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Monitoring multiple aspects of learning when design-based learning meets science education

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Abstract

Curricular reforms are increasingly positioning design-based learning as an integral part of secondary school science education. This growing emphasis is posing challenges for science teachers. One such challenge concerns the formative assessment of student learning in a context known for its wide range of potential learning goals. This study sought to explore this underexamined area by investigating an experienced chemistry teacher's formative assessment reasoning. We were specifically interested in the breadth of aspects of learning that a science teacher may focus on in a design context. We collected data during weekly reflection conversations with the teacher, conducted over the course of her implementation of a design project for 10th-grade chemistry education. Qualitative data analysis showed that the teacher monitored diverse aspects of learning, namely students' chemical thinking, design practices, research practices, social interactions, ownership, behaviour and emotions. The case furthermore showed how the teacher connected different aspects of learning which could support her interpretation of student learning, but also demonstrated tensions between desired learning outcomes. The findings offer suggestions for future development of design-based learning frameworks, and for teacher educators who seek to support teachers' formative assessment in contexts where design and science meet.

Keywords Design-based learning · Science education · Formative assessment · Teacher reflection · Chemistry education

Introduction

Twenty years ago, the integration of design and technology education with other secondary school subjects was, "at least in theory", emphasised in several national curricula (Rasinen, 2003, p. 46). Since then, reforms in secondary school science education have been seeking to further increase the integration of design (and technology) education with science

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education (incl. National Research Council, 2012; Board of Tests & Examinations, 2014). Design-based learning is being positioned more and more as an *integral* part of effective and relevant science education. Engagement in design practices is, for example, seen as being "as much a part of learning science as engagement in the practices of science" (National Research Council, 2012, p. 12). Educational research has furthermore brought about pedagogical frameworks to support the implementation of design-based learning in science education (incl. Apedoe et al., 2008; Fortus et al., 2004; Kolodner et al., 2003). Nevertheless, design-based learning also poses challenges for science education and science teachers. One of these challenges concerns how teachers can gain insight into student learning, and provide students tailored support in contexts where design and science meet. In other words, this concerns what formative assessment during design-based learning entails for science teachers.

Traditional science lessons typically involve a whole class working towards a certain disciplinary goal, such as developing understanding of a specific science concept. Through formative assessment, teachers can gauge where students stand in their progress towards that goal, and adjust their teaching to better support student learning (Black & Wiliam, 2009; Cowie & Bell, 1999). Design-based learning, however, differs from the more typical approaches in science education. Design-based pedagogies are, for instance, well known for the rather wide variety of learning goals they may serve. A single design project for science education may seek to enhance students' conceptual understanding, research practices, collaborative skills and metacognitive skills (Kolodner et al., 2003). Students even tend to draw on various untargeted ideas and skills when designing, due to the multifaceted and open-ended nature of design challenges (Siverling et al., 2019; Watkins et al., 2018; Stammes et al., 2023).

Research in design and technology education has underlined that teachers' formative assessment should indeed involve multiple aspects of student learning (Fox-Turnbull, 2006). Yet, what aspects of learning science teachers actually monitor in the rich and reform-based context of design-based learning remains to be investigated. What a teacher in practice considers meaningful and feasible to assess may not be the same as what is advocated in literature or curriculum materials (Shapiro & Wardrip, 2019). Moreover, the so-called 'substance' of teachers' formative assessment (i.e., what type of learning is assessed) is often neglected in educational research (Coffey et al., 2011). Investigating *what* teachers assess can, however, offer a complementing perspective on the research and pedagogical supports that focus more on the *how* of formative assessment (i.e., the tools and strategies that teachers can use; Coffey et al., 2011; Cowie et al., 2018).

In the present paper, we aim to obtain insight into the possible substance of a science teacher's formative assessment in a design context through conducting an explorative case study (c.f. Patton, 2014). We will examine the aspects of learning that lie at the centre of an experienced science teacher's formative assessment reasoning regarding a design project for 10th-grade chemistry education. Formative assessment can be taken to encompass processes occurring within the bustle of the classroom (e.g., Ruiz-Primo, 2011), and processes taking place during moments of deliberation (e.g., Shapiro & Wardrip, 2019; Tomanek et al., 2008). In our exploration, we focus on these more deliberate processes, occuring outside of classroom constraints. These include, for example, a teacher designing tasks to elicit learning (Black & Wiliam, 2009), examining evidence of student learning (Talanquer et al., 2013), or planning follow-up responses (Black & Wiliam, 2009). Illuminating formative assessment from this vantage point provides access to a teacher's assessment reasoning (e.g., Tomanek et al., 2008), and can help unveil the aspects of learning that a teacher monitors (e.g., Van Es & Sherin, 2008; Watkins et al., 2021).

This study's results offer a unique window into the aspects of student learning that can substantiate a science teacher's formative assessment reasoning in the context of design-based learning. The study's purposive selection of a teacher who has some experience with design-based learning, but is also actively engaged in developing this expertise furthermore yields insights into the resources and challenges that are important to consider in professional development activities and curriculum materials that seek to support science teachers in implementing a design-based pedagogy.

Theoretical background

Design-based learning in science education

Views on design-based learning in science education are often influenced by the 'Learning-by-Design' framework. In their seminal work, Kolodner and colleagues (2003) describe how this design-based pedagogy offers opportunities for learning in science classrooms. Key elements of the framework include engaging students in designing a working artefact in an iterative way. The iterations mean that students continuously refine their conceptual understanding, skills and practices in addition to their design solution (Kolodner et al., 2003). Experiencing that a designed artefact does not function as expected, for example, can help a class identify science concepts that need to be explored further to be able to improve the design. Another key element of the framework concerns the collaborative nature of design-based learning (Kolodner et al., 2003). Sharing experimental results or design ideas with the class, for instance, allows students to receive feedback on their (scientific) reasoning while peers are simultaneously provided with useful design suggestions.

Design-based learning in science education is furthermore known for the variety of learning goals it can serve. Fortus and colleagues (2004), for example, describe how their design-based pedagogy targets students' "construction of scientific knowledge and 'designerly' problem-solving skills" (p. 1085). Kolodner and colleagues (2003) talk about students "learning science concepts and skills and their applicability, in parallel with learning cognitive, social, learning, and communication skills" (p. 495). Previous research showed that science teachers can similarly see design-based learning as a way to address a range of learning goals (Stammes et al., 2020). Less is known yet, however, about teachers' ongoing formative assessment of these aspects of learning.

Formative assessment

Formative assessment entails the ongoing processes that provide teachers insight into student learning, insights they can use to tailor their actions to students' needs during a learning process (Black & Wiliam, 2009; Cowie & Bell, 1999). Formative assessment processes have been conceptualised in various ways.

An often referenced model distinguishes three main processes: clarifying learning goals and success criteria; creating activities that elicit evidence of student learning; and providing feedback (Black & William, 2009). Teachers, peers and students themselves can be actors of these processes (Black & William, 2009). Other researchers have stressed that formative assessment also includes teachers interpreting elicited student information (Ruiz-Primo, 2011). Formative assessment is often thought of as being guided by predetermined learning goals (e.g., Black & Wiliam, 2009; Ruiz-Primo, 2011), but some have highlighted that goals can also arise unexpectedly, such as through a teacher's interactions with students (e.g., Coffey et al., 2011; Cowie & Bell, 1999). There is formative assessment research that focuses on processes occurring during the interactive phase of teaching, within the bustle of the classroom (e.g., while a teacher is in conversation with students; Ruiz-Primo, 2011). Others target assessment processes that take place outside of the classroom, during lesson planning and reflection. This type of research has, for example, examined teachers' reasoning as they select tasks to elicit learning (e.g., Tomanek et al., 2008), or interpret evidence of student learning (e.g., Talanquer et al., 2013).

Formative assessment research has also been criticised. Science education researchers have argued that research has focussed too much on the strategies and tools that teachers use to gauge and advance student learning (Coffey et al., 2011). Rather than zooming in on what teachers do, these researchers state that the heart of formative assessment research and practice should involve a teacher's attention to what and how students are thinking and participating (Coffey et al., 2011). Investigations into the so-called 'substance' of formative assessment can also help enlighten the context-specific nature of formative assessment processes (Coffey et al., 2011; Russ, 2018). Research has shown, for instance, how experienced STEM educators may recognise students' science thinking in a design context more easily than pre-service teachers (Dalvi & Wendell, 2017). Others have seen that a teacher's focus regarding students' design practices can change over time (Watkins et al., 2021). However, investigations into teachers' formative assessment objects still remain to be conducted with respect to the breadth of aspects of learning that science teachers encounter in a design-based learning context. A study conducted in a non-design context did describe experienced science teachers as formatively assessing science, personal and social aspects of student learning (Cowie & Bell, 1999). Others have furthermore posited that navigating a multitude of learning aspects in a design-based classroom may not be a straightforward task for teachers (Watkins et al., 2018).

In this study, we seek to examine this area of science teachers' formative assessment in design-based learning contexts. We will specifically explore the breadth of aspects of learning that lies at the heart of an experienced science teacher's formative assessment reasoning over the course of a 4-week design project. We focus our exploration on assessment processes accessible in a teacher's reflections on classroom practice. Illuminating formative assessment from the vantage point of teacher reflection does not emphasise what a teacher does in class. Rather, it highlights a teacher's reasoning involving students' ongoing learning and formative assessment of that learning (see, e.g., Watkins et al., 2021; Tomanek et al., 2008). We discuss literature on teacher reflection next.

Teacher reflection

Engaging in reflection entails making sense of practice-based experiences, and using insights to inform decision making and future actions (Korthagen & Kessels, 1999; Schön, 1983). Multiple parallels can be drawn between reflection processes and formative assessment processes. For example, interpreting events that occurred in a particular classroom, and using obtained insights to plan follow-up actions can be found in both formative assessment and teacher reflection frameworks (e.g., Black & Wiliam, 2009; Korthagen & Kessels, 1999). Provoking teacher reflection may thus provide insight into a teacher's formative assessment thinking. Yet, researchers have cautioned that framing teacher reflection as 'self-study' can cause teachers to focus on themselves rather than on students (Levin et al., 2009). Our present study uses a specific reflection method to help guide reflection towards discussion of formative assessment of student learning.

Reflection through midstream modulation

In this study, we will use a conversational approach called 'midstream modulation' to provoke teacher reflection (also see Fisher, 2007; Flipse et al., 2013). The approach is characterised by the use of a four-component conversation protocol which was originally developed through ethnographic research conducted in the field of science and engineering. In order to observe and stimulate scientists' or engineers' reflection on practice, and support their decision making for future actions, a so-called "embedded" researcher with a social science background would observe participants at work, and engage them in regular conversations around their decisions' opportunities, considerations, alternatives and outcomes (i.e. the four components of the protocol). Different from a more typical interview approach, there is no list of prepared questions. Rather, the four components offer a general yet structured basis to provoke reflection through naturally developing conversations between the participant and embedded researcher (Fisher, 2007; Fisher et al., 2016).

Similar as for scientists and engineers, engaging teachers in conversation with others has also been found to be a fruitful way to encourage reflection (incl. Rodgers, 2002; Schön, 1988). As in midstream modulation, common teacher reflection approaches also tend to include a focus on reflection on situations from participants' practice with the aim to improve practice; collaborative inquiry between the participant and a coach; and the use of a multi-component protocol to guide reflection (also see, e.g., Korthagen, 1985; Rodgers, 2002). Nevertheless, midstream modulation research additionally describes how a desired novel perspective can be amplified and introduced by the embedded researcher during reflection (such as ethical or societal perspectives in the case of scientists or engineers; Fisher, 2007; Flipse et al., 2013; Smolka et al., 2020). Given our study's focus on formative assessment, midstream modulation provided us with a method to encourage adoption of a formative assessment perspective during reflection conversations. Moreover, by using this reflection approach with teachers rather than with scientists or engineers, this study responds to the call of investigating new opportunities for teacher reflection around design education (Watkins et al., 2021). Details of how we used the midstream modulation protocol to provoke teacher reflection around formative assessment are presented in the data collection section.

Research aim

Guided by our literature review, this study seeks insight into aspects of student learning that can substantiate a science teacher's formative assessment reasoning in the rich and reform-based context of design-based learning. We conducted an in-depth, explorative case study involving an experienced chemistry teacher who was in the process of building expertise in design-based learning as member of a professional learning community. Such purposeful selection of a single case that is accessible for intense studying, permits in-depth research into a phenomenon of interest (Patton, 2014). In fact, studies of phenomena as "subtle and complex" (p. 469) as involving learning even *require* detailed and authentic examinations of individuals (Taber, 2000). These detailed accounts can then form the starting point for constructing more general-applicable models (Taber, 2000). In this study, we focussed on investigating the aspects of learning that shaped a teacher's formative assessment processes as observable in a teacher's reflection on classroom practice. We provoked teacher reflection through conversations conducted weekly over the course of a design project for 10th-grade chemistry education in the Netherlands.

Methods

The teacher

The science teacher participating in this study was Joanne (pseudonym). Joanne had been teaching secondary school chemistry for over 20 years, and general STEM education for 7 years. This teacher was purposefully selected for the study because she presented access to the phenomenon of interest (Patton, 2014), namely a science teacher's formative assessment reasoning during design-based learning. As an active member of a professional learning community (PLC) on design-based learning in chemistry education and formative assessment, Joanne was engaged in developing, testing and evaluating design-based lesson materials with specific attention to formative assessment of student learning (Stammes et al., 2020). We expected Joanne's formative assessment reasoning to be revealing because of this PLC's context, and also because she had already gained experience with design-based learning before joining the PLC, and was previously found to have a relatively rich practical knowledge regarding design-based learning (Stammes et al., 2020). A teacher's practical knowledge as gained through experiences acts as an important resource supporting their formative assessment (Falk, 2012). Lastly, because of Joanne's experience on the one hand and her engagement in a professional development programme on the other, her case offered one that is illustrative of a science teacher who has begun building up expertise in design-based learning but who is also engaged in learning about this type of science education. Studying Joanne's case could thus yield insight into the challenges and resources that such a science teacher may face in formatively assessing student learning. These insights could be relevant to researchers and teacher educators who are similarly seeking to support science teachers in implementing (national) standards regarding design-based learning.

The design project

The present study's data collection took place when Joanne implemented a new design project, one year into the PLC. In this design project, the Thermo Challenge, chemistry students iteratively design a product that harnesses chemical energy to change the temperature of a drink or food item. Students work in teams, and set their own design problem within the challenge. Examples of products students have developed using everyday and lab materials for construction or sometimes even a 3D printer include: a cup that cools soft drinks on hot days, a cup that warms baby milk for busy parents on the go, and a container that can heat up your lunch.

The project version Joanne implemented aimed to help students apply and develop understanding about chemistry concepts (specifically reaction energy, rate and heat), and several skills relevant in design-based science education (specifically argumentation, drawing and collaboration; also see Kolodner et al., 2003; Roth, 1994; Siverling et al., 2019). The project's activities, which spanned eleven lessons for Joanne, were informed by the Dutch chemistry curriculum (e.g., setting design requirements; Board of Tests &

Examinations, 2014), and Learning-By-Design approach (e.g., connecting research and design activities; Kolodner et al., 2003). Activities in the design project included setting design requirements informed by the analysis of an existing product; experimenting with endothermic and exothermic chemical reactions and ways to increase reaction rates; drawing and reasoning about potential design solutions; and constructing, testing and evaluating prototypes. The design cycle guiding students' design activities is presented in Fig. 1, and includes a 'short cut' route to demonstrate that the design cycle does not need to be followed as a fixed, stepwise process (an idea suggested by another of the PLC's teachers). In the first version of the project, the one Joanne implemented in this study, 'making a design drawing' was still called 'going back to the design'. More details on the Thermo Challenge design project are presented in Stammes et al., 2023.

Opportunities for formative assessment were incorporated throughout the project. Suggested activities included a whole-classroom discussion to establish success criteria for argumentation and drawing (also see Wiliam & Leahy, 2015), whole-class 'white-boarding' sessions to formulate learning goals and lessons learned (Kolodner et al., 2003), and teams providing suggestions for each other's designs. Student workbooks served to guide students through the design activities, and to offer teachers a source of information on student learning.

Joanne implemented the design project in her 10th-grade chemistry class consisting of 28 students (15–16 years old). The project implementation took about four weeks, during which we collected data. Joanne was informed about the research, and gave her consent.

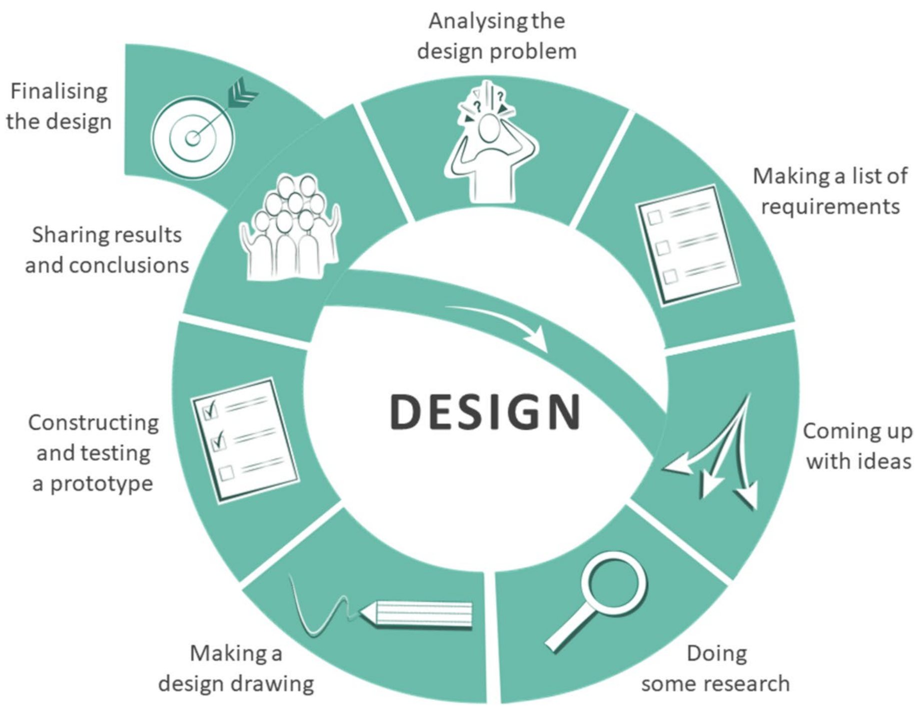

Fig. 1 Design cycle guiding the Thermo Challenge's activities

Data collection

We collected data by engaging Joanne in weekly reflection conversations over the course of the design project. The first author took up the role of the embedded researcher, and conducted these conversations using the 'midstream modulation' approach with an emphasis on formative assessment. We describe key elements of this approach to provoking teacher reflection next.

To provoke teacher reflection, we used the midstream modulation conversation protocol (Fisher et al., 2016). The protocol encourages reflection by asking questions according to four components: opportunities, considerations, alternatives, outcomes (also see Fisher, 2007). Examples of questions we used, tailored to our study's setting, included: 'What stood out to you in the last lessons [opportunities]?'; 'Why did you think that to be important [considerations]?'; 'What are other ways you could try out [alternatives]?'; 'What would you prefer to do, and why [outcomes]?'.

Throughout a conversation, the embedded researcher encouraged adopting a formative assessment perspective by using questions and making statements that aimed to amplify or suggest this way of thinking. Example questions included: 'Would you want to ask students about that [elicit student information]?'; 'Why do you think students did that [interpret information]?'; 'Do you feel like you know what students were thinking while engaged in construction [consult, interpret information]?'; and 'What are you planning to do if you encounter that misunderstanding [act on information]?'. The researcher also encouraged the teacher's consultation of student artefacts during a reflection conversation (asking, e.g., "Do you still have their brainstorms somewhere?" to encourage Joanne to describe her observations with a source of student information present; also see, e.g., Luna & Selmer, 2021). The researcher furthermore used her own observations (e.g., as obtained through classroom visits and literature studies) to help elicit and support teacher reflection (cf. Smolka et al., 2020). This occurred, for example, when Joanne was looking for an alternate course of action, but could not think of one.

During a conversation, the researcher made notes on a piece of paper divided into four quadrants to facilitate the process of moving through the protocol's components. However, the components of the protocol were not treated as a fixed, stepwise procedure, but as a fluid and iterative process in which it was important to let a conversation develop naturally (Fisher et al., 2016).

Using this approach, we conducted four reflection conversations with Joanne at her school. Conversations were audio recorded. Conversations one to three were 44 to 56 min in duration. The fourth conversation took place when the project had just ended, and was shorter in duration (15 min). We also collected secondary data to gain contextual information and aid data analysis. This data included field notes of observed lessons (one lesson per week), teacher-made quizzes and presentations, student workbooks, student focus groups, and semi-structured interviews conducted with Joanne before and after the project. The questions for these interviews were more general in nature than those of the weekly reflection conversations, and included asking about the teacher's learning goals for the design project, and (plans for) implementation of instructional and assessment activities during the project.

Data analysis

Audio recordings were transcribed and qualitatively analysed in order to characterise the aspects of student learning that formed the focus of Joanne's formative assessment reasoning during the reflection conversations. We describe the analysis process in detail below.

Selecting formative assessment segments

First, we selected the segments in the transcripts that concerned formative assessment comments. As a provisional analysis framework, we used the formative assessment processes distinguished in Black and Wiliam (2009). Their formative assessment model and its more recent versions (specifically Wiliam & Leahy, 2015) had played a central role in our interactions with the PLC's teachers. While reading the transcripts and selecting fragments, we came to adjust this initial framework. For example, as well as coming across segments where Joanne talked about *clarifying* learning goals to students (also see Black & Wiliam, 2009), we noticed that Joanne's reasoning involved *identifying* learning goals for students (see Table 1 in the Supplementary Information for an example). Also informed by research that considered the identification of goals to be an essential part of formative assessment (e.g., Haug & Ødegaard, 2015), we incorporated this process in our selection framework.

Through this combined deductive and inductive analysis approach (also see Miles et al., 2013, pg. 86), we ultimately came to select all segments that involved Joanne talking about: identifying and/or clarifying learning goals and/or success criteria; eliciting and/or consulting information about student learning; interpreting information about student learning; and/or, acting on information about student learning. As well as selecting segments where Joanne was the main actor of these formative assessment processes, we included segments were her reasoning involved students as actors (e.g., students identifying what they needed to learn; students giving each other feedback; following Black & Wiliam, 2009). Selected responses could concern formative assessment processes already implemented (e.g., when Joanne talked about having shared a learning goal with students in a lesson), taking place during a reflection conversation (e.g., when Joanne discussed student workbooks she consulted during the conversation), or being planned (e.g., when Joanne considered what eliciting questions to ask students next lesson). We did not select segments revolving around a summative assessment purpose (i.e., assessing student learning at the end of a learning process rather than during). Two examples of segments and their evaluation against selection criteria are presented as Supplementary Information (SI, Table 1).

Coding aspects of student learning

With the segments selected, we proceeded to identifying and coding the aspects of student learning Joanne focussed on. This meant turning our analytic efforts to the substance of formative assessment processes (e.g., what learning goal did Joanne say to have clarified; what information about student learning did Joanne plan to elicit; etc.). Again, our analysis approach had both deductive and inductive characteristics as we sought to develop codes with both theoretical and empirical relevance.

Our initial coding framework was informed by Cowie and Bell's (1999) finding that teachers attended to science, social and personal aspects of learning, and a characterisation of chemistry teachers' pedagogical ideas about design-based learning (Stammes et al., 2020). During the analysis process, we also referred to additional relevant works (incl. Talanquer et al., 2013; Luna et al., 2018; Watkins et al., 2018; Heredia et al., 2021; Zhang et al., 2020; National Research Council, 2005). This occurred, for instance, when we observed Joanne attending to students' emotions that arose during the design project. This facet was not captured in our initial coding framework, but is described as an important aspect of (design-based) learning in other works (National Research Council, 2005; Zhang et al., 2020).

Through this process, we ultimately developed seven codes describing the aspects of student learning that Joanne focused on. These codes were: students' chemical thinking, design practices, research practices, social interactions, ownership, emotions, and behaviour. We present these codes, their descriptions and examples from the data as Supplementary Information (SI, Table 2). One transcription segment could receive multiple codes. One such example (also see SI, Table 1) concerned Joanne talking about learning goals involving students' chemical thinking (specifically concerning energy diagrams and the energy transfer formula), and engagement in design practices (design in general and design planning specifically). As well as applying the seven major codes, we used inductive, in vivo coding to capture details of Joanne's attention within an aspect of learning. For instance, subcodes regarding the aspect of chemical thinking included 'energy diagram quiz', 'did not consider amount of substances', and 'busy calculating'.

Lastly, we sought patterns in the coded data to help us describe the details of Joanne's assessment foci, observe any changes over the course of the conversations, and explore connections between aspects of learning. This phase entailed examining each coded reflection conversation to determine which aspects Joanne focused on (e.g., was chemical thinking an aspect of interest?), what Joanne focused on within each aspect of learning (e.g., what kind(s) of chemical thinking did she focus on?), and how Joanne connected different aspects in her assessment comments (e.g., is her focus on chemical thinking in this comment connected to another aspect of learning?). To help us find and verify patterns (also see Miles et al., 2013), we referred to analytic memo's, looked for counter examples, and calculated and plotted code (co)occurrences. Throughout all analysis phases, we also consulted secondary data sources (e.g., checking field notes for evidence of the teacher enacting a reflected on assessment strategy; checking teacher-made quizzes for the type of learning elicited), and discussed emerging patterns within the research team.

Findings

Data analysis led to the identification of seven main aspects of student learning. These aspects of learning formed the centre of the teacher's formative assessment reasoning in the design-based learning context, as observed through reflection conversations. The aspects identified were: students' chemical thinking, design practices, research practices, social interactions, ownership, behaviour and emotions.

We found that teacher the teacher's formative assessment comments revolved around these seven aspects of learning in every reflection conversation. Students' chemical thinking and design practices formed the substance of Joanne's comments most often. Examining what the teacher focused on within each aspect of learning, furthermore revealed the details of Joanne's assessment interests, including some changes over time. In the following sections, we first describe this substance of the teacher's formative assessment reasoning per identified aspect of learning in the form of thick descriptions. Descriptions of the seven codes, and examples from data are also presented as Supplementary Information (SI, Table 2). Lastly, we describe how the teacher made connections between aspects of learning.

Chemical thinking

Students' chemical thinking was one of the main aspects of learning shaping Joanne's formative assessment reasoning. In the first reflection conversation, Joanne talked about how she had shared with students that they were to 'learn several chemistry things' during the design-based learning project. Learning goals involving chemistry concepts were not only important to her because students had a chemistry test coming up, but also because some concepts were relevant to the design challenge. However, she thought that this was not the case for every chemistry topic addressed in the lesson materials. Joanne (conv. 1):

> You can let them draw such an [energy] diagram, like what [diagram] suits the reaction that you choose. That is the exercise they get. And, in principle that fits fine. But, if you provide a wrong answer to that question, it has no consequences for the rest of the design process. So, it's not as if it cannot be connected to the story, but it's not truly part of the design process.

Joanne did at first seek to teach and assess the topic of energy diagrams by assigning reading material and a quiz as homework for students (conv. 1). Through consulting submitted quizzes, however, she observed that students made 'many mistakes', and decided to allocate some time to 'set it right' after the design project, during 'normal' lessons (conv. 2).

While Joanne's interest in students' thinking about energy diagrams thus decreased over time, she came to focus more on students' thinking about enhancing energetic benefits of chemical reactions. Joanne thought that this topic, which included students' understanding about the energy transfer formula ($Q = mc\Delta T$), could be better linked to students' design process since students would actually measure temperature change (ΔT) when testing their prototype (conv. 1). Moreover, she had noticed through observing and conversing with students when they were constructing and testing their first prototypes, that not all students understood that changing the temperature of a larger drink volume, required using a larger amount of reactants (conv. 2). Informed by her observations, Joanne sought to advance students' understanding in subsequent lessons through, for instance, asking them to write down the formula $Q = mc\Delta T$, and reply to questions like 'So, how can you increase ΔT?' (conv. 3).

Joanne also occasionally referred to student thinking about concepts such as properties of matter and reaction rates, but these did not grab her assessment interest as much. Over the course of the conversations, Joanne's formative assessment of students' learning of 'chemistry things' thus came to concentrate on thinking involving the energetic benefits of chemical reactions; a topic she could relate directly to the design challenge.

Design practices

We also found Joanne's formative assessment comments to revolve around students' application and development of design practices. In the first lesson, Joanne said, she had also clarified to her students that they were 'to learn to design' during the project (conv. 1). Across the reflection conversations, Joanne's comments regarding design practices encompassed a wide range of practices, including setting design requirements, making choices, drawing design ideas, constructing prototypes, and improving designs. Often, she talked about students being engaged in practice or not, and/or whether active engagement helped students progress towards a successful design solution. For example, informed by her observations of student actions and workbooks involving a design construction and test lesson, she said that some students had quickly started tinkering, and had been able to conduct multiple tests, while others had not (conv. 2). Sometimes, Joanne zoomed in on a particular facet of a design practice. Regarding drawing design ideas, for instance, she looked specifically for evidence of students improving earlier design ideas and including annotations, as opposed to merely making a pretty or colourful drawing (conv. 4).

Within this aspect of learning, we found Joanne repeatedly talking about students' generation of design ideas, and the quality of their ideas. She typically referred to this as whether students were 'thinking' when developing ideas. For instance, Joanne had interpreted her observation of a student placing insulation material *between* his prototype's reaction and drink compartments as a student who 'had not been thinking' (conv. 2). As the project progressed, Joanne's assessment reasoning came to zoom in more on students' idea generation regarding the scales of their design and its compartments. For example:

> There was a group, they really had such a glass beaker, and in it they had, I believe, almost one litre of water. And, they had put something in that should heat up or cool down that whole business. Then you just know that that is not going to happen, hahaha. On a different, smaller scale, however, more thought through… (conv. 2)

Joanne came to identify students considering their design's scales as the key to developing a successful solution, but also noticed that many students were not (convs. 2, 3). Among her follow-up actions, she said to be looking more deliberately for evidence (incl. in design drawings, prototypes, verbal statements) that students were beginning to develop ideas for their design's proportions (convs. 2, 3, 4). In the last conversation, Joanne could finally share the observation that some students had 'clearly changed the ratio between the compartment where the reaction takes place, and the drink itself'.

Research practices

The third aspect of learning around which the teacher's assessment reasoning revolved was that of students' research practices. From the first conversation onwards, Joanne's comments involving research practices focussed on students' 'measurement taking' (phrase from conv. 1). Joanne regularly consulted information that showed which temperatures students were measuring during investigatory lab activities or prototype tests. Joanne:

> […] yesterday I quickly scanned through all graphs, and I saw in all of them that a maximum or minimum had appeared. […] This graph goes from 19 to 70 [degrees], this one to 60, 65. (conv. 1)

Joanne also remarked on whether or how students were taking measurements (e.g., 'doing the tests one after another instead of at the same time'; conv. 1), whether or how students were documenting measurements (e.g., 'they write down some of their observations' conv. 3), and students' measurement expectations (e.g., 'of course the measurement does not go as they expected'; conv. 2). Following such observations, Joanne repeatedly described taking actions to help students measure larger temperature changes (e.g., suggesting using larger amounts of reactants).

Social interactions

Students' social interactions during the design-based project also grabbed the chemistry teacher's attention. Joanne had held a whole-classroom discussion on success criteria for collaboration, which had made her conclude early on in the project that students 'knew quite a lot about working together' (conv. 1). Instead of orchestrating such a discussion, she would in future rather present students her own suggestions on what to be mindful of when collaborating (conv. 1). We found more instances in Joanne's formative assessment comments where she seemed to see little value in students interacting as learning resources for each other. For example, a peer feedback activity around teams' design drawings had not resulted in much design progress, Joanne had found, and she planned to give students some pointers herself instead (conv. 3). There were some counter examples too. Joanne, for instance, said that she had responded to students who were insecure about their design plan that they could 'learn from what they had heard from others' (conv. 4). Within this aspect of learning, we furthermore found Joanne referring to group composition and roles (e.g., 'there are those taking initiative and the following types'; conv. 2), and students' influence on each other's behaviour and emotions (e.g., 'they are influencing each other with that 'cool guy' behaviour'; conv. 2).

Ownership

Joanne's formative assessment comments also concerned students' ownership, specifically students taking responsibility over their own learning and design (process). Joanne referred to this as students' 'adoption of an active attitude' (conv. 3). She expected students to, for example, ask her questions if they did not understand something, and take the design challenge seriously despite not receiving a grade (convs. 1–4). However, observing and interacting with students in class, and checking students' products (incl. workbook assignments), repeatedly led her to conclude that not all students were taking up these responsibilities (convs. 1, 2, 3). Perhaps, Joanne said, this could be traced back to a school-wide culture:

> Maybe the problem is that we are creating, here at school, the type of students who are too much like consumers [...] So, the student leans back, opens its mouth, and the teacher stuffs everything in. Something like that. Well, that is not an option with these kinds of projects. (conv. 3)

As follow-up actions Joanne considered, for example, that getting confronted with one's own design idea failing and other students' designs working successfully could make students reconsider their attitude (conv. 1). Joanne found, nevertheless, that many of her advancing tactics were not really improving the situation, except for giving students more freedom. In the last lesson, for instance, she had decided to let students choose themselves which assignment criteria they wanted to adhere to, which did appear to help students to take on an active role (conv. 4).

Behaviour

This aspect of learning involved formative assessment comments concerning students' (general classroom) behaviour, specifically on-/off-task behaviour, and the overall quality of the tangible products of that behaviour. For example, while looking through students' workbooks in the second conversation, Joanne generally remarked:

> I was a little bit disappointed by this group, because earlier they had been nicely engaged in drawing and were working well, like brainstorming and so. And, now they suddenly bring forth little. I don't know why honestly.

Within this category, Joanne often zoomed in on the more negative examples of students' behaviour, talking in particular about teams where she had noticed off-task behaviour and/or lacking products (e.g., a couple of groups were giggling and chatting instead of putting something on paper; conv. 1).

At the time of the third reflection conversation, Joanne's 'frustration' about the negative facets of students' behaviour had become particularly high. As follow-up actions, she considered immediately terminating the project (conv. 3), but ultimately decided to give students one last opportunity to construct and test their designs (convs. 3, 4). In the final conversation, students' negative behaviour was suddenly not a major focus anymore. Then, Joanne just mentioned how she had observed a good-working student group to have neatly completed an assignment (conv. 4).

Emotions

Joanne's formative assessment remarks also revolved around students' emotions, in particular whether students were enjoying lesson activities. She had expected students, especially the more lazy types, to have fun as they would be trying to learn by 'doing something different, with lots of practical stuff' (conv. 3). Students could also 'give it their own twist', since she was not prescribing what their design should look like (conv. 3). Indeed, Joanne had observed students enjoying, for example, choosing their own design situation (conv. 1), and thinking of ways to improve their design (conv. 2). However, she also noticed that many students were not enjoying activities like drawing yet another version of their design (conv. 4), or seeing that the temperature of the drink in their first prototype changed only a little bit (convs. 2, 3).

Joanne found classroom moral to be especially low at the time of the third reflection conversation. Acting on this interpretation, she hoped to be able to wrap up the project with a 'positive experience' by suggesting students to change their design's substance-to-drink ratios, and giving students a final opportunity to construct and test their design (conv. 3). In the last reflection conversation, Joanne was relieved to have seen that constructing their adapted design and measuring a larger temperature change had indeed been satisfying for students (conv. 4). She subsequently remarked: 'They were happy, so I was happy'.

Connecting aspects of learning

In addition to examining the teacher's formative assessment reasoning for attention to different aspects of learning, we explored how the teacher connected these aspects in her reasoning. We found that Joanne typically connected two or more aspects of learning. For instance, when talking about her observations during a design construction and test lesson, Joanne's comments connected students' emotions (frustration, disappointment), research practices (measuring temperature), design practices (evaluating functioning of design), and chemical thinking (not realising role of volume, lacking knowledge). Joanne:

> […] I noticed a lot of frustration in some groups, and maybe that's actually good. But… there were some who said: 'It's not working at all'. And, then I said: 'You didn't measure a difference at all?' 'Well, half a degree or one degree, so it still works but not well enough.' Yeah, they then feel that it just does not work. Well, and then one group wanted to give up already. […] they don't realise that that extra volume they added to heat up, that that [volume] starts to play a role too […] They didn't already have the knowledge to understand that. And then you measure something disappointing, and then you don't really understand where that comes from. Whereas, if they had had that piece of theory already, then you could have referred them to it once you started to notice like, ooh now they are starting to look very sad. (conv. 2)

In this example, Joanne's attention to multiple aspects of learning appeared to help her in interpreting her observations of the lesson. In other examples, though, we saw the teacher to experience tensions in her seeking to probe and support multiple aspects of learning. These tensions concerned, for example, Joanne wanting students to enjoy the design project and to develop certain chemical thinking and design practices, but contrastingly noticing that students were disliking some activities that sought to promote their thinking and practices. Another involved Joanne seeking, on the one hand, to give students ownership over their design process, and opportunities to learn from each other or to learn from design failure. On the other hand, she observed that encouraging these types of learning did not necessarily lead to students generating successful design ideas or novel chemical thinking. Consider, for instance, this excerpt in which Joanne shares to have ultimately 'spoon fed' targeted ideas to a group of students, a teacher move she was trying to prevent:

> […] I think that that particular group doesn't really understand what they are doing. At the time of the first prototype [design], I just let them muddle along but then they also didn't really think of anything. And then I decided like, just try it out and see what you run into. […] But, well, they didn't learn any lessons from that, and of course it was all due to other things and not because of them. And, in fact, we're still at that stage. And also the comments I make, because at one point, I practically spoon fed them like 'Write down the formula, how can you get a larger 'delta T', yes indeed then 'm' needs to be smaller, very well'. (conv. 3)

While most of the formative assessment comments involved the teacher connecting aspects of learning in such ways, Joanne's reasoning did occasionally revolve around a single aspect of student learning. This occurred, for instance, when she talked in general terms about having clarified the learning goals of a particular lesson to students (e.g., certain design practices; conv. 2), or about having asked students to make a standard quiz (e.g., assessing understanding of the progress of chemical reactions; conv. 3).

Discussion and conclusions

Curricular reforms are increasingly positioning design-based learning as an integral part of secondary school science education (incl. National Research Council, 2012; Board of Tests & Examinations, 2014). This growing emphasis poses new challenges for science teachers, including formatively assessing student learning in a context where design and science meet. This context is known for the particularly wide range of learning goals that teachers need to navigate (Kolodner et al., 2003; Watkins et al., 2018). Yet, what aspects of learning science teachers actually monitor in this rich and reform-based setting was still underexamined. This so-called 'substance' of teachers' formative assessment is often neglected in educational research (Coffey et al., 2011). To explore this area, the present study examined the breadth of aspects of student learning that lied at the centre of an experienced chemistry teacher's formative assessment reasoning. We elicited teacher Joanne's reasoning through conducting weekly reflection conversations over the course of the teacher's implementation of a design project for 10th-grade chemistry education.

This study's findings firstly reveal the multidimensionality of a science teacher's formative assessment objects in a design-based learning context. We found that students' chemical thinking, design practices, research practices, social interactions, ownership, behaviour as well as emotions were monitored by the teacher throughout the design project. Some of these identified aspects of learning concerned learning goals that the teacher addressed explicitly within the project (also see the findings regarding chemical thinking and design practices). Other assessment objects, however, seemed to concern more implicit or emerging goals. Researchers, particularly from the field of teacher noticing, have previously noted that there tends to be great variety in the objects that grab a teacher's attention (incl. Erickson, 2011). However, this possible breadth of learning aspects had not yet been specified in the context of design-based learning in science education.

As well as capturing and characterising the multidimensionality of a science teacher's assessment objects in a design context, this study reveals that a science teacher can have or can develop a specific assessment focus within an aspect of learning. We observed this focus, for instance, in Joanne's attention to students' chemical thinking and research practices. These two assessment objects are quite typical in science education, but can nevertheless be challenging for (beginning) science teachers to pay attention to, particularly in design contexts (Dalvi & Wendell, 2017; Talanquer et al., 2013). It may be that Joanne's narrow(ing) assessment focus helped her to monitor students' science learning in the open-ended and multifaceted context of design. The teacher concentrated on those science concepts and research practices for which she saw a very clear and meaningful connection with the design context (i.e., they were necessary for a successful design or for measuring design success). Science teachers' recognition of connections between science and students' design process is key for students' design-based science learning (Kolodner et al., 2003), and – as Joanne's case suggests – also in an experienced teacher's formative assessment of that learning.

This study's results furthermore demonstrate that students' design practices can be a major formative assessment object for a science teacher. Some early frameworks for design-based learning valued teaching science content and research practices over design (see, e.g., Fortus et al., 2004), and science teachers can also express such an instrumental view of design-based learning (Stammes et al., 2020). Our present study contrastingly shows that a science teacher's assessment objects may (come to) align more closely with newer curricular perspectives that regard design practices as an integral part of science education (National Research Council, 2012; Board of Tests & Examinations, 2014). It may be that Joanne's experience with teaching design in general STEM education, where learning to design is emphasised over learning science content or research practices, or her engagement in the PLC helped her to also appreciate and assess students' design practices in a chemistry class.

Joanne's case additionally brings students' ownership, behaviour and emotions to the light as aspects of learning that can be meaningful to science teachers implementing a design project. These aspects are sometimes made explicit in design-based learning literature (see, e.g., Vossen et al., 2020; Zhang et al., 2020), but unlike students' social interactions their relevance is not commonly highlighted in design-based learning frameworks and materials, nor typically recognised as worthy formative assessment objects. Shapiro and Wardrip (2019) note, for instance, how formative assessment perspectives sometimes 'neglect the full scope of information that can be interesting and useful to teachers in practice (such as engagement)' (pg. 25). Others have also observed how curriculum materials that portray design as a series of steps may even reduce students' experience of ownership over a design process (Vossen et al., 2020).

While attending to aspects of learning like students' on-/off task behaviour or enjoyment alone may not provide reliable evidence of student learning, attention to one aspect of learning can support a teacher's attention to another (Watkins et al., 2018), and this process may even play a role in teachers' adoption of a reform-based science pedagogy (Preminger et al., 2024). In the present study, we also observed that a science teacher may make helpful connections between aspects of learning in a design context. We saw this, for instance, when Joanne made sense of students' design frustration by also taking into account students' level of chemical thinking. However, tensions between different aspects may also arise (Richards, 2013), as our case study demonstrated for design-based learning. We saw, for instance, how Joanne sought to balance helping students develop certain chemical and design ideas with encouraging students' ownership and learning from one another. She struggled to come up with follow-up actions that could meet all these goals. Design-based pedagogical strategies that may have helped mediate such situations, like whole-class whiteboarding (Kolodner et al., 2003), were not yet part of this science teacher's repertoire.

Together, the outcomes of this empirical case study demonstrate the importance of science teachers, curriculum developers and teacher educators recognising the multidimensionality of the objects that may substantiate formative assessment during design-based learning in science education. The aspects of learning that are important to a science teacher implementing a design project can go beyond those emphasised in curriculum materials or pedagogical frameworks. Specifically, this study's observations suggest directions for the development of design-based learning materials and frameworks. Such efforts could acknowledge the role of students' emotions and ownership in design-based science learning more explicitly, and propose strategies for teachers who seek to elicit and support these aspects of learning in addition to typical disciplinary learning. Curriculum developers and professional development facilitators could furthermore use this study's outcomes by recognising that a science teacher, who may still be learning about design-based learning or who is faced with practical constraints like school-wide science tests, may want to use a design context for the learning of a much more narrow set of science concepts or research practices than typically advocated in design-based learning frameworks (see, e.g., Apedoe et al., 2008; Kolodner et al., 2003). Creating more space and support for this teacher perspective might help certain science teachers to include design-based learning as a pedagogy in their classrooms.

Finally, this study's characterisation of the substance of a teacher's formative assessment reasoning offers an initial framework to help science teachers become aware of, and perhaps even connect and balance formative assessment objects during design-based learning. Lenses that explicate what types of learning may be relevant to assess are an important counterpart to ones that mainly tackle the how of formative assessment (i.e., the strategies and tools; Coffey et al., 2011; Cowie et al., 2018). This study's unique analytic focus on the *what* of a teacher's formative assessment reasoning has yielded such an initial framework that can be useful for teachers and teacher educators in contexts where design and science meet.

Limitations and directions for future research

While providing new insights into design-based learning in science education and its formative assessment, our exploratory case study's findings are framed by our specific research context. Future research would be required to learn, for instance, how the substance of a science teacher's formative assessment reasoning compares to their classroom practice or connects to the use of assessment strategies and tools. Also, our exploratory study involved a single teacher and design context, and there may be science teachers who pay attention to an even wider or more narrow range of aspects of learning in certain design contexts (consider, e.g., students' cultural learning; Heredia et al., 2021).

How science teachers can develop formative assessment expertise that best supports students' design-based learning also remains to be studied. Such research efforts could use the present study's identification of aspects of learning to help teachers recognise what may be relevant to assess, and what productive assessment interests within an aspect of learning might or might not look like. Researchers have been seeking to describe and foster teachers' productive attention within typical disciplinary aspects of learning (e.g., Dini et al., 2020; Watkins et al., 2021), but assessing and supporting aspects of learning like students' emotions could also be explored from a design perspective (also see Zhang et al., 2020). Lastly, we think that the present study's productive use of an adapted midstream modulation approach for provoking teacher reflection with a specific focus through conversation invites future research into the affordances of this approach to support teacher reflection and possibly teacher learning.

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Declarations

Ethical approval This study was ethically approved by the Human Research Ethics Committee of Delft University of Technology (reference number: 2026).

Conflicts of interest The authors have no conflicts of interest to declare.

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