenting the *generation* and *improvement* of the knowledge base in terms of these design principles (McKenney et al., 2006; Nieveen et al., 2006). There are two arguments for this. First, the described process of elaboration of and refinement of strategy components can be considered as theory building (Reeves, 2006; Van den Akker, 2006) since the formulation of (additional) strategy components is theory driven (Burkhardt, 2006; diSessa & Cobb, 2004). Second, the understanding of the cultural historical approach and the knowledge about how to use this approach within chemistry or science education is improved (the 'why') because it is described in an argued way how parts of the cultural historical approach were successfully incorporated into an teaching-learning process ('the how').

We have to mention an important issue in relation to the stages of the presented method. The choice of a specific learning theory as theoretical background influences the concretising of the four stages (Barab & Squire, 2004). During the description of the prescriptive stage when the teaching-learning process is designed, we find a strong influence of the theoretical background on the elaboration during the selection of strategy components and the formulation of design principles. As a result of the choice of a cultural historical approach as theoretical background for learning, the activities of students, tasks and procedures have a central place in the design (and the design principles). The formulation of design principles and the selection of strategy components will be different when a design is based on other theoretical backgrounds e.g. a conceptual change approach.

The cyclic character of DBR becomes visible with the redesign steps Y and Z (Figure 1). In this study, the redesign step Y is illustrated by the detailed description of one strategy component of the context-principle. A more extensive description of the arguments with regard to the sequence-principle and the content-principle see the Chapter 4 and 5. In the situation that the intended effects are fully achieved, a detailed described explanation for the use of strategy components can be found in the 'why' and 'how' sections of the design. When the conclusion is 'not achieved', the strategy component or its elaboration do not function well or do not have the intended effect. Then there is a need for a reconsideration of the theoretical background. When the intended effects are partly achieved, the elaboration of the strategy components can be refined or adapted, and therefore the design principle could change. However, there must be indications that the intended effect could be achieved by using the strategy components or by replacing or adding strategy components. In the case when the design principle needs to be adapted, new theoretical insights or background due to a better understanding of the problems is necessary. This can lead to add new strategy components to or replace one in the design principle, as was the case for the content-principle.

Most of the presented methodological stages can be recognized in other studies in which design-based research is used as method (Cobb et al., 2001; Knippels, 2002; Komerek et al., 2004; Meheut, 2004; Psillos et al., 2004; Verhoeff, 2003; Westra, 2007; Westbroek, 2005). In most of these studies possible solutions to overcome a specific educational problem are developed, enacted and refined to support learning when addressing a specific educational problem. Probably these studies can be best described as evidence-based problem solving by using design research or validation studies in which a possible solution is *proofed* (Nieveen, 2009). This is of course a worthwhile contribution for educational problems. However, a specific knowledge claim as a contribution towards the development of a knowledge base remained to be to a large extent implicit.

Design principles

As part of the knowledge claim, we have developed three empirically underpinned design principles which appeared to be useful to design a teaching-learning process in chemistry education (Chapter 3, 4 and 5). The question is, whether the empirically underpinned design principles are useful to design other teaching-learning processes within science education. According to Plomp (2009), the heuristic design principles will proof to be additionally powerful if they have been validated in the successful design of other similar interventions in various contexts. The same research method was applied in a case study by Prins, Bulte & Pilot (2009) for problems on models and modelling in chemistry education. This research method in which design principles are considered as part of the knowledge claim appears to be powerful in that case study (Prins, Bulte & Pilot, accepted). However, the extent of detail with which resulting strategy components and intended effects can be generalized needs further studies.

The value of these design principles is certainly not: 'if one uses these strategy components then one obtains this effect', because the validity of the design principles is situated. The general use of design principles is restricted by the situation in which they are validated: the chosen science content, the chosen teaching and learning theory, subsequently the selection of a context for learning, the national and local situation, the choices made regarding teachers and students, and the specific choices made with respect to the details of students' work. However, when applied as heuristic guidelines, we think that the presented design principles offer a worthwhile contribution to the field of science education because it gives insight in selecting and validating design alternatives at the level at which they are consequential for learning (diSessa & Cobb, 2004). It can help designers and teachers to select and apply the design principles and framework presented in Table 1 in their own settings (McKenney et al., 2006).

Validity and rigour of the outcomes

The knowledge claim of the case study with the presented method can be twofold. The first knowledge claim can be the design principles based on the evidence of a valid process of refinement or/and adaptation. When the elaboration of the strategy components indeed lead in a sufficient extent to the intended effects, a better understanding of the design is achieved and a possible way of using theoretical background is better understood through refinement. Evidence based acceptance or rejection of (parts of) the theoretical background is an important outcome of this method. The second knowledge claim can be the framework with the learning phases (see Table 1 and Appendix B) and the evidence-based understanding of this framework. This can be useful for the design of other teaching-learning processes. It can be a design tool, which clarifies the decisions in the design process and most important, it can provide a detailed insight into the teaching-learning process, the essential parts of the design, and the way it is designed or constructed in detail.

The knowledge claim that can be obtained by the presented method is acquired in a valid way through three activities. The first activity is the construction of a clear and valid description of the arguments and how these arguments lead to the design choices with regard to the design principles as hypothesis. The presented method asks for insight in the connections between theoretical perspective, and strategy components to achieve the intended effect in the form of design principles (see Table 4). Second, the choice of qualitative and quantitative instruments is part of common instruments (third column in Table 4), if these are used in the accepted valid way. Third, the validity is increased by using three validation strategies: triangulation, a thick description (a short overview is presented in Table 4) and peer review. For a valid study at least two validation strategies are necessary (Creswell, 2007; p. 209).

Table 4 Stages and activities and research instruments in each stage (see Figure 1) used in this case study

Stage in method	Activities within each stage	Qualitative or quantitative procedures in research approach
1. Research clarification stage	Analyse the educational problems Sketch a new strategy to address the reported problems	- Review the literature
2. Descriptive stage	a. Select a theory of teaching and learning b. Analyse and redefine the content	- Analyse documents with respect to content - Interview experts related to specific content - Produce independent coding of the statements of the experts by two researchers - Undertake a peer review

3. Prescriptive stage	a. Formulate initial design principles and research questions b. Design a teaching-learning process: • Use a framework of teaching-learning phases • Elaborate the strategy components • Describe a 'model of the teaching-learning process • Formulate expectations c. Formulate a plan of evaluation	- Produce a detailed description of the design - Formulate a plan of evaluation as a framework for analysis
4. Evaluative stage	a. Enact the teaching-learning process and collect data b. Analyse data and use validation strategies c. Formulate findings and draw conclusions d. Formulate implications and improvements (redesign step Y or Z)	- Interpret the video and voice recordings, and written data - Triangulate data sources - Produce a detailed 'thick' description - Undertake a peer review

The improvement of the design had not been possible by using a traditional approach in qualitative research. The way of obtaining a knowledge claim in design-based research differs from the five accepted approaches: case study, phenomenology, grounded theory, narrative research and ethnography (Creswell, 2007). Design-based research can be considered as a new approach with its own method (Plomp, 2009), although some questions arise about the role of context (Barab & Squire, 2004), formative evaluation and objectivity of the researcher when he or she is also a designer (Nieveen, 2009). Within this respect, this study is a contribution to explicitly describing the research stages of this method. Because, the high quality of engineering constructs in other fields like industrial design or mechanical engineering is not obtained by a single study or by using only physical and mathematical laws (Petroski, 2006), the cyclic approach of this study can be considered as a valid step by step demonstration of a proof of principle (Freudenthal, 1991; Petroski, 2006). We have illustrated a process of improvement and refinement through failures that have been uncovered by a detailed analysis. This process is naturally incorporated in the educational design process and can lead to new fruitful educational innovations (Petroski, 2006; Dewey, 2009) as a contribution to the body of knowledge in science education.

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Appendix A. Conceptual analysis

We designed three authentic tasks – in the field of biochemistry, polymer chemistry and inorganic chemistry, using research papers and other relevant literature. We consulted experts in the related professional authentic practices, who used their own specific expert knowledge to solve problems. We used both the literature survey analyses and the empirical data from the expert consultations to reconstruct and redefine the content. As expected, experts included macro-micro thinking in their reasoning, although with a different focus and using different models compared to traditional chemistry education. In this stage of our design-based research method, qualitative research instruments are used as document analysis and peer review, semi structured interviews; data sources were analysed by two researchers independently.

The essence in the case study is that macro-micro thinking involves a domain specific example of systems thinking, which may lay closer to a more intuitive thinking of students. A material is considered as a system built up from other subsystems. In Figure A1 the different levels within the system for the example bread/dough/gluten is presented from macro level (10^{-1} m) via intermediate meso (from 10^{-2} to 10^{-6} m) to a sub-micro level (10^{-9} m). For example, dough (10^{-1} m) can be considered as a system, which is built up from gas holes with walls (10^{-2} m). These walls are built up from a protein layer (10^{-5} m) of gluten in which starch granules are imbedded. The gluten layer is a three dimension network of long gluten chains (10^{-6} m) which are built up from entwined and sometimes connected gluten molecules (10^{-9} m).

These systems arise from interactions between subsystems of lower levels (Aguilera, 2006; Wilensky & Resnick, 1999). This system of sub systems or intermediate levels becomes manifest when studying structures and properties of macroscopic objects and materials in typical context-related tasks about e.g. foods, cloths and designed everyday artefacts (cf. Aguilera, 2006; Cussler & Moggridge, 2001). Structure-property relations are the causal relations between meso- and micro structures within a material, in this case illustrated by 'if gluten chains are entwined and connected by Sulphur-bridges then it is possible that the walls of the gas holes are elastic'. Such explicit structure-property relations, as a new component of the content, are not presented in research papers and science textbooks; the formulation needed to be based on the reasoning of experts and through an in-depth document analysis (Chapter 2 of this thesis).

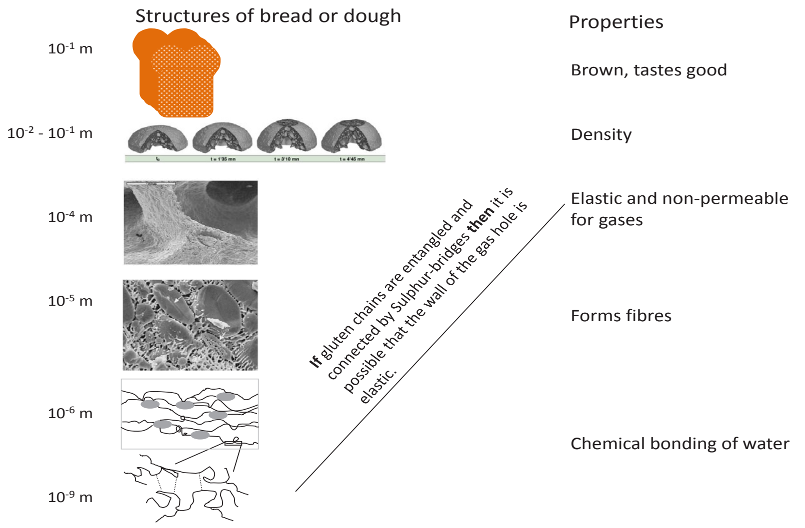

Figure A1 Conceptual schema with structures and properties for bread/dough. Left the different systems or structures are presented scaled from macro via meso to sub-micro (in series: bread, dough during rising with gas cavities, wall of single gas cavity, a detail of the wall, protein network and long gluten molecules). One example of a structure-property relation is presented.

Appendix B

The teaching-learning process of cycle 2 with description of learning-teaching phases, and for each design principle the strategy components with intended effects concretized as detailed expectations for phase I and V. Not all detailed expectations are shown.

		Context-principle		*Sequence-principle*		*Content-principle*	
Learning phase	Expectation	Strategy component	Detailed expectation	Strategy component	Detailed expectation	Strategy component	Detailed expectation
I Orientation	Expectation: Students experience the relevance of the task: design a gluten-free corn bread as an exemplar of a class of food products for people who have coeliac disease.	Select a focused task	Students accept the task of designing a class of gluten-free food products as realistic and understand that it is necessary to accomplish the task for people with coeliac disease. Students have the opportunity to participate by developing a shared motive to accomplish the task.	iv. Use a procedure based on intuitive notions of students	Students are able to construct a plan of action based on their intuitive notions of the procedure: analyse the problem, make the food product, test and evaluate.	-	Students are able to relate the concepts to their conceptual pre knowledge.
		ii. Use intuitive notions of students with regard to procedural steps	[detailed expectations not shown]	v. Sequence motives	Students find the task realistic and understand that professionals are working on such tasks. A motive is evoked in students to accomplish the task.	vii. Use intuitive notion of the cause of a property	Students have the notion that a replacement for gluten is necessary
		iii. Enable productive interaction between participants	[detailed expectations not shown]				

II Definition of the task	Expectation: Students refine the problem: find a replacement for gluten which could be added to corn dough, because gluten is important for the quality of bread.	*--- not applicable in this phase ---*	iv. Use a procedure based on intuitive notions of students v. Sequence motives	*[detailed expectations not shown]*	vi. Use systems thinking vii. Use intuitive notion of the cause of a property	*[detailed expectations not shown]*
III Extension and use of knowledge	Students proceed through a sequence of activities and learn and apply knowledge until a satisfactory solution to the problem is obtained: a selection of replacements for gluten based on scientific arguments and tests them.	*--- not applicable in this phase ---*	iv. Use a procedure based on intuitive notions of students v. Sequence motives	*[detailed expectations not shown]*	vi. Use systems thinking vii. Use intuitive notion of the cause of a property viii. Use intuitive notions with regard of the concepts ‘structure’ and ‘property’.	*[detailed expectations not shown]*
IV Reflection on design and thinking process	Students have a motive to reflect on whole process and macro-micro thinking.	*--- not applicable in this phase ---*	v. Sequence motives	*[detailed expectations not shown]*	*--- not applicable in this phase ---*	

V reflection and transfer	Students make explicit the learned conceptual and procedural knowledge and used this to solve another problem.	*--- not applicable in this phase ---*	iv. Use a procedure based on intuitive notions of students	Students are able to select a substitute and to use the procedure and macro-micro thinking in designing another food product.	vi. Use systems thinking vii. Use intuitive notion of the cause of a property	Students are able to construct the conceptual schema as yield of the design. Students are able to use this conceptual schema in a new task.
			v. Sequence motives	Students have a motive to use the procedure and macro-micro thinking in another task to design a food product.		

Chapter 1:
Introduction and overview

Part I

Chapter 2:
Conceptual analysis of macro-micro thinking: structure-property relations for chemistry education

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Part II
Two cycles of design, enactment and evaluation

Chapter 3:
Establishing a context for learning macro-micro thinking

Chapter 4:
Sequencing teaching-learning activities to evoke students' motives for learning macro-micro thinking

Chapter 5:
Elaboration and evaluation of macro-meso-micro thinking using structure-property relations

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Part III

Chapter 6:
A method for design-based research focusing on design principles for science education

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Chapter 7:
Conclusions and reflection

Chapter 7 Conclusions and reflection

Overview of this chapter

This chapter presents a short summary of this study, followed by general conclusions and limitations of these conclusions. It also describes a reflection on the important decisions for the design and a reflection on the knowledge claims of this study. The chapter ends with an outlook for further research.

Introduction

Macro-micro thinking is considered to be a key concept in chemistry and therefore in chemistry education. However, it is very difficult for students to learn. This difficulty can be described as a twofold problem: 1) the difficulty in relating macroscopic properties or phenomena to sub microscopic models, and 2) the relevance of learning these sub microscopic models which can be used to explain these properties or phenomena.

This study aimed to generate a deeper understanding of the students' learning of macro-micro thinking with structure-property relations and the incorporation of intermediate meso-levels in teaching-learning processes within an appropriate relevant context for students in secondary chemistry education. In relation to the students' learning problems with respect to the conceptual area of macro-micro thinking, three challenges of 'relevance' were explored in the design of a teaching-learning process for macro-micro thinking:

1. The context is relevant from the students' perspective;

2. Every teaching-learning activity is relevant for students because they have motives about what they are doing, and why and how they are going to proceed;

3. Students experience it as relevant to extend their knowledge with regard to the necessary concepts for macro-micro thinking with structure-property relations and intermediate meso-levels.

The central research question of this study was:

> *How to incorporate macro-micro thinking with structure-property relations and intermediate meso levels in pre-university chemistry education so that it is experienced as relevant by students?*

General conclusions

In order to answer the central research question a short overview of this research is presented. This study was roughly divided into three parts (Chapter 1). Part I was about the reformulation of the chemical content with regard to macro-micro thinking with structure-property relations and intermediate meso-levels. This was necessary because an authentic practice was chosen as a context to make the learning of macro-micro thinking relevant for students. In this way, the choice of a context and consequently a (learning) task is based on theories on social practices (Vygotsky, 1978). When students accomplish such a task, the procedures, norms and values of the chosen practice and the (chemical) content should be a coherent whole. When the learning environment of students resembles an authentic practice, the participants may be using other chemistry concepts than those that are taught in common secondary chemistry education e.g., the choice for concepts originating from chemical and material engineering differs from a conventional orientation on the particulate model of matter. Therefore, a re-orientation on the chemistry content was necessary.

In Part I, the following research question was answered: What structures, properties and explicit structure-property relations can be identified within the domain of chemistry and material science and how to make the connection between macroscopic phenomena and submicroscopic models explicit within a conceptual schema?

In order to relate macroscopic phenomena to submicroscopic structures, three cases from different research fields were studied in detail: gluten-free bread (biochemistry), bullet-proof jacket (polymer chemistry) and ceramics (inorganic chemistry). Document analysis and the consultation of three experts led to the construction of a conceptual schema as depicted in Figure 1. This conceptual schema describes a material in which structures can be distinguished at several intermediate levels between the macroscopic and submicroscopic levels. Macro-micro thinking can be considered as a domain-specific case of systems thinking, in which structure-property relations are the causal relations between the properties of the system and interactions between the sub systems (Chapter 2).

Part II describes the results of two design cycles. After the stage of research clarification each cycle consisted of three following stages: 1) a descriptive stage in which an analysis of the three challenges with regard to ‘relevance’ took place; 2) a prescriptive stage consisting of the formulation of design principles and research questions, the design of the teaching-learning process and the description of the evaluation of the enactment; and 3) an evaluative stage which consisted of the enactment and evaluation of the teaching-learning process.

During the descriptive phase, seven strategy components were formulated, which were used by the educational designers as the tools to elaborate a teaching-learning process to achieve the intended pedagogical effect(s). Strategy components, intended effects together with the arguments based on the literature (T), empirical evidence from previous design cycles (E) and practical experiences (P) of the members of the design team form a design principle as is presented in Figure 2 (cf. McKenney, Nieveen & Van den Akker, 2006).

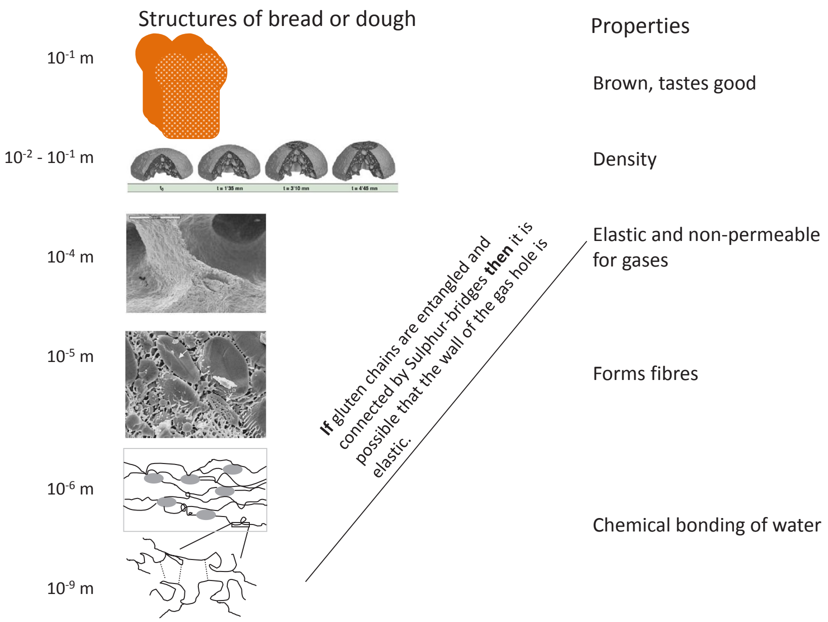

Figure 1 A conceptual schema of structures in bread or dough connected with properties (Chapter 5 of this thesis). This figure contains one example of a structure-property relation.

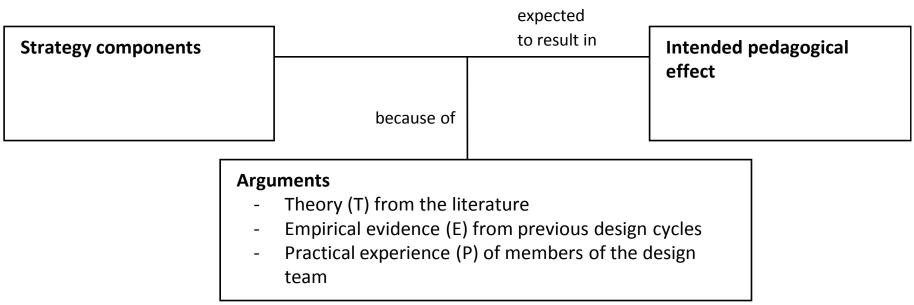

Figure 2 General representation of a design principle

Three design principles were formulated in this part of the study: the context-principle, the sequence-principle and the content-principle. The context-principle dealt with the design of a setting in which students were given a task (strategy component i) which they experience as realistic, and should lead to a shared motive to accomplish the task. The task should bring a specific designed behavioural environment into focus in which students know intuitively how to accomplish the task (strategy component ii) and in which productive interaction is established (strategy component iii). The sequence-principle dealt with the sequence of teaching-learning activities in which students know ‘what to do next and why’. Therefore, two strategy components were used: an authentic procedure based on the intuitive notions of students (iv) and a reflection on one activity that provides an orientation for the next activity (v). The content-principle was related to the intended macro-micro thinking with structure-property relations in which initially two strategy components were used: use of systems thinking (vi) and the intuitive notion of students that the cause of a property lies within a material (vii). Although in this study the design principles were separately described in different chapters, in the teaching-learning process these three design principles formed a coherent whole, and could therefore not be separately elaborated into the design of the teaching-learning process.

In this part six research questions were formulated relating to each of the design principles:

Context-principle (Chapter 3)	1. To what extent does the elaboration of the strategy components lead to the intended effect: the establishment of a context as a condition to make the students’ learning relevant?
	2. What is the formulation of the empirically underpinned context-principle?
Sequence-principle (Chapter 4)	3. To what extent does the elaboration of the strategy components lead to a sequence of teaching-learning activities in which students realize that they know ‘what to do next, and why’ when learning about macro-micro thinking using structure-property relations?
	4. What is the formulation of the empirically underpinned sequence-principle?
Content-principle (Chapter 5)	5. To what extent does the elaboration of the strategy components lead to the intended effect that students acquire macro-micro thinking using structure-property relations?
	6. What is the formulation of the empirically underpinned content-principle?

The seven strategy components were elaborated into a teaching-learning process. A framework of teaching-learning phases was used for the design which contained detailed concretized descriptions of the intended effects. The enactment of the teaching-learning process took place in a classroom in a small setting in which data from several data sources were collected. This was followed by the evaluation consisting of the analysis of the data, including validation strategies, the formulation of the findings and the drawing of the conclusions. The first design cycle led to several major and minor implications for changes, but showed an overall potential of the elaboration of the seven strategy components into the teaching-learning process. A major change was the addition of a third strategy component to the content-principle: use students’ intuitive notions with regard to the concepts ‘structure’ and ‘property’. This brings the total number of strategy components up to eight. Furthermore, the first strategy component of the context-principle was refined: the use of a *focused* task. A second design cycle was necessary in the teaching-learning process to achieve that students experience macro-micro thinking with structure-property relations as relevant to use and to learn. Based on the data analysis and findings of the second cycle, the following conclusions were drawn (Chapters 3, 4 and 5):

1. The use of an authentic practice as a context (for students at pre-university education) can be restricted to a relevant task with a clear goal enabling productive interaction between the participants of the community; a procedure to accomplish this task has to be in line with this goal (Chapter 3).

2. It is possible to realize a sequence of motives in the teaching-learning process with a well-designed procedure adapted from an authentic practice which is connected to the intuitive notions of students (Chapter 4).

3. Students (aged 17-18; pre-university education) were (partly) able to acquire the intended way of macro-micro thinking with structure-property relations through the use of intuitive notions with regard to the concepts 'structure' and 'property' about the nature of materials, and the use of systems thinking in the teaching-learning process (Chapter 5).

Part III is a description of the design-based research method used in this study. The purpose was to explicitly describe the procedures and to reflect on these procedures to provide a valid insight into each stage of the research activities of the educational designer developing design principles as a part of the knowledge claim of design-based research (McKenney et al., 2006) with the incorporation of four stages (Blessing & Chakrabarti, 2009). The three design principles were developed with an empirical basis which was theory driven. Therefore this development can be seen as a contribution to the body of (educational) knowledge (Chapter 6).

This leads to the answer to the overall research question: 'How to incorporate macro-micro thinking with structure-property relations and intermediate meso levels in pre-university chemistry education so that it is experienced as relevant by students?'

To achieve a learning of macro-micro thinking with structure-property relations that was relevant from the students' perspective an argued and entwined elaboration was done of the strategy components in a framework of learning phases and detailed expectations. The strategy components were: i) use a focused task, ii) use students' intuitive notions with regard to procedural steps, iii) enable productive interaction, iv) use a procedure based on students' intuitive notions, v) sequence motives in such a way that the reflection on one teaching-learning activity provides the orientation for the next , vi) use systems thinking, vii) use intuitive notions with regard to the cause of a property and, viii) use intuitive notions with regard to key concepts 'structure' and 'property'.

Regarding the three challenges of relevance the following effects were achieved:

1) *Related to the context.* Students experienced the setting as relevant. A clear focused task was necessary.

2) *Related to the sequence of the teaching-learning activities.* Students knew what they were doing, and why and how they were going to proceed. We used a procedure for the design of a product, which was close to the intuitive notions of students.

3) *Related to the content (macro-micro thinking).* Students could determine structures and properties and were able to explain properties with structures at a meso level in the material. Students were also able to represent their way of macro-micro thinking in a conceptual schema, using structure-property relations. Students were able to explain how and why macro-micro thinking proceeded as was intended. Students did explain properties with entities of sub systems which had properties other than the properties of the whole system.

With these results, we enhanced the understanding of how to bridge to a large extent the gap between macro level and submicro level. However, some remaining problems provide insight for a further enhancement of this understanding:

1. *Related to understanding the context.* In the design of the teaching-learning process, it is not necessary to focus on the role identification of students as junior (food product) developers.

2. *Related to understanding the sequence of the teaching-learning activities.* To a large extent students knew what they were doing, and why and how they were going to proceed. We used a design procedure which could be intuitively evoked in students. However, this design procedure was not fully in line with the learning goal of the teaching-learning process. Full alignment of the learning goal and the goal of the procedure is needed.

3. *Related to understanding macro-micro thinking:*

    a. The scaling of structures was difficult for students especially when the scale was far from human proportions. It proved to be a challenge to find a fine-tuned balance between a real authentic practice as a context and an adapted practice as a context for learning within the school setting

    b. The use of metaphors hindered the intended conceptual development because we did not pay enough attention to the differences and similarities between the physical entities and metaphors.

    c. Although students could *explain* properties as intended (conclusion 3), the 'upwards reasoning or modelling' from a lower level or sub system to a level at a higher scale or system to *predict* properties appeared to be difficult.

4. *The learning process of the teacher*, who needs to be able to deal with the rather new teaching and learning aspects related to context, sequence and the new content needs attention. The role of the teacher was critical in guiding and coaching students and evoking motives in students. Teachers need to develop new domain-specific expertise (Dolfing, Bulte, Vermunt & Pilot, in press).

Underpinned by the empirical results, the three design principles are formulated as:

Context-principle (Chapter 3)	*If* students as participants of a community of practice within the classroom are provided with a focused practice-related task (strategy component i) *and* have their own plan of action based on intuitive notions (strategy component ii) *and* productive interaction is enabled (strategy component iii), *then* a context is established at the start of the teaching-learning process as a condition to make the learning of chemical concepts relevant to students (intended pedagogical effect).
Sequence-principle (Chapter 4)	*If* a procedure is used which is built on intuitive notions of students (strategy component iv), *and* motives are sequenced in such a way that the reflection on one teaching-learning activity provides the orientation for the next (strategy component v), *then* students experience a sequence of teaching-learning activities in which they know 'what to do next, and why' (intended pedagogic effect).
Content-principle (Chapter 5)	*If* students use systems thinking by conceiving a material as a system of sub systems (intermediate meso-levels) (strategy component vi) *and* the intuitive notion is used that the cause of a property lies within a material (strategy component vii) *and* the intuitive notions about 'structure' and 'property' are used (strategy component viii) *then* students acquire macro-micro thinking using structure-property relations (pedagogical effect).

Regarding the sequence-principle, it is recommended to adapt it by adding a condition to the formulation of strategy component iv (addition in italics): … a procedure is used which is built on intuitive notions of students and *aligned with the learning goal of the teaching-learning process* … . Additionally, for the content-principle, at least three strategy components should be added to the formulation: 3a) scaling was a problem for students and 3b) the use of macroscopic metaphors hindered the intended conceptual development and, 3c) for prediction of properties, we suppose that this strategy component requires at least three entwined parts: a) use the notion that a system can be built up from sub systems, b) use the notion that the cause of a property is found in the interactions between sub systems and c) use the notion that interactions between sub systems can be used to predict a property.

Another part of the knowledge claim of this study is the framework with learning phases and detailed expectations as concrete descriptions of the intended effects. This framework is presented in an Appendix to this chapter.

Limitations of this study and reflection on the design decisions in this study

In this study, the exploration of the educational problem started with a new conceptual analysis because the choice of an authentic practice as a context required a thorough analysis of the chemistry content. As a result, intermediate levels between the macro and submicro level in macro-micro thinking came to the fore as concepts used within such an authentic practice. However, this way of macro-micro thinking has never before been described for use in education. We developed three cases in which the use of macro-micro thinking with structure-property relations is essential. We realize that these three cases are exemplary for the content analysis. However, the literature within different chemistry-related research fields (such as material and chemical engineering) and the consultation of three experts provided us with a generic pattern for macro-micro thinking with structure-property relations. In the explorative study (Chapter 2), this construction of the chemistry content showed a potentially rich way of macro-micro thinking which could function as a proof of principle, worth investigating for use in chemistry education.

Another limitation of this explorative study was the use of two small groups of students and two teachers. The feasibility and potential of macro-micro thinking with structure-property relations for chemistry education in an authentic practice context can be investigated with a limited group of students, because one small group of students provides to a large extent similar findings to those of a research setting with two or more groups of students and teachers. In this research design, many variables may influence the outcome of the enactment of the teaching-learning process, e.g., the students, the teacher, the situation at school, the time period within a year, the complexity of the chemistry content, and the use of context as an adapted version of an authentic practice. However, at this stage of exploration, it is sufficient to draw meaningful conclusions based on the evaluation of two cycles with small groups. Therefore, these limitations are acceptable.

During this research study, several specific decisions have been made which had consequences for the set-up and execution of this study. These decisions were important because they determined to a large extent the design of the teaching-learning process, and consequently could also influence the conclusions. The most important decisions, arguments and implications are described below.

Choosing the design of gluten-free bread as a task

One main reason was decisive in the choice of bread. The connection with coeliac disease and food offered a clear advantage because of the apparent relevance for students, although food is not part of traditional chemistry courses in secondary school. However, the design of gluten-free bread is a complex task. Bread is a complex food product involving the mixing of at least four ingredients which are mixtures by themselves. Furthermore, the baking process is complex, the chemistry behind gluten networks is still partly unknown (Singh & MacRitchie, 2001; Don, Lichtendonk, Plijter, Van Vliet & Hamer, 2005) and there are many relations between structures and properties.

Parallel to this research study, two other exemplary teaching-learning units were designed for the purpose of curriculum innovation with a context of ceramics and a context of super absorbent materials. Although the content is less complex, the design of these units (Bulte, Houben, Meijer & Pilot, 2008) involved the same kind of design principles and appeared to provide similar learning outcomes. In the case of ceramics, the nature of the models was less complicated than with the subject of bread. To set up a curriculum line for macro-micro thinking with structure-property relations, we recommend starting with a task for students that requires fewer intermediate levels and less complicated models to explain it. Examples are the high strength of Kevlar or the isolation value of a woven pullover as described in Chapter 2. During such a curriculum line, the complexity of models and the number of levels could be raised up to the level of gluten-free bread as is used in this thesis. Since we achieved to a large extent macro-micro thinking with structure-property relations within a complex problem, this provides indications that the described idea of a curriculum line has potential. In retrospect, the subject of gluten-free bread has a Janus face: it has a complicated chemistry nature which influences the complexity of the design of the teaching-learning process but it is close to the daily life of students and relevant for them.

Choosing design-based research as a method

The decision to use design-based research as a method for this research on learning and teaching macro-micro thinking was based on the arguments that this method could be used for the formulation and validation of models and theories about the design of a teaching-learning process (Blessing & Chakrabarti, 2009). Design-based research is to generate an understanding of 'why' and 'how' a teaching-learning process will function in a class situation (Lijnse & Klaassen, 2004). Designing a teaching-learning process involves decisions about elements, such as the task that students are asked to solve, the kind of discourse that is encouraged, the form of participation that is established within a context, the tools and related material means provided, and the practical means by which classroom teachers can orchestrate relations among these elements (Cobb, Confrey, diSessa, Lehrer & Schauble, 2003). This requires knowledge and understanding of these elements that are necessary for achieving the intended pedagogical effects. It requires strategies for how to incorporate the necessary elements into a designed teaching-learning process, which were developed in terms of design principles.

This kind of knowledge and understanding could only be provided by an iterative process of design, enactment and reflection which could not be obtained by using a single qualitative approach or a combination of qualitative approaches like a case study or grounded theory, which are accepted approaches in qualitative research (Creswell, 2007). Many variables have to be optimized to a sufficient extent into a design of a teaching-learning process. The design-based research method led to a deeper understanding of the design, and an understanding of 'how' and 'why' certain effects are related to underlying mechanisms. As a method, it was adequate for this study. It was theory driven. It guided the decisions to revise, refine or improve thinking about teaching and learning, and it was product driven. Finally it facilitated the efforts to validate the knowledge claim of the study and the designed teaching-learning process (Blessing & Chakrabarti, 2009; Lesh, Kelly & Yoon, 2008; Van den Akker, Gravemeijer, McKenney & Nieveen, 2006).

Meta reflection on knowledge claims of this thesis

The design principles and the framework with teaching-learning phases are considered as the main parts of the knowledge claim (Chapter 6). The following is presented as a meta-reflection about the improved understanding with respect to these knowledge claims. This understanding is related to the three design principles, *context*, *sequence* and *content*, and involves the use of context, the sequence of teaching-learning activities and the use of macro-micro thinking with structure-property relations. It discusses the argumentation for the formulation of the three design principles.

Understanding the context

In this study an adapted authentic practice was used as a context for relevant teaching and learning of macro-micro thinking. Previous research (Westbroek, 2005; Bulte, Westbroek, De Jong & Pilot, 2006) recommended explicitly investigating which components could be taken from the authentic practice to incorporate into science education. In our study, the selected focused task defined the activity of the participants who intuitively knew what they had to do and how to accomplish the task (Van Oers, 1998). In other words, when the setting is relevant from the students' perspective, with a clear focused task (Chapter 3), there is a context in which learning becomes relevant for students. When a task or focal event is determined (Gilbert's third criterion, 2006), the subsequent teaching-learning activities are framed by the task, as was shown empirically in this study (Chapter 3).

In both cycles, a community of practice was not established at once. In the teaching-learning process of the second cycle, students divided the different tasks over the group, which was necessary to achieve the common goal. But students had to be given time and opportunities, and were stimulated by several teaching-learning activities to form a community. Thus, the intended community of practice could not be realized at once. This is to some extent in contrast with the first criterion of Gilbert (2006): 'Students must value the setting as a social, spatial, and temporal setting for a community of practice. They must value their participation in a community of practice through productive interaction and develop personal identities from the perspective of that community' (p. 961). When starting a teaching-learning process, students do not experience the existence of a community. They do what is expected of them by the material, the function of the teaching-learning activities and the stimulating role of the teacher. When students experience that their input and contribution matter, then they begin to share this with others. So, forming a community can be considered as an effect that can be achieved as a result of the enactment of the teaching-learning process, instead of a criterion from the start of the teaching-learning process.

Consequently, the 'dolling up' of the teaching-learning process in this study did not have a specific added value for the emerging process of forming a community of practice (Chapter 3). From the students' perspectives, all factors (e.g., look-alike articles, virtual scientist, a fictive company), were not needed in the establishment of a community of practice. As a result they perceived it more as a fake simulation of the authentic practice than a useful contribution to the relevance of the task. In a study by Witteck, Most, Kienast & Eilks (2007) the same results were found, and students mentioned the self-regulation as a more important factor than the setting itself. The intended role identification as junior food product developers by students did not fit with the idea of identity which refers to how a person sees and projects him or herself (Sadler, 2009). Both identity and discourse are related to the community of practice and the way the persons behave themselves during written or spoken dialogue within a community of practice. Students could not adopt another identity. Role-identification to bridge the gap between real science and school science is still an unsolved problem due to difference in gender, culture and social class (Archer et al., 2010).

The use of an authentic practice as a context, as chosen in this study, does not fit into a curriculum where the main emphasis is 'solid foundation', that is: stresses chemistry as cumulative knowledge (Roberts, 1982). Within the emphasis of a solid foundation, the purpose is to provide students with cumulative chemistry concepts as preparation for specific further studies in chemistry. The use of an adapted authentic practice as a context consists of a specific task or focal event which frames the teaching-learning activities and chemical language. Therefore, only the concepts and skills are introduced to students on a need-to-know basis (Pilot & Bulte, 2006). Students should experience the relevance of learning these concepts and skills, which are relevant for the purpose of the authentic practice as a context. When concepts are introduced which are not necessary to accomplish the task from the students' perspectives, the use of the authentic practice as a context is undermined, because these concepts are placed outside the frame determined by the task or focal event. Therefore, in a curriculum that mainly consists of such context-based units, the key concepts of chemistry should be integrated in the set of units. Then it is impossible to cover all traditional chemistry concepts in the restricted time available for the chemistry curriculum and to avoid an overloaded curriculum with a superficial coverage (Gilbert, 2006).

Another consequence of the choice of an adapted version of an authentic practice as a context is that a re-orientation and reconstruction of the chemistry content was necessary before it could be elaborated into a teaching-learning process. This reconstruction of the chemistry content required an escape from the present chemistry curriculum content (Van Berkel, Bulte & Pilot, 2009). Additionally, the change in education was not restricted to the chemistry content, but also to the pedagogical way of teaching; the teaching-learning activities changed from individually performing exercises towards group discussions, meetings and students' influence on practical work, inspired by another vision of chemistry education: from becoming a chemist towards becoming scientifically literate citizens (Gilbert & Treagust, 2009b; Millar, 2006).

Understanding the sequence of teaching-learning activities

Procedure for design and knowledge development

In the teaching-learning process we have chosen to focus on the task to design a food product. Such a task also involves a procedure inspired by the corresponding procedure of the authentic practice (Westbroek, Klaassen, Bulte & Pilot, 2010). An advantage of the use of a procedure is the integration of skills and concepts in the learning process. Skills become in this way an integrated part of the chemistry curriculum. However, a one-to-one copy of the procedure of the authentic practice is not intended. The learning process requires specific efforts to obtain the intended learning goal for students, which is not part of the purposes of the related authentic practice. For example, students are not experts in the development of food products and therefore additional teaching-learning activities are necessary, such as analysis of the task, interpretation of new information and concept development. Especially, the procedure had to be in line with the goal of the task, which has to be in line with the learning goal for students: acquiring macro-micro thinking with structure-property relations.

In the first cycle, the procedure was a combination of an inquiry procedure and a design procedure. In the second design cycle the procedure was adapted to a design procedure, which could be more easily intuitively evoked in students and led to a large extent to the intended sequence of teaching-learning activities in which students experienced why and how they had to perform an activity. However, the design procedure in the second cycle was too much directed towards designing and did not focus enough on knowledge development (Chapter 4). So if the choice is that a design procedure is used as a strategy component, since this procedure can be intuitively evoked in students, the optimal choice is to design a *concept* of the product with all related knowledge to be made explicit. Then the knowledge about the design of the concept is a logical part of the outcome of the procedure.

Teaching-learning phases

In the second cycle, the sequence of teaching-learning activities was directed by a framework with five learning phases: I: orientation on the task, II: problem definition, III: extension and use of knowledge, IV: motive to reflect on the task, and V: reflection and transfer of knowledge (Figure 3). Phase IV is important because this phase directs why students should proceed from the specific project activities to the explicit formulation of the intended conceptual understanding (macro-micro thinking). However, students appeared to be focused on product development and not so much on acquiring knowledge. Therefore, the function of this learning phase was not fully fulfilled (Chapter 4).

To achieve that students constantly have the acquiring of knowledge in mind, we recommend to adapt the five phase framework by 'spreading out' the teaching-learning activities of phase IV during the entire teaching-learning process (Figure 3, right-hand side). In fact, the teaching-learning process can be better divided into four phases in sequence and a continuous 'phase' (or function) from start to end (Figure 3, right-hand side). This new phase IV has the function of recalling that learning needs to be directed towards knowledge development and helps students to connect each teaching-learning activity with this goal.

The division of the teaching-learning process into five phases, presented in Figure 3 (right-hand side), is comparable to the phases of ChiK units (Parchmann et al., 2006). The difference is mainly in the proposed phase IV which is not present in the ChiK learning phases. This phase relates to the 'need-to-know' basis for basic concepts and skills (Parchmann et al., 2006; p. 1060). The presence of motivational dimensions

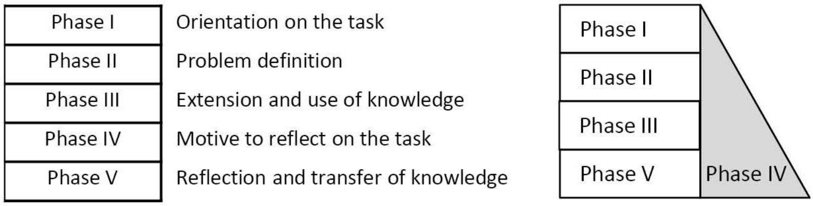

Figure 3 The teaching-learning phases which could be distinguished in cycle 2 (left-hand side) and a new proposal (right-hand side) to increase the connection between teaching-learning activities and the learning goal

and social significance is mentioned as being important in sequences of teaching-learning activities (e.g., Meheut, 2004).

Komorek & Duit (2004) and Kabapinar, Leach & Scott (2004) used the same number of phases. However, the function of these teaching-learning phases differs from the phases of the teaching-learning process presented in Figure 3 (right-hand side). Komorek & Duit (2004) used a teaching-learning process in which the design of the first and second phase resembles to a large extent the procedure of prediction, observation, and explaining (p. 625). The function of the third and fourth phase was generalization and reflection. Again, a clear motive for students to go from one phase of teaching-learning activities to the next one was not reported by them. Kabapinar et al. (2004) used four phases: introduction, creating a need for a model, construction of the model and using the model. The design of these phases was teacher centred (p. 640), although the aim was that students would construct their own model. Kabapinar et al. (2004) draw the conclusion that they needed to pay more attention to students' ideas about science teaching in order to motivate them (p. 650).

All these studies confirm that the explicit formulation of learning phases and/or functions to direct students' motives to reflection on the acquisition of knowledge remained implicit. We recommend that this aspect becomes part of the design of teaching-learning processes, especially because transfer is an important activity to consider in education. It is needed, but it is difficult to make explicit what should be learned in the teaching-learning process in such a way that it can be used in more or less related tasks (Gilbert, Bulte & Pilot, 2010). Therefore, it is necessary to evoke a motive in students for making the acquired knowledge suited for transfer into other situations. An adapted procedure taken from an authentic practice does not naturally include a phase in which transfer takes place. In this study, we intended to design activities which make the acquired knowledge explicit and which could be combined with the function of the transfer phase. We did not achieve this to the intended extent within one unit, so the design of effective activities for acquiring transfer is still a problem for further research.

Understanding macro-micro thinking with structure-property relations

The use of structure-property relations to explain a property of a substance or a material is not common in secondary chemistry education. In science education research, macro-micro thinking is strongly connected to the particulate model and expressed in terms of a triplet relationship between macro, micro and symbolic levels, and is used to explain properties (e.g., Gilbert & Treagust, 2009a). According to Talanquer (2009), the use of this triplet relationship has become almost paradigmatic in science education. Although in material and chemical engineering it is common to use structures at intermediate levels with scales (Aguilera, 2006; Gani, 2004; Hill, 2004), explicit description or use of macro-micro thinking with structure-property relations is hard to find in the educational literature (e.g., Scheffel, Brockmeier & Parchmann, 2009; Talanquer, 2009; Chapters 2 and 5).

This study describes macro-micro thinking as a domain-specific case of systems thinking (Luisi, 2002; Chapter 5, Figure 1). The sub structures refer to sub systems, connected by structure-property relations. The sub systems are defined by the structure-property relation because the interactions of these sub systems (structural elements) explain the emergent property. For example, when students need to explain the brown colour of bread, they have to use a different set of meso levels than when they need to explain the elongation of dough.

The key idea developed in this study is macro-meso-micro thinking with structure-property relations (Figure 4; Chapters 2 and 5; Harré & Madden, 1975; Wilensky & Resnick, 1999; Craver, 2001). The essence of macro-meso-micro thinking is 'stepwise zooming in' when explaining properties, and 'stepwise zooming out' when predicting properties. First, the explaining of properties is discussed below with three examples, then the predicting of properties.

Explaining consists of the following: consider a structure which has a property. This structure is built up from sub structures. The property of the structure could be explained by the interactions between the sub structures (Rappoport & Ashkenazi, 2008). In this way, material structures can be interpreted as systems and sub systems with properties. Different sub systems can be distinguished from each other because they are separated due to differences in structures and properties. Structure-property relations are the specific relations between the sub structures in the corresponding sub system and the emergent property.

In the next description, macro-meso-micro thinking is illustrated with three examples: 1) the elongation of wheat bread, 2) stiff and strong bike wheels made of Poly-p-phenylenebenzo-bisoxazole (PBO) and 3) the stable character of the benzene ring.

The first example that is used in this study is the elongation (property) of wheat dough (structure). Bread can be described with the following sub structures: bread as a final form after the baking of dough; the walls of gas holes; the gluten network and the entwined gluten chains; and the polypeptide chains with Sulphur-bonds (Figures 1 and 5). Each of these structures has specific properties: these are, respectively, bite and resilience; elasticity of the wall; elasticity of the network; and flexibility of the

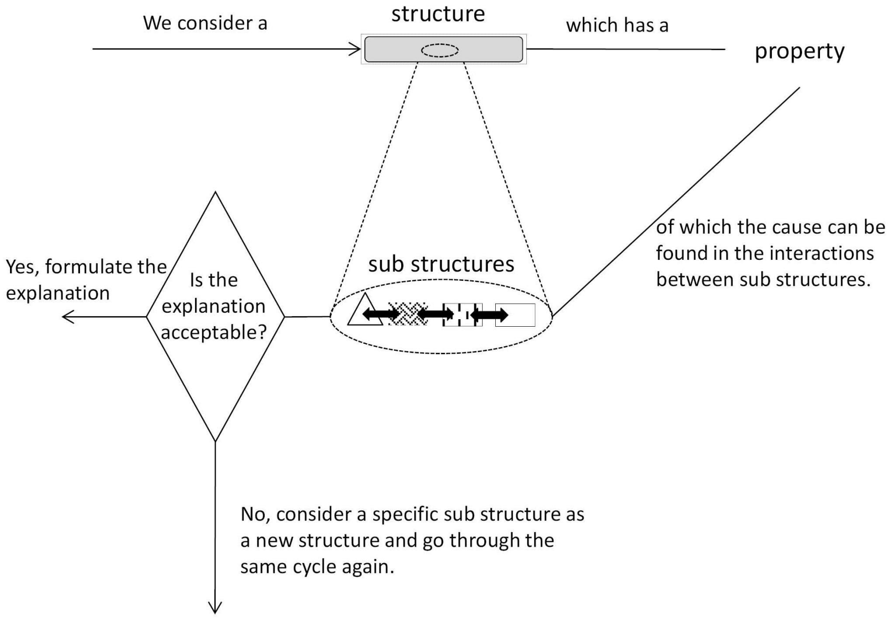

Figure 4 Key idea of macro-meso-micro thinking as 'stepwise zooming in' for explaining a property by using a sub structure at a lower scale.

In Figure 5, macro-meso-micro thinking is repeated four times before an acceptable explanation of the resilience of dough can be formulated. This explanation needs four structure-property relations. In this case, it is not necessary to 'descend' to the level of the sequence of amino acids because the sequence of these amino acids does not provide new information which contributes to a deeper explanation of the resilience of dough.

The second example concerns the explanation of the high strength and stiffness of bike wheels (Figure 6). The high strength of a bike wheel means that high stress is needed to deform the material. A high value for the stiffness refers to the elastic modulus (E) of a material; it describes the quotient between stress and strain when this material undergoes elastic deformation. Poly-p-phenylenebenzo-bisoxazole (PBO) has a very high E modulus (E_{PBO} is about 370 GPa), higher than the elastic modules of stainless steel (210 GPa) or polyethene (shopping bags, 0.7 GPa).

Figure 6 represents meso structures as sub systems within a bike wheel made of PBO: a spoke consisting of a bundle of fibres; a single fibre which is built up from regular micro fibrils; ordered sheets of longitudinal directed molecular chains; and molecular chains. Each of these sub systems respectively has the following properties: flexible and high strength, stiffness, high E-modulus, a high tensile strength.

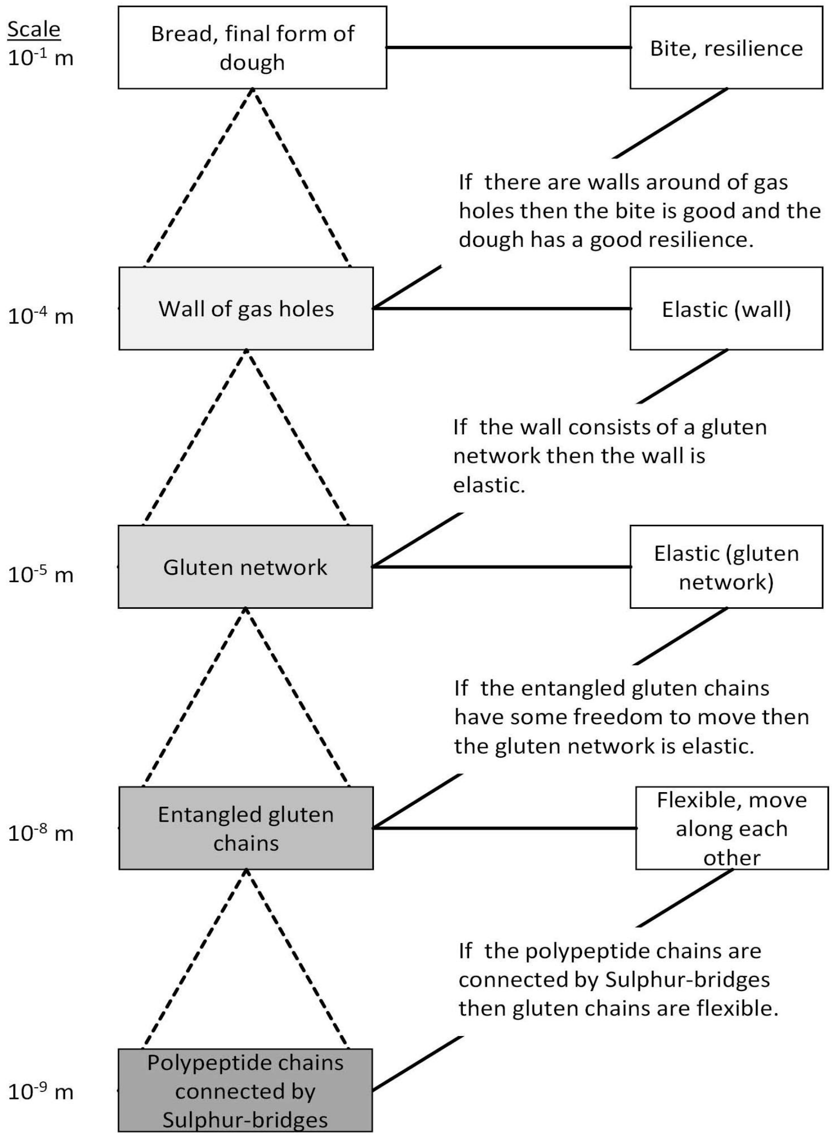

Figure 5 The example of gluten-free bread. The property resilience is explained by a repetition of macro-meso-micro thinking

In this second example, downwards macro-meso-micro thinking takes place as follows. The high strength of a PBO spoke is caused by a bundle of fibres. However, the bundling is not the only cause of the high strength; the bundle is stiff. The stiffness is cause by the same orientation of all fibre which has a high E modulus; under a high stress, the fibre shows a low deformation. The stiffness of a fibre is caused by a regular ordering of macro fibrils orientated along the length axes of the fibre. These macro fibrils are high crystalline parts with a high tensile strength. The crystalline parts consist of sheets of parallel oriented sheets of molecular chains. The high tensile strength is caused by the high energy input necessary to break the covalent bonds and stability of the aromatic rings which are longitudinally orientated along the length axes of the macro fibril.

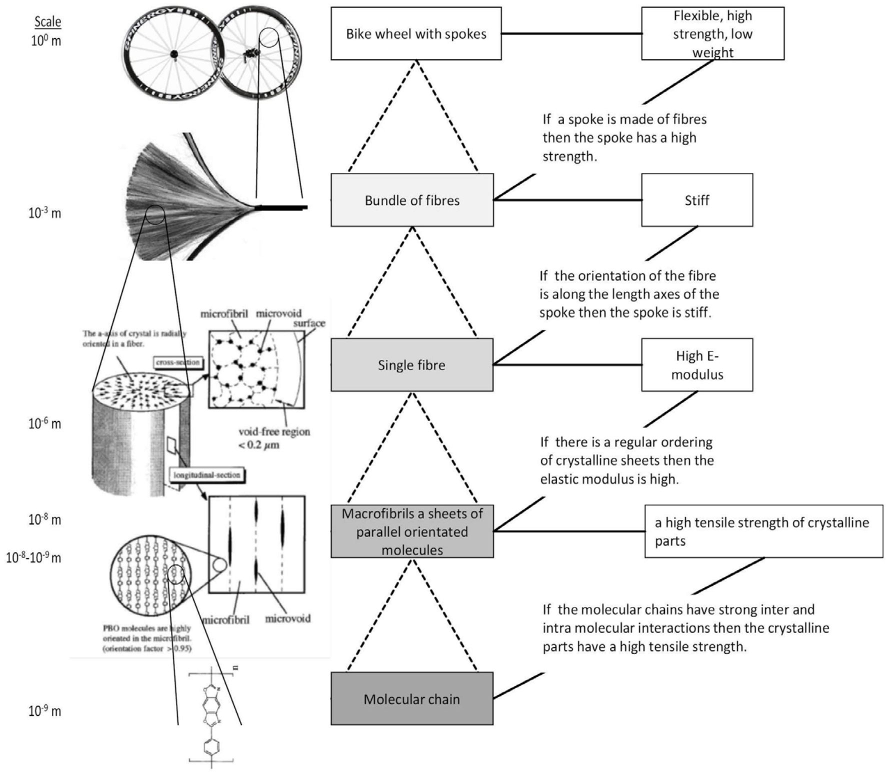

Figure 6 The explanation of the flexibility and high strength of bike wheels made of PBO by using the key idea presented in Figure 4 (pictures adapted from http://www.spinergy.com & Kitagawa, T., Murase, H., Yabuki, K. (1998). Morphological Study on Poly-p-phenylenebenzobisoxazole (PBO) Fiber, *Journal of Polymer Science: Part B:Polymer Physics*, *36*, 39-48).

A third example is the rather inert property of benzene that emerges from the interaction between sp2 orbitals of six carbon atoms (sub structures). This inert property is different when the molecular structure of the molecule consists of five carbon atoms or when one carbon atom is replaced by nitrogen. Then the substance does not have a similar inert stable property.

In this third example a property is explained by interactions between sub systems, the six delocalized electrons as a sub structure. In this case, a property of a substance can directly be explained by structures at a sub micro level, as is frequently done in traditional chemistry education. Compared to the two other examples, these types of structure-property relations from the macro directly to the sub micro level can be considered as a limiting case of a more general macro-meso-micro thinking as described in Figure 4.

In summary, these examples show the potential to generalize macro-meso-micro thinking in chemistry education. Explaining a property implies 'stepwise zooming in' until a property can be explained by interactions between sub systems or sub structures. In most cases, macro-meso-micro thinking implies several steps in repetition or at once for explaining chemical properties of pure substances as a limiting case.

Johnstone's triangle (1991) with the paradigmatic use of a triplet relationship between macro, submicro and symbolic (Gilbert & Treagust, 2009a) needs revision. Addressing today's material and chemical engineering with its common use of structures at intermediate levels with scales (Aguilera, 2006; Gani, 2004; Hill, 2004) requires that students do descend in more than one single step from macro to submicro level. When using the repetition of stepwise zooming in, the steps are mostly much smaller, with a discontinuity between each level of sub systems: there is not a gradual connection between the properties at the different levels. The proposed way of reasoning between macro via meso to submicro level with structure-property relations seems continuous when considering sizes and scales, however it is discontinuous in properties. The full implications of this, including the use of symbols and metaphors, have to be an issue for further research.

With respect to the *prediction* of properties, the 'upwards reasoning', using structures and sub structures needs attention. Material engineers, nano scientists and chemists design materials with specific properties. They can predict properties on the basis of expected interactions between sub structures and then design such materials by manipulating sub structures. This is 'upwards reasoning' and is represented by the line upwards from sub system toward a property (Figure 4). However, in this study, the focus in the design task for students was rather on explaining the elastic property of gluten. We did not pay much attention to the prediction of properties or modelling by using the interactions between structures at the meso or submicro level. Further elaboration on how to incorporate this way of reasoning is necessary because the relation between a property and a sub structure is not evident to students. The difficulty is to evoke intuitive notions in students about emergence of properties or 'upwards reasoning' (Chi, 2005). Chi proposed two steps for 'upwards reasoning' to avoid students giving properties of a sub system to the whole system (Chapter 5). First, students should recognize and use the interactions between the sub systems.

Second, students should become able to understand and describe what will happen with the whole system when asking themselves questions like: 'what would happen if the interactions become weaker or stronger?' or 'what would happen if the molecules could not be brought into line with each other?'. In this way, students are provided with an understanding of the underlying structure of emergent processes (Chi, 2005).

Outlook

Based on the conclusions and discussion, the following issues are recommendations for future research:

1. Macro-micro thinking with structure-property relations

   Systems thinking is an accepted way of thinking in biology education. Although biologists are interested in behaviour and function instead of properties, the presented way of thinking (Figure 4) is applicable in systems thinking in biology. In this study, macro-micro thinking was considered as a domain-specific case of systems thinking. A possible next step is to study what is common and different between the ways of thinking in different disciplines. In this way, a more general approach to science education could be developed, which should acknowledge the students' intuitive notions (Chi, 2005).

2. Transfer in context-based science education

   This study has also attempted to address the issue of transfer, that is, to use the obtained knowledge in a different situation or task. In this first exploration, the focus was to generate deeper understanding of underlying mechanisms or ways of thinking, and not on the use of superficial similarities which can be easily recognized. Surely in the situation where one specific context is used, the transfer of concepts and ways of thinking might be more difficult due to the situativity of knowledge and the strong focus on one task (Gilbert, 2006). The meaning of concepts is determined by the situation, that is, the context in which the task is relevant. For students, it is an effort to recognize deeper similarities and differences between situated tasks at a level of procedural steps and conceptual structures (Gentner & Wolff, 2000; Gilbert et al., 2010). Based on findings in this study (Chapters 4 and 5), the learning results with respect to transfer were rather limited. For studying transfer issues, a close alignment between curriculum units addressing macro-meso-micro thinking is necessary.

3. Metaphors and advance organizers in science education

   Language is an important medium for acquiring knowledge and for communication. It is essential that persons who communicate with each other acquire the same meaning regarding the object of their communication process. A metaphor is a vehicle to give a concrete meaning to abstract entities and therefore is important in science and science education (Davidson, 2001). Metaphors are always connected to the macro level. In this study, the use of metaphors therefore hindered the intended conceptual development at meso and submicro level. A possible solution for using metaphors as a medium for conceptual development is presented by Gentner & Wolff (2000). They proposed metaphor comparison as an activity to connect metaphors with the concepts to be learned. Metaphor comparison is a process of alignment and mapping between pairs of structured representations. Comparing and aligning requires an existing schema of concepts and representations. So, for acquisition of a new concept it is presumed that a prior presence of the concept itself is needed. This corresponds with educational ideas of germs of learning (Davidov, 1990) and an advance organizer (Ausubel, 1968; Arievitch & Haenen, 2005; Van Oers, 1998). Further research is needed on how to use metaphors in macro-meso-micro thinking, in what form and in what activities.

4. The role of the teacher in an innovative science curriculum

   The unit in this study involved new chemistry content, which is not at present part of teachers' expertise. New elements in the role of the teacher in the student-centred activities also ask for the development of new expertise. This can be achieved by the sustained professional development of teachers which is a prerequisite for reaching expert levels of performance. When the change in a part of the curriculum is large, the teacher needs time to acquire new expertise to teach new content at a sufficient level and to adapt his or her role in the new process of teaching and learning. This requires a special programme for the professional development of teachers as a pathway for the development of the teachers' expertise (Anders Ericsson, 2006; Dolfing et al., in press; Stolk, Bulte, De Jong & Pilot, 2009a, 2009b; Vos, Taconis, Jochems & Pilot, 2010).

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Appendix

Framework of the teaching-learning process of cycle 2 with description of learning phases. For each design principle the strategy components with intended effects concretized as detailed expectations. The most important expectations are shown.

Learning phase I: Orientation	Expectation: Students experience the relevance of the task: design a gluten-free corn bread as an exemplarily of a class of food products for people who have coeliac disease.				
Context-principle		Sequence-principle		Content-principle	
Strategy component	Detailed expectation	Strategy component	Detailed expectation	Strategy component	Detailed expectation
i. Select a focused task	Students accept the task of designing a class of gluten-free food products as realistic and understand that it is necessary to accomplish the task for people with coeliac disease.	iv. Use a procedure which is built on intuitive notions of students	Students are able to construct a plan of action based on their intuitive notions of the procedure: explore the problem, find a solution by making the food product, test and evaluate.	-	Students are able to relate the concepts to their conceptual pre knowledge.
	Students have the opportunity to participate by developing a shared motive to accomplish the task.	v. Sequence motives	Students find the task realistic and understand that professionals are working on such tasks.	vii. Use the intuitive notion of students that the cause of a property lies within a material	Students have the notion that a replacement for gluten is necessary
ii. Use intuitive notions of students with regard to procedural steps	Students have a notion about the main steps of the design procedure: exploring the problem, finding solutions, testing, improving design and report the findings. Students are able to extend their notions about the procedure with the use of a replacement for gluten and knowledge about baking bread.		A motive is evoked in students to accomplish the task.		
iii. Enable productive interaction between participants	Students experience that they can influence the task and the process to accomplish the task. Students become participants in the community of practice by accepting their role as junior designers of food products.				

Learning phase II: Definition of the task	Expectation: Students refine the problem: find a replacement for gluten which could be added to corn dough, because gluten is important for the quality of bread.			
Context-principle	Sequence-principle		Content-principle	
Strategy component	Detailed expectation	Strategy component	Detailed expectation	Strategy component
--- not applicable in this phase ---	iv. Use a procedure which is built on intuitive notions of students v. Sequence motives	Given their intuitive notions about the procedure expressed in phase I and based on new information, students are able to adapt and improve their project plan. Students have a motive to extend their knowledge about what causes the properties of gluten and to execute their project plan to accomplish the given task.	- vii. Use the intuitive notion of students that the cause of a property lies within a material	Students have to the notion that the quality of wheat bread is better than corn bread. Students are able to relate the gluten content with the quality of bread. Students have the notion that a replacement for gluten has to add to corn bread to improve the quality of it.
Learning phase III: Extension and use of knowledge	Expectation: Students proceed through a sequence of activities and learn and apply knowledge until a satisfactory solution to the problem is obtained.			
Context-principle	Sequence-principle		Content-principle	
Strategy component	Strategy component	Detailed expectation	Strategy component	Detailed expectation
--- not applicable in this phase ---	iv. Use a procedure which is built on intuitive notions of students v. Sequence motives	Students extend their knowledge about the procedure to select an additive for replacement of gluten, to design a new/adapted product, and to find an explanation through additional experiments. Students have a motive to find an explanation why the product is improved although it still has inferior quality caused by the absence of gluten and to use an explanation about the elasticity of gluten for the improvement of their designed food product.	viii. Use the intuitive notions about 'structure' and 'property'	Students are able - to formulate a meaning for the concepts 'structure' and 'property' in terms of ▪ Structure: a pattern, arrangement, construction, how things are built. ▪ Property: a characteristic, a function, something the material does. - to use these meanings in further teaching-learning activities.

			vi. Use systems thinking vii. Use the intuitive notion of students that the cause of a property lies within a material vii. Use the intuitive notion of students that the cause of a property lies within a material	Students understand the thinking process using macro-micro thinking and structure-property relations. Students can formulate an explanation of the elastic property of wall of gas holes using their own formulations of structure-property relations by using the notions: - If there are walls around of gas holes (10^{-4} m) then the bite is good and the dough has a good resilience (10^{-1} m). - If the wall consists of a gluten network (10^{-6} m) then the wall is elastic (10^{-4} m). - If the entangled gluten chains (10^{-8} m) have some freedom to move then the gluten network is elastic (10^{-6} m). - If the polypeptide chains are connected by Sulphur-bridges (10^{-10} m) then gluten chains are flexible (10^{-8} m). Students search for an explanation for properties in the nature of the dough (structures at meso levels or system of structures).

<table>
<tr><td>Learning phase IV: Reflection on design and thinking process</td><td colspan="4">Expectation: Students have a motive to reflect on the design procedure and on macro-micro thinking.</td></tr>
<tr><td colspan="1">Context-principle</td><td>Sequence-principle</td><td></td><td colspan="2">Content-principle</td></tr>
<tr><td>Strategy component</td><td>Strategy component</td><td>Detailed expectation</td><td colspan="2">Strategy component</td></tr>
<tr><td>--- not applicable in this phase ---</td><td>v. Sequence motives</td><td>Students have a motive to reflect on their activities and thinking process (macro-micro thinking) to obtain the knowledge claim of designing a gluten-free food product.</td><td colspan="2">--- not applicable in this phase ---</td></tr>
<tr><td>Learning phase V: reflection and transfer</td><td colspan="4">Expectation: Students make the learned procedural and conceptual knowledge explicit and used this to solve another problem.</td></tr>
<tr><td>Context-principle</td><td>Sequence-principle</td><td></td><td>Content-principle</td><td></td></tr>
<tr><td>Strategy component</td><td>Strategy component</td><td>Detailed expectation</td><td>Strategy component</td><td>Detailed expectation</td></tr>
<tr><td rowspan="2">--- not applicable in this phase ---</td><td>iv. Use a procedure which is built on intuitive notions of students</td><td>Students are able to select a substitute and to use the procedure and macro-micro thinking in designing another food product.</td><td>vi. Use systems thinking</td><td>Students are able to construct a conceptual schema.</td></tr>
<tr><td>v. Sequence motives</td><td>Students have a motive to use the procedure and macro-micro thinking in another task to design a food product.</td><td>vii. Use the intuitive notion of students that the cause of a property lies within a material</td><td>Students are able to use this conceptual schema in a new task.</td></tr>
</table>

Summary

Macro-micro thinking is considered to be a key conceptual area in the domain of chemistry. It is concerned with the understanding and prediction of properties and transformations of materials. Chemists construct *submicroscopic* models for investigating, explaining and using properties of known and new substances and their transformations at the *macroscopic* level. The macro level refers to directly observable phenomena, e.g., colour, smell, conduction of heat or electricity, mass or taste. The submicro level refers to models with structures at the level of molecules or atoms, or in general, invisible particles with a dimension of about 10^{-9}-10^{-10} m, much smaller than we can observe.

However, in chemistry education macro-micro thinking is very difficult for students to learn. This difficulty is described as a twofold problem:

1. Students have difficulty in relating macroscopic properties to submicroscopic models;

2. Students do not experience that submicroscopic models are relevant for explaining the world they live in.

This research project investigated the twofold problem by means of designing and evaluating a new strategy for learning macro-micro thinking situated within a context. It did not focus on teaching the particulate model, but addressed the way of thinking used in the context of material science, chemical engineering and food science. In these fields of chemistry and technology, properties of materials and foods are described, understood and predicted using structures in relation to properties. Properties like elongation, elasticity, and hardness are related to structures in between the macro and submicro level (*meso levels*), and are often not directly related to the molecular or atomic level. Therefore in this study, *macro-meso-micro thinking with structure-property relations* was the central idea to be incorporated into chemistry education.

As a theoretical perspective, an adapted authentic practice was used as a context. In an authentic practice, activities, procedures, norms, values and concepts form a coherent whole. A realistic task derived from an authentic practice must make the task relevant for students, providing them with a broad motive for following the procedures adapted from an authentic practice, and consequently for learning macro-micro thinking. It requires a teaching-learning process in which all activities are sequenced such that all activities in its sequence are relevant.

The term 'relevant' has at least three different aspects: 1) relevance of a task in which students get the opportunity to use their own ideas; 2) relevance of performing teaching-learning activities in a sequence based on intuitive notions of students with regard to the procedural steps; and 3) relevance of acquiring new chemistry concepts related to macro-micro thinking with structure-property relations. Consequently, 'relevance' implied three challenges, which were explored in the design of the teaching-learning process:

a. The context is relevant from the students' perspectives;

b. Within the context-based teaching-learning process, every teaching-learning activity is relevant for students because they have motives about what they are doing, and why and how they are going to proceed;

c. Students experience the relevance of extending their knowledge with regard to the necessary concepts for macro-micro thinking with structure-property relations.

This study generated a deeper understanding of how to incorporate macro-micro thinking with structure-property relations in pre-university chemistry education in such a way that students experience their learning as relevant. The central research question for this study was:

> *How to incorporate macro-micro thinking with structure-property relations and intermediate meso levels in pre-university chemistry education so that it is experienced as relevant by students?*

The research activities of this study were divided into three parts:

I. A new conceptual analysis of macro-micro thinking with structure-property relations using intermediate meso levels;

II. A design-based research approach with two cycles of design, enactment and evaluation of the teaching-learning process which includes the new conceptual analysis; and

III. A reflection on the methodological steps of the design-based research approach developed during both design cycles.

Part I: Conceptual analysis of macro-micro thinking with structure-property relations and intermediate meso levels

Since explicit rules for the proposed way of macro-meso-micro thinking were not available in the literature, the description of these rules was a starting point in this study. Therefore, the first research question to be answered (Chapter 2) was: *What structures, properties and explicit structure-property relations can be identified within the domain of chemistry and material science and how to make the connection between macroscopic phenomena and submicroscopic models explicit within a conceptual schema?*

Chapter 2 presents experts' thinking on addressing a theme-specific task. This analysis led to a general conceptual schema for macro-meso-micro thinking with structure-property relations. An example of one such conceptual schema for bread is presented in Figure 1. Bread can be defined as a final fixed form of dough. Figure 1 shows a representation of how experts repeatedly 'zoomed deeper' into dough by distinguishing certain meso structures, such as walls of gas holes, threads, granules imbedded in networks and entangled long molecules. These meso structures are related to properties such as the elasticity of walls of gas holes.

In this way, macro-micro thinking with structure-property relations is described as a domain-specific way of systems thinking. A material has a specific property which is built from sub structures at a lower scale. The property is caused by the interactions between all sub structures at that lower scale. So, structure-property relations are the causal relations between properties and the sub structures in the material. As a result of this perspective on macro-micro thinking with structure-property relations, we proposed that the commonly used triangle of macro, submicro and symbolic levels was replaced by a scheme in which all macro, meso and submicro levels are represented by concepts, graphs, representations and relations between each level, and not by one single symbolic level.

By the analysis of experts' thinking, the rules for macro-micro thinking with structure-property relations were made explicit. In this way of macro-micro thinking, the sub structures in the material are relevant because they are necessary for explaining a property.

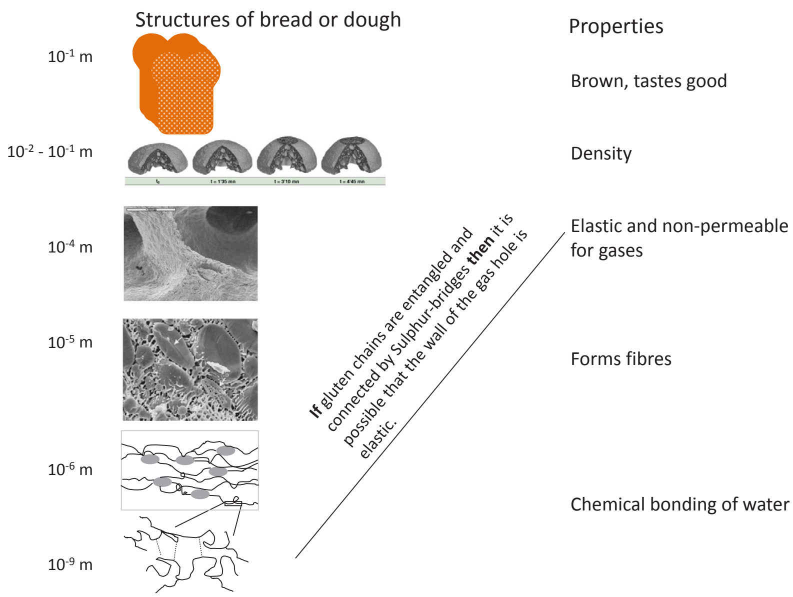


Figure 1 A conceptual schema of structures in bread or dough connected with a scale and properties. This figure contains one example of a structure-property relation

Part II: Exploration of macro-micro thinking in a teaching-learning process; the development of design principles

Theories about teaching and learning did not directly provide specific guidelines and strategies for designing a teaching-learning process with the specific intended pedagogical effects. Therefore, new heuristic guidelines were necessary to relate essential strategy components, underlying theoretical arguments and the specific intended pedagogical effect. These three elements together were defined as a design principle. Essential strategy components, arguments and pedagogical effects were described and used to develop and establish three design principles, based on an empirical basis by research in the classroom. The *context-principle* was related to the relevance of the task given to students. The *sequence-principle* was related to the relevance of the sequence of teaching-learning activities to accomplish the task. The *content-principle* was related to macro-micro thinking with structure-property relations in such a way that students experience the acquiring of this as relevant.

Although these design principles were entwined within the design of a teaching-learning process, the development and refinement of each design principle is separately described in three different chapters of this thesis. Table 1 presents the research questions related to each of the design principles.

Table 1 Design principles, intended pedagogical effect and related research questions

Design principle	*Intended effect*	*Research question*
Context-principle (Chapter 3)	Establishing a context in which the learning of macro-micro thinking is relevant for students	1. To what extent does the elaboration of the strategy components lead to the intended effect: the establishment of a context as a condition to make the students' learning relevant? 2. What is the formulation of the empirically underpinned context-principle?
Sequence-principle (Chapter 4)	Students experience a sequence of teaching-learning activities in which they know 'what to do next, and why'	3. To what extent does the elaboration of the strategy components lead to a sequence of teaching-learning activities in which students realize that they know 'what to do next, and why' when learning about macro-micro thinking using structure-property relations? 4. What is the formulation of the empirically underpinned sequence-principle?
Content-principle (Chapter 5)	Students acquire macro-micro thinking using structure-property relations	5. To what extent does the elaboration of the strategy components lead to the intended effect that students acquire macro-micro thinking using structure-property relations? 6. What is the formulation of the empirically underpinned content-principle?

All strategy components were elaborated in a teaching-learning process. In the designed teaching-learning process, students had to develop a gluten-free corn bread for people with coeliac disease (intolerance to gluten). Gluten is a large protein naturally present in wheat. The presence of gluten causes dough to rise. Corn dough does not naturally contain gluten and consequently it does not rise. Students needed to find a replacement for gluten which could be added to corn flour to obtain corn bread of an acceptable quality. Two cycles of design and evaluation of the teaching-learning process provided answers to the research questions (see Table 1). The design also included a justification of the design of the teaching-learning process together with a plan of evaluation which contained detailed expectations as concrete descriptions of the intended pedagogical effects. After enactment in class, the elaboration of the strategy components in the designed teaching-learning process was evaluated.

Chapter 3 presents the answers to the research questions on the context-principle**.** In the design, an adapted authentic practice was used as a context to increase the relevance of the chemistry concepts. The strategy components were: (i) an adapted authentic task; (ii) an intuitive notion of a procedure; and (iii) enabling productive interactions. A community of practice was designed in which students work together on the task in a fictive company. The elaboration of these strategy components into a teaching-learning process is presented for both cycles. After the second cycle, the combined elaboration of the strategy components together has led to the intended effect. The empirically underpinned context-principle is formulated as: *If* participants of a community of practice within the classroom are provided with a focused practice-related task *and* have their own plan of action based on intuitive notions *and* productive interaction is enabled (strategy components), *then* a context is established as a condition to make the learning of chemical concepts relevant to students (intended pedagogical effect).

Chapter 4 aims to answer the research questions on designing a sequence of teaching-learning activities. An adapted procedure from the authentic practice of food product development, based on intuitive notions of students (first strategy component) was elaborated into a teaching-learning process together with a second strategy component in which every teaching-learning activity must evoke a motive in students to start the next one. The elaboration of both strategy components was largely effective as intended. In the second cycle, the expectations regarding the use of the procedure were realized to a large extent despite the fact that the learning goal was not equal to the goal of the task. The intuitive notions of students could be productively used. Sequencing motives was effective until the teacher took over the regulation of the activities. Furthermore, in the teaching-learning process, students did not have a motive to reflect on their procedural steps and way of macro-micro thinking and to use this in another situation. The empirically underpinned sequence-principle is formulated as: *If* a procedure is used which is built on intuitive notions of students (strategy component iv), *and* motives are sequenced in such a way that the reflection on one teaching-learning activity provides the orientation for the next (strategy component v), *then* students experience a sequence of teaching-learning activities in which they know 'what to do next, and why' (intended pedagogic effect). Additionally, it is recommended that the first strategy component is adapted by adding a condition to the formulation of this strategy component (the addition is in italics): … a procedure is used which is built on intuitive notions of students and *aligned with the learning goal of the teaching-learning process* ….

Chapter 5 reports on the elaboration of the strategy components with regard to macro-micro thinking with structure-property relations. In the first cycle, two strategy components were used: systems thinking and the intuitive notion regarding the cause of a property. The first cycle led to the necessity of a new strategy component: the use of students' intuitive notions of the concepts 'structure' and 'property'. The elaboration of the three strategy components was evaluated by the enactment and analysis of the second cycle. The intended pedagogical effect was largely achieved. However, during the enactment students did not easily grasp the scales of meso levels below 10^{-5} m. Two reasons are found for this: 1) Metaphors, related to the macro level in students' material and in discourse both used as a tool to increase the understanding at submicro level, hindered the conceptual development of students; and 2) The scaling was a problem for students. The empirically underpinned content-principle is formulated as: *If s*tudents use systems thinking by conceiving a material as a system of sub systems (intermediate meso levels) (strategy component vi) *and* the intuitive notion is used that the cause of a property lies within a material (strategy component vii) *and* intuitive notions about 'structure' and 'property' are used (strategy component viii) *then* students acquire macro-micro thinking using structure-property relations (effect). At least two more strategy components should be added to this content-principle with respect to the scaling of structures and the use of metaphors. A reformulation of the strategy component 'systems thinking' is recommended and should include the notion that interactions between sub systems are used to predict a property.

Part III: The methodology of the design-based research approach

A design-based research (DBR) approach was applied. Although agreement exists on general methods for design-based research, such methods are seldom described in a reflective way.

Chapter 6 describes a specific set of procedural stages which were applied in this design-based research study to obtain a valid knowledge claim. It includes a explicit description of qualitative research instruments and actions of the researcher. Theories on design of learning and teaching were linked with design principles. Design principles and the framework with learning phases containing detailed expectations as concrete descriptions of the intended effects were presented as the twofold knowledge claim of this design-based research.

Conclusions and reflection

Chapter 7 provides the conclusions and reflection on the answer to the central research question. A deeper understanding was generated on how to incorporate macro-micro thinking with structure-property relations in secondary chemistry education in a way which is relevant for students.

In answer to the overall research question: *'How to incorporate macro-micro thinking with structure-property relations and intermediate meso levels in pre-university chemistry education so that it is experienced as relevant by students?'*, the incorporation of macro-micro thinking with structure-property relations in a way that was relevant from the students' perspective was carried out by an argued elaboration of eight strategy components in the framework of learning phases with detailed expectations. The elaboration of argued strategy components and their intended pedagogical effects are presented as design principles (see Table 2).

Table 2 Design principles, strategy components and intended effects as knowledge claim of this study

Design principle	Strategy component	Intended pedagogical effect
Context-principle	i. Select a focused task ii. Use intuitive notions of students with regard to procedural steps iii. Enable productive interaction between participants	Establishing a context at the start of the teaching-learning process as a condition to make the learning of chemical concepts relevant to students.
Sequence-principle	iv. Use a procedure which is built on intuitive notions of students v. Sequence motives in such a way that the reflection on one teaching-learning activity provides the orientation for the next	Experiencing a sequence of teaching-learning activities in which they know 'what to do next and why'.
Content-principle	vi. Use systems thinking vii. Use the intuitive notion of students that the cause of a property lies within a material viii. Use the intuitive notions of students about 'structure' and 'property'	Acquiring macro-micro thinking using structure-property relations.

The elaboration of the strategy components is presented as a framework of learning phases with detailed expectations as concrete intended effects for structuring a teaching-learning process using an authentic practice as a context for acquiring macro-micro thinking using structure-property relations. Both design principles and the framework of learning phases are the main part of the knowledge claim of this study.

With regard to the three challenges of relevance the following empirical underpinnings of the design principles should be mentioned:

1) *Related to the context.* To a large extent students experienced the setting as relevant. A clear focused task was necessary. However, the design of the teaching-learning process should not focus too much on the role identification of students as junior food product developers.

2) *Related to the sequence.* To a large extent students knew what they were doing, and why and how they were going to proceed. We used a procedure which was close to the intuitive notions of students. However, this procedure was not fully in line with the learning goal of the teaching-learning process. Intended motives were evoked in students as intended, until the teacher took the lead instead of guiding and coaching the students to formulate their own motives.

3) *Related to the content.* To an acceptable degree students could determine structures and properties and were able to relate properties to structures at a meso level in the material. Students gave these entities or sub systems properties other than those of the whole system. Students were also able to represent their way of thinking into a conceptual schema, together with the used structure-property relations. Students were able to explain why and in what way the thinking process was intended.

However, two additional strategy components and a reformulation of one strategy component are needed. In the reflection on this study a further understanding was discussed with regard to the context, the sequence of teaching-learning activities and the macro-micro thinking with structure-property relations. Further research is needed with respect to macro-micro thinking with structure-property relations in different disciplines, transfer in context-based science education, metaphors and advance organizers in science education and the role of the teacher in an innovative science curriculum.

Samenvatting

Macro-micro denken is een belangrijk conceptueel onderdeel binnen het chemisch werkveld. Macro-micro denken gaat over het begrijpen en voorspellen van eigenschappen in materialen en over transformaties van materialen. Chemici maken daarbij gebruik van *submicroscopische* modellen om de eigenschappen en transformaties op *macroscopisch niveau* te onderzoeken, te verklaren en te voorspellen. Het macroscopische niveau refereert aan direct waarneembare fenomenen zoals kleur, geur, geleiding van warmte, geleiding van elektriciteit, gewicht en smaak. Het submicroscopische niveau is gerelateerd aan modellen op moleculaire of atomaire schaal, of in algemene zin tot onzichtbare, niet met het blote oog waarneembare, deeltjes met een afmeting van 10^{-9}-10^{-10} m.

Echter, in het chemieonderwijs in het voortgezet onderwijs blijkt dat het voor leerlingen lastig is om zich macro-micro denken eigen te maken. Dit wordt veroorzaakt door twee problemen:

1. Leerlingen vinden het moeilijk om macroscopische eigenschappen te relateren aan de submicroscopische modellen;

2. Leerlingen ervaren niet dat submicroscopische modellen relevant zijn voor het verklaren van de wereld waarin ze leven.

In deze studie worden deze problemen onderzocht door het ontwerpen en evalueren van een nieuwe strategie voor het verwerven van macro-micro denken. In deze studie wordt niet gebruik gemaakt van het deeltjes-model maar van de manier van denken die gehanteerd wordt in de context van materiaalkunde, chemische technologie en voedingsmiddelentechnologie. In deze werkvelden binnen de chemie en technologie worden eigenschappen van materialen en voedselproducten beschreven, verklaard en voorspeld door gebruik te maken van relaties tussen structuren en daaraan gerelateerde eigenschappen. Eigenschappen zoals rek, elasticiteit en hardheid hebben vaak een relatie met structuren op *meso niveaus* op een schaal die liggen tussen het macro- en submicro-niveau. Deze eigenschappen worden dus zelden in verband gebracht met het moleculaire of atomaire niveau. Om deze reden is het macro-meso-micro denken met structuur-eigenschap relaties een centraal idee voor het chemieonderwijs in havo en vwo.

Voor de ontwikkeling van het onderwijs is gebruikt gemaakt van een aangepaste authentieke praktijk als een context voor het onderwijsleerproces. In een authentieke praktijk vormen de activiteiten, procedures, normen, waarden en de (wetenschappelijke) concepten een coherent geheel. Een voor leerlingen relevante en realistische taak, afgeleid van een taak uit de authentieke praktijk, is gebruikt om motieven op roepen bij leerlingen om de noodzakelijke procedurele stappen uit te voeren. Verwacht wordt dat het macro-micro denken met structuur-eigenschap relaties dan relevant is voor leerlingen. Dit vereist een onderwijsleerproces met een sequentie van activiteiten waarin de leerlingen de relevantie zien om elke activiteit in die sequentie achtereenvolgens uit te voeren.

In deze studie heeft de term *relevant* tenminste drie aspecten:

1) de relevantie van een taak waarbinnen de leerlingen de ruimte krijgen om hun eigen ideeën gestalte te geven,

2) de relevantie om onderwijsleeractiviteiten uit te voeren in een volgorde die gebaseerd is op intuïtieve denkbeelden van leerlingen met betrekking tot de procedurele stappen en

3) de relevantie om zich nieuwe chemische concepten eigen te maken die gerelateerd zijn aan het macro-micro denken met structuur-eigenschap relaties.

Daaruit volgt dat er drie uitdagingen zijn te formuleren die gestalte moeten krijgen in het ontwerp van het onderwijsleerproces:

a. De context is relevant vanuit het perspectief van de leerlingen,

b. De leerlingen voeren activiteiten uit, die elk onderdeel zijn van het op contexten gebaseerde onderwijsleerproces. Vanuit het perspectief van de leerlingen is het relevant om die activiteiten uit te voeren omdat ze een motief hebben voor wat ze gaan doen, waarom ze dat gaan doen en hoe ze dat gaan doen,

c. Leerlingen ervaren vervolgens de relevantie van het uitbreiden van hun kennis van de chemische concepten die noodzakelijk zijn voor deze activiteiten. Deze concepten zijn gerelateerd aan het macro-micro denken met structuur-eigenschap relaties.

Het doel van deze studie is om een beter begrip te verkrijgen van het inpassen van macro-micro denken met structuur-eigenschap relaties in het chemieonderwijs van bovenbouw vwo, op een manier die leerlingen ervaren als relevant. De centrale onderzoeksvraag in deze studie is:

> *Hoe kan macro-micro denken met structuur-eigenschap relaties en tussenliggende meso-niveaus ingepast worden in het chemieonderwijs (bovenbouw vwo) op een manier die door leerlingen als relevant wordt ervaren?*

In deze studie zijn er drie stappen te onderscheiden in de uitgevoerde onderzoeksactiviteiten:

I. Een conceptuele analyse van het macro-micro denken met structuur-eigenschap relaties en tussenliggende meso-niveaus,

II. Twee ontwerpcycli, die gebaseerd zijn op ontwerponderzoek, bestaande uit het ontwerpen van het onderwijsleerproces op basis van de conceptuele analyse, het uitvoeren en evalueren van dit onderwijs, en

III. Een reflectie op de methodologische stappen binnen de gekozen benadering van het ontwerponderzoek die ontwikkeld zijn gedurende de twee ontwerpcycli.

Deel I: Conceptuele analyse van macro-micro denken met structuur-eigenschap relaties en tussenliggende meso-niveaus

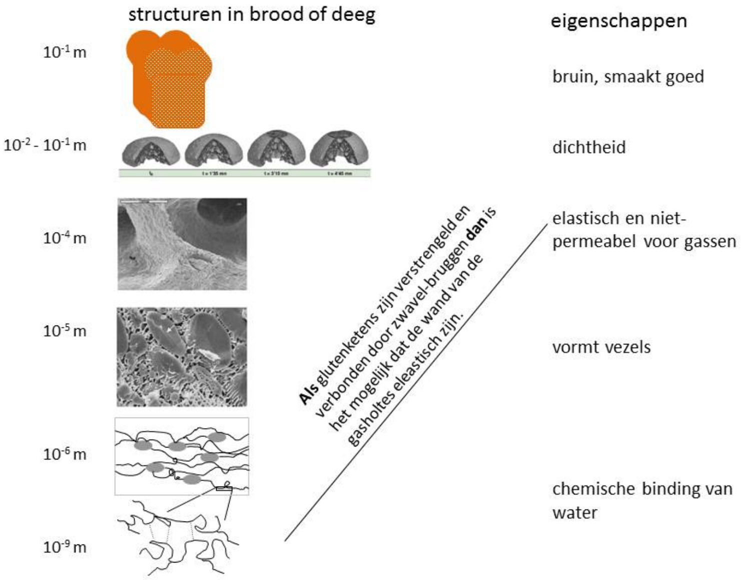
In de literatuur is er geen expliciete beschrijving te vinden van de voorgestelde manier van macro-micro denken. Deze studie begint daarom met deze beschrijving. De eerste onderzoeksvraag, die wordt beantwoord in hoofdstuk 2, is:

Welke structuren, eigenschappen en expliciete structuur-eigenschap relaties kunnen worden geïdentificeerd binnen het werkveld van chemie en materiaalkunde en hoe kan het verband tussen macroscopische fenomenen en submicroscopische modellen geëxpliciteerd worden in een conceptueel schema?

In **hoofdstuk 2** wordt het denken van experts, die een thema-specifieke taak oplossen, gepresenteerd en geanalyseerd. Deze analyse leidt tot een algemeen conceptueel schema met betrekking tot macro-micro denken met structuur-eigenschap relaties. Een voorbeeld van een dergelijk conceptueel schema voor brood is weergegeven in figuur 1. Daarin wordt brood beschouwd als een gefixeerde vorm van deeg. Figuur 1 geeft weer hoe experts herhaaldelijk 'inzoomen' op een structuur op een kleinere schaal. Daarbij worden meso-structuren onderscheiden zoals de wanden van gasholtes, draden, zetmeelgranules ingebed in een netwerk en lange verstrengelde moleculen. Deze meso-structuren worden gerelateerd aan eigenschappen zoals de elasticiteit van de wanden rond een gasholte.

Op deze manier kan macro-micro denken met structuur-eigenschap relaties beschouwd worden als een domein-specifieke invulling van systeemdenken. Een materiaal met een specifieke eigenschap is opgebouwd uit substructuren met een kleinere afmeting. De betreffende eigenschap wordt veroorzaakt door interacties tussen de betreffende substructuren. Structuur-eigenschap relaties zijn causale relaties tussen eigenschappen en de interacties tussen de substructuren in het materiaal. Binnen het didactische werkveld wordt veelal een driehoek gebruikt met macro, submicro en symbolische denkniveaus. Het perspectief dat verkregen is door de beschreven analyse geeft aanleiding om deze driehoek te vervangen door een schema waarin alle concepten, grafieken, representaties en relaties tussen elk niveau worden weergegeven.

Door de analyse van het denkproces van experts, is de beschrijving van macro-micro denken met structuur-eigenschap relaties geëxpliciteerd. De gepresenteerde manier van denken (zie figuur 1) laat zien dat de in het materiaal aanwezige substructuren relevant zijn omdat ze noodzakelijk zijn voor een verklaring van een eigenschap.



Figuur 1 Een conceptueel schema van structuren in brood of deeg die gerelateerd kunnen worden aan afmetingen en eigenschappen. Eén structuur-eigenschap relatie is weergegeven als voorbeeld.

Deel II. Implementatie van macro-micro denken in een onderwijs-leerproces; ontwikkeling van ontwerpprincipes.

De huidige theorieën met betrekking tot het leren en onderwijzen bevatten geen specifieke richtlijnen en strategieën voor het ontwerp van een onderwijsleerproces met het specifieke beoogde onderwijseffect: het verwerven van macro-meso-micro denken met structuur-eigenschap relaties op een voor leerlingen relevante manier. Daarom is het noodzakelijk dat er nieuwe heuristische richtlijnen komen die de relatie omschrijven tussen essentiële strategie-componenten, onderliggende theoretische argumenten en de gespecificeerde beoogde effecten. Deze drie elementen samen worden gedefinieerd als een ontwerpprincipe. Essentiële strategie-componenten, de argumenten (mede gebaseerd op empirisch onderzoek in een lessituatie) en de beoogde effecten zijn beschreven. Deze worden gebruikt om drie ontwerpprincipes te ontwikkelen: het context-, sequentie- en content-principe, Het context-principe is gerelateerd aan de relevantie van de taak die gegeven werd aan de leerlingen. Het sequentie-principe is gerelateerd aan de volgorde van onderwijsleeractiviteiten die als relevant wordt ervaren door leerlingen omdat zij inzien dat elke onderwijsleeractiviteit nodig is om de taak uit te voeren. Het content-principe is verbonden met het eigen maken van het macro-micro denken met structuur-eigenschap relaties op een manier die relevant is voor de leerlingen.

Binnen het ontwerp van het onderwijsleerproces zijn deze drie ontwerpprincipes met elkaar verweven. De ontwikkeling, evaluatie en verfijning van elk ontwerpprincipe zijn echter apart beschreven in drie verschillende hoofdstukken. In tabel 1 worden de onderzoeksvragen gepresenteerd die gerelateerd zijn aan elk ontwerpprincipe.

Tabel 1 Ontwerpprincipes, beoogde pedagogische effecten en daarmee verbonden onderzoeksvragen

Ontwerp principe	*Beoogde effect*	*Onderzoeksvraag*
Context-principe (Hoofdstuk 3)	Opzetten van een context waarin het leren van macro-micro denken relevant is voor leerlingen.	1. In welke mate leidt het uitwerken van de strategie-componenten tot het beoogde effect: het ontwikkelen van een context als een voorwaarde om het leren van chemische concepten relevant te maken voor leerlingen? 2. Wat is de formulering van het empirisch onderbouwde context-principe?
Sequentie-principe (Hoofdstuk 4)	Leerlingen ervaren de sequentie van onderwijsleeractiviteiten als zinvol, zodat ze weten 'wat ze gaan doen en waarom ze dat gaan doen'.	3. In welke mate leidt de uitwerking van de strategie-componenten tot een volgorde van onderwijsleeractiviteiten waarin de leerlingen weten 'wat ze gaan doen en waarom ze dat doen' met betrekking tot het leren van macro-micro denken met structuur-eigenschap relaties? 4. Wat is de formulering van het empirisch onderbouwde sequentie-principe?
Content-principe (Hoofdstuk 5)	Leerlingen maken zich macro-micro denken met structuur-eigenschap relaties eigen.	5. In welke mate leidt de uitwerking van de strategie-componenten tot het beoogde effect dat leerlingen zich macro-micro denken met structuur-eigenschap relaties eigen maken? 6. Wat is de formulering van het empirisch onderbouwde content-principe?

Alle strategie-componenten zijn uitgewerkt in een onderwijsleerproces. Hierin krijgen de leerlingen de taak om een gluten-arm maisbrood te ontwikkelen voor mensen met coeliakie (glutenintolerantie). Gluten is een groot eiwit dat van nature aanwezig is in tarwe. De aanwezigheid van gluten zorgt ervoor dat het deeg kan rijzen. Maïsdeeg bevat van nature geen gluten met als gevolg dat het niet zal rijzen. De leerlingen moeten een vervanger voor gluten vinden en die vervolgens toevoegen aan maïsmeel om een maisbrood te verkrijgen van voldoende kwaliteit.

Er zijn twee cycli in het ontwerponderzoek. Ze bestaan elk uit het ontwerp van het onderwijsleerproces, de uitvoering en de evaluatie ervan. Dit moet leiden tot het verkrijgen van de antwoorden op de gestelde onderzoeksvragen (zie tabel 1). Het ontwerp van het onderwijsleerproces bevat naast het eigenlijke ontwerp een verantwoording van het ontwerp, samen met een evaluatieplan dat bestaat uit gedetailleerde verwachtingen in de vorm van concrete beschrijvingen van de beoogde onderwijseffecten. Na de uitvoering van het onderwijsleerproces in de klas wordt de uitwerking van de strategie-componenten in het ontworpen onderwijsleerproces geëvalueerd.

In **hoofdstuk 3** worden de antwoorden gegeven op de onderzoeksvragen over het context-principe. In het ontwerp van het onderwijsleerproces wordt een aangepaste authentieke praktijk gebruikt als een context om de relevantie te vergroten van de chemische concepten die de leerlingen zich eigen moeten maken.

De gebruikte strategie-componenten zijn:

(i) een aangepaste authentieke taak,

(ii) intuïtieve denkbeelden van leerlingen met betrekking tot een procedure en

(iii) het mogelijk maken van productieve interactie.

De leerlingen werken samen aan een taak in een op de praktijk gerichte leer-gemeenschap in een fictief bedrijf. De uitwerking van de strategie-componenten in het onderwijsleerproces is beschreven voor beide cycli van het ontwerp-onderzoek. Na de tweede cyclus, is geconcludeerd dat de gecombineerde uitwerking van de strategie-componenten leidt tot het beoogde effect. Het zo verkregen, empirisch onderbouwde context-principe wordt geformuleerd als volgt: *Als* in een klassensituatie leerlingen een aangepaste authentieke taak krijgen met een duidelijke focus (strategie-component i), met een duidelijk plan dat gebaseerd is op hun intuïtieve denkbeelden (ii), en een productieve interactie tot stand wordt gebracht (iii) *dan* wordt een context gevormd die het leren van chemische concepten relevant maakt voor leerlingen.

In **hoofdstuk 4** wordt antwoord gegeven op de onderzoeksvragen over het ontwerpen van een sequentie van onderwijsleeractiviteiten. Een procedure afkomstig uit de praktijk waarin voedselproducten worden ontwikkeld, is zodanig aangepast dat die aansluit bij de daarover aanwezige intuïtieve denkbeelden bij leerlingen (strategie-component iv). Een tweede strategie-component is dat elke onderwijsleeractiviteit een motief moet oproepen bij leerlingen om te beginnen met de daaropvolgende activiteit (strategie-component v). De uitwerking van beide strategie-componenten in het onderwijsleerproces was grotendeels zoals beoogd. In de tweede ontwerpcyclus, werden de verwachtingen met betrekking tot de procedure grotendeels gehaald, met uitzondering van het feit dat het leerdoel niet in lijn was met het doel van de taak. Leerlingen konden hun intuïtieve denkbeelden over de procedure productief maken; hun intuïtieve ideeën over de benodigde procedurele stappen konden uitgebreid worden naar de beoogde procedure. De sequentie van motieven om de volgende activiteit uit te voeren na reflectie op de voorafgaande, was effectief tot het moment dat de docent (onbedoeld) bepaalde wat leerlingen zouden gaan doen. Daarnaast bleek dat de leerlingen geen motief hadden om te reflecteren op hun procedurele stappen, op de manier van macro-micro denken en op het gebruik van deze beide in een andere situatie.

Het sequentie-principe op empirische basis luidt: *Als* een procedure wordt gebruikt, die gebaseerd op de intuïtieve denkbeelden van leerlingen (strategie-component iv) en de motieven zijn in een zodanige volgorde geplaatst dat een reflectie op een onderwijsleeractiviteit leidt tot een oriëntatie op de volgende (strategie-component v) *dan* ervaren de leerlingen een sequentie van onderwijsleeractiviteiten als relevant, omdat ze weten wat ze doen en waarom ze dat doen (beoogde onderwijseffect). Daarbij wordt aanbevolen om de formulering van de strategie-component (iv) aan te passen door er een voorwaarde aan toe te voegen (aangegeven in cursief): … een procedure wordt gebruikt, die gebaseerd is op de intuïtieve denkbeelden van leerlingen en *die in lijn is met het leerdoel van het beoogde onderwijsleerproces …*

In **hoofdstuk 5** wordt gerapporteerd over de uitwerking van de strategie-componenten met betrekking tot het macro-micro denken met structuur-eigenschap relaties. In de eerste ontwerpcyclus worden twee strategie-componenten gebruikt: het gebruik van systeemdenken en het gebruik van de intuïtieve denkbeelden van leerlingen over de oorzaak van een eigenschap. In de eerste ontwerpcyclus blijkt uit de analyse van uitvoering dat er een derde strategie-component toegevoegd moet worden: het gebruik van de intuïtieve denkbeelden van leerlingen met betrekking tot de concepten ‘structuur’ en ‘eigenschap’. Tijdens de tweede ontwerpcyclus is de uitwerking van deze drie strategie-componenten geëvalueerd. Daaruit blijkt dat het beoogde effect grotendeels is bereikt. Tijdens de uitvoering blijkt evenwel dat de leerlingen moeite hebben met de schalen van meso-niveaus beneden 10^{-5} m. Er zijn twee redenen hiervoor gevonden. De eerste reden is het gebruik van metaforen in het lesmateriaal en tijdens de onderwijsleergesprekken, die bedoeld waren om het begrip op submicro-niveau te vergroten. Het gebruik hiervan hindert de conceptuele ontwikkeling van leerlingen. Dat komt doordat de metaforen gerelateerd zijn aan het macro-niveau. De tweede reden is het koppelen van een meso- of submicro-niveau aan een specifieke afmeting. Op basis van deze empirische bevindingen kan het content-principe worden geformuleerd als: *Als* leerlingen gebruik maken van systeemdenken door een materiaal te beschouwen als een systeem opgebouwd uit subsystemen (strategie-component vi), als ze daarbij het intuïtieve denkbeeld gebruiken dat de oorzaak van een eigenschap gezocht moet worden in het materiaal (strategie-component vii) *en* als zij de intuïtieve denkbeelden over de concepten ‘structuur’ en ‘eigenschap’ gebruiken (strategie-component viii), *dan* maken leerlingen zich macro-micro denken met structuur-eigenschap relaties eigen (beoogde effect). Op grond van de analyse wordt aanbevolen tenminste twee andere strategie-componenten toe te voegen aan het content-principe: het gebruik van metaforen en het schalen van structuren. Ook een herformulering van de strategie-component ‘het gebruik van systeemdenken’ wordt aanbevolen en zou in ieder geval de notie moeten bevatten dat interacties tussen subsystemen gebruikt worden om een eigenschap van een materiaal te voorspellen.

Deel III: methodologie van de gebruikte benadering van ontwerponderzoek

In dit onderzoek is gebruik gemaakt van een specifieke benadering van ontwerponderzoek. De gebruikte methode voor ontwerponderzoek wordt in **hoofdstuk 6** beschreven en toegelicht met voorbeelden uit het onderzoek naar macro-micro denken. Ook wordt op een reflectieve wijze teruggekeken op deze methode. Eerst worden in hoofdstuk 6 de procedurele fasen beschreven die in dit ontwerponderzoek gebruikt zijn om een valide kennisclaim te verkrijgen. In de procedurele fasen worden ook de kwalitatieve onderzoeksinstrumenten en de methodologische activiteiten van de onderzoeker toegelicht. Er wordt een directe verbinding gemaakt tussen theorieën over leren en onderwijzen en ontwerpprincipes. De ontwerpprincipes en het raamwerk met leerfasen die gedetailleerde verwachtingen bevatten in de vorm van geconcretiseerde beschrijvingen van de beoogde effecten, worden gepresenteerd als een tweeledige kennisclaim van dit ontwerponderzoek.

In **hoofdstuk 7** worden de conclusies en het antwoord op de centrale onderzoeksvraag geformuleerd en vindt een reflectie daarop plaats. De nadruk ligt op de inzichten over het incorporeren van macro-micro denken met structuur-eigenschap relaties in het chemieonderwijs (met name bovenbouw vwo) op een manier die relevant is voor leerlingen.

In dit hoofdstuk wordt ook de hoofdvraag beantwoord: '*Hoe kan macro-micro denken met structuur-eigenschap relaties en tussenliggende meso-niveaus ingepast worden in het chemieonderwijs (bovenbouw vwo) op een manier die door leerlingen als relevant wordt ervaren?* Deze incorporatie is uitgevoerd door een beargumenteerde uitwerking van acht strategie-componenten in een raamwerk van leerfases met gedetailleerde verwachtingen. De strategie-componenten en de daaraan verbonden beoogde effecten zijn gepresenteerd als ontwerpprincipes (zie tabel 2).

De uitwerking van de strategie-componenten in een onderwijsleerproces wordt gepresenteerd als een raamwerk van leerfasen met daarin gedetailleerde verwachtingen als concrete beschrijvingen van de beoogde effecten. Het raamwerk kan gebruikt worden om een onderwijsleerproces te structureren waarin een authentieke praktijk gebruikt wordt als context voor het zich eigen maken van macro-micro denken met structuur-eigenschap relaties. De ontwerpprincipes en het raamwerk van leerfasen vormen het belangrijkste deel van de kennisclaim van deze studie.

Wat betreft de drie uitdagingen met betrekking tot relevantie worden de volgende empirische argumenten behorend bij elk ontwerpprincipes beschreven:

1) *Relevantie, gerelateerd aan de context.* De leerlingen ervoeren de context in hoge mate als relevant. Daarvoor was een taak met een duidelijke focus noodzakelijk. Het ontwerp van het onderwijsleerproces hoeft er echter niet op gericht te zijn dat de leerlingen zich identificeren met junior ontwikkelaars van voedselproducten.

2) *Relevantie, gerelateerd aan de sequentie.* De leerlingen wisten in hoge mate wat ze gingen doen, waarom ze dat deden en hoe ze verder moesten. Om dat te bereiken is gebruik gemaakt van een procedure die aansloot bij de intuïtieve denkbeelden van leerlingen. Deze procedure was echter niet in lijn met het gestelde leerdoel. De beoogde motieven konden worden opgeroepen bij leerlingen, zoals dat bedoeld was, waarbij de docent de rol van begeleider vervulde en de leerlingen hun eigen motieven konden formuleren. Toen de docent onbedoeld de leiding overnam, stopte dit type sequentie.

Tabel 2 ontwerpprincipes, strategie-componenten en beoogde effecten als kennisclaim van deze studie

Ontwerpprincipe	**Strategie-component**	**Beoogd effect**
Context-principe	i. Selecteer een gefocuste taak ii. Gebruik intuïtieve denkbeelden van leerlingen met betrekking de procedurele stappen iii. Maak productieve interactie tussen de deelnemers mogelijk	Het ontwikkelen van een context als een conditie om het leren van chemische concepten relevant te maken voor leerlingen.
Sequentie-principe	iv. Gebruik een procedure die gebaseerd is op intuïtieve denkbeelden van leerlingen v. Plaats de motieven in een zodanige volgorde dat een reflectie op een onderwijsleeractiviteit leidt tot een oriëntatie op de volgende	De leerlingen ervaren een zinvolle sequentie van onderwijsleeractiviteiten als ze weten wat ze doen en waarom ze dat doen.
Content-principe	vi. Gebruik systeemdenken vii. Gebruik het intuïtieve denkbeeld van leerlingen dat de oorzaak van een eigenschap gezocht moet worden in het materiaal viii. Gebruik de intuïtieve denkbeelden van leerlingen over de concepten 'structuur' en 'eigenschap'	De leerlingen maken zich macro-micro denken met structuur-eigenschap relaties eigen.

3) *Relevantie, gerelateerd aan de content.* De leerlingen waren in staat op een acceptabel niveau structuren en eigenschappen vast te stellen en eigenschappen te relateren aan de betreffende structuren op meso-niveau in het materiaal. De leerlingen gaven deze subsystemen eigenschappen die anders waren dan die van het materiaal of het gehele systeem. De leerlingen waren ook in staat om de gebruikte denkwijze weer te geven in een conceptueel schema samen met de gebruikte structuur-eigenschap relaties. De leerlingen konden uitleggen waarvoor de denkwijze bedoeld was en wat de denkwijze inhield.

Aanbevolen wordt bij een volgend ontwerp van het onderwijsleerproces twee strategie-componenten toe te voegen en een andere strategie-component te herformuleren. In de reflectie op deze studie wordt ook ingegaan op de verkregen inzichten over de context, de volgorde van onderwijsleeractiviteiten en macro-micro denken met structuur-eigenschappen relaties.

Nader onderzoek is gewenst naar:

- het gebruik van macro-micro denken in andere disciplines zoals biologie en natuurkunde,
- het gebruik van verworven kennis in andere situaties (vooral in onderwijs dat op contexten is gebaseerd),
- het gebruik van metaforen, leerkiemen en advance organizers in natuurwetenschappelijk onderwijs en
- de rol van de docent in een innovatief natuurwetenschappelijk curriculum.

Dankwoord.

'There and back again' (Tolkien, J.R.R. 1937, the Hobbit of there and back again)

Centraal in mijn promotietraject staat het heen-en-weerdenken, de jip-en-janneke-versie van macro-micro denken met structuur-eigenschap relaties. Heen-en-weer is een wederkerend thema in mijn promotieonderzoek. Het gaat dan niet alleen om de twee of drie keer per week daarheen-en-weer-terug tussen Breda en Utrecht of om het chemische inhoudelijke deel van deze promotie, maar ook het heen-en-weer-slingeren tussen meningen van allerlei collega's waartussen je een eigen weg moet zien te vinden.

'There and back again' heeft ook betrekking op mijn twee 'banen', de ene als promovendus waarvan u het onderzoeksresultaat in handen hebt en de andere 'praktijk' als docent in het voortgezet onderwijs. Daar-en-weer-terug slaat hier op de stap tussen 'onderzoek en 'praktijk' die niet altijd even soepel te overbruggen is. Het 'overbruggen' kwam de docent wel goed te pas: de pas verworven kennis werd de volgende dag (en soms een week later) al in de praktijk gebruikt. Maar de onderzoeker in opleiding had meer last van het pragmatische gedrag van de docent: sneller tevreden, minder goed geformuleerd en gefocust op het ontwerp in plaats van het onderzoek. Nu ben ik niet schizofreen; het loopt zoals gewoonlijk door elkaar bij mij.

Hobbits of beter Halflings, met een lengte van ongeveer 60-120 cm, zijn een vredelievend volk, dat een rustig en voorspelbaar leven leidt. Het gevoel van 'kleiner zijn' is normaal bij het begin van een promotietraject, iedereen heeft altijd wel een mening paraat of schetst er een vanuit een totaal ander perspectief, waar je nooit aan had gedacht. Kortom, als promovendus heb je al snel een jachtig bestaan, dat elke week weer een ander perspectief oplevert. Gedurende een promotietraject verdwijnt het gevoel van een 'halfling zijn', maar ook niet helemaal … er zijn altijd nieuwe inzichten. Dit gevoel van verder komen en weer terug te vallen is kenmerkend geweest voor mijn gedachten en inzichten.

Het heen-en-weerslingeren kenmerkt zich ook in mijn perspectief op de inschatting van de haalbaarheid van doelen en de hoeveelheid te verrichten werk in die tijd. Niet dat ik ooit een deadline heb gemist. Mijn ambities en het daarmee gepaard gaande perspectief op de werkelijkheid zijn één kant van de medaille en de weerbarstige praktijk of mijn beperkte inschattingsvermogen de andere kant.

Nu zijn er nogal veel mensen die op een of andere manier betrokken zijn bij mijn heen-en-weergeslinger. En dit is de enige plek in een proefschrift waar je iedereen mag bedanken, waarbij je weet dat er nooit genoeg woorden en uitdrukkingen zijn te vinden om collega's, vrienden en familie (en al die anderen die ik uiteraard vergeet) te bedanken. Maar ik doe toch een poging.

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Curriculum Vitae

Marijn Meijer werd geboren op 4 september 1967 te Oostflakkee. Achtereenvolgens rondde hij de mavo, havo en vwo succesvol af aan het Scholengemeenschap Zuid te Enschede. Direct daarna werd in 1987 gestart met de opleiding Chemische Technologie aan de Universiteit Twente die in maart 1993 werd afgerond met een specialisatie proceskunde. De eerste graads lesbevoegdheid scheikunde werd gehaald in 1996. Na een korte periode gewerkt te hebben aan R.S.G. Stad en Esch te Meppel werd hij in januari 1997 aangesteld aan het Newmancollege. Daar werkt hij nu nog als docent en als coördinator van het technasium. Gedurende deze periode is hij betrokken geweest bij de ontwikkeling van voorbeeld-lesmateriaal bij de vakgroep chemiedidaktiek van de universiteit Utrecht, Jet-Net en heeft hij een lesbevoegdheid ANW gehaald.

Van 1 augustus 2004 tot 1 augustus 2008 was hij aangesteld als deeltijd promovendus bij de vakgroep chemiedidactiek aan de Universiteit Utrecht bij het Freudenthal Instituut voor didactiek van Wiskunde en Natuurwetenschappen (FIsme) van waaruit dit promotieonderzoek is uitgevoerd. Hier is hij ook betrokken geweest als ontwikkeldocent in de regio Zuidwest Nederland bij het ontwikkelen van modules voor de curriculum-vernieuwing genaamd ‘nieuwe scheikunde’. Er zijn gedurende die tijd een tweetal modules voor de derde klas havo/vwo en een module voor vwo 5 ontwikkeld en getest. Van 1 augustus 2008 tot heden is hij aangesteld als deeltijd junior docent/onderzoeker bij de vakgroep chemiedidactiek.

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