REVIEW ARTICLE

Designing an Ice Cream Making Device: A Design-based Science Learning Approach

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ABSTRACT

In this study, middle school students' (8th grade, n = 24) problem-solving processes were investigated while implementing a design-based science learning (DBSL) approach. DBSL tries to incorporate science learning with the processes of engineering design. A DBSL module was developed by the research team within which students were expected to design an ice cream making device from simple and easily available materials. The goals of the study were: (a) To develop an understanding of the processes of student design including difficulties they face within the DBSL setting; (b) to determine how science knowledge was used by students in a design situation; and (c) to explore how student design processes and design products can be characterized and eventually, assessed. Data were gathered from students' written reports, video-recorded classroom observations, and teachers' oral feedback. The findings reveal that the crucial aspects for design success were the students' understanding of the scientific phenomena, the operational principles behind the ice cream making device, and the understanding of the design criteria. Lack of one or more led to unrealistic design ideas. The initial difficulties were overcome by peer support, teacher guidance, and trial and error experiences. A set of assessment criteria, able to characterize student design products, were developed. As a result of this study, practical guidelines for curriculum developers and teachers on how to facilitate further implementation of DBSL in the classroom are provided.

KEY WORDS: design-based science learning; problem-solving; middle school; assessment

INTRODUCTION

In Australia, North America, and Europe, different frameworks have been developed to define the essential skills needed for succeeding in the 21st century (e.g. Partnership for 21st Century Skills, 2006; Binkley et al., 2010). Although differing in detail, it is agreed amongst these frameworks that the primary emphasis in education needs to be given to the development of students' creativity, critical thinking, problem-solving, communication, and collaboration skills to be able to solve complex problems and respond to existent and future challenges (Binkley et al., 2010).

Engineering design problems provide excellent opportunities for students to express their creative and critical thinking, as well as develop their collaboration skills while creating their design solutions. The development of students' design skills, when included as a part of science education, has also been highlighted in recent years (International Technology Education Association [ITEA], 2007; Next Generation Science Standards, 2012). Design problems are considered to be among the most ill-structured and complex, as they are open-ended and similar to everyday problems (Jonassen, 2011; Hathcock et al., 2015). According to Jonassen (2011), design problems commonly include a set of subproblems, such as decision-making and troubleshooting problems that need to be solved to arrive at a satisfactory design solution. Therefore, they are good examples to facilitate the development of higher-order thinking and collaboration in science classrooms. Design tasks need to support students in finding unique pathways that do not necessarily result in a single "right" design solution (Miller, 1995 as cited in Crismond, 2001). It is expected that design tasks act as triggers for learning science by making students feel the need to expand their knowledge to be able to solve a given problem (Hmelo et al., 2000). Or in other words, the design drives the science that needs to be learned (Apedoe et al., 2008).

Design-based science learning (DBSL) is one of the teaching approaches that try to incorporate science learning and the processes of engineering design. DBSL attempts to engage students in scientific reasoning through solving authentic design problems in situations that are quite similar to engineers' (designers') everyday work (Mehalik et al., 2008; Apedoe and Schunn, 2013; Vaino et al., 2015). DBSL is similar to, and in part stems from, other pedagogical approaches, such as learning by design (LBD) (Hmelo et al., 2000; Kolodner et al., 2003), Science by Design (TERC, 2000), design-based learning (DBL) (Apedoe et al., 2008), and DBS (Mamlok et al., 2001; Fortus et al., 2004). As it becomes difficult to set strict boundaries between all these approaches, the most significant similarities highlighted here are:

1. Starting from an authentic problem, students themselves design artifacts and solutions to solve a given problem.

2. Learning is learner-centered and collaboration-oriented. The teacher's role in the learning process is seen as a facilitator of learning rather than a source of knowledge.
3. The iterative nature of design processes is modeled through 1–3 design cycles, the last, though, is adapted to the school situation.
4. An attempt is made to integrate knowledge from science, mathematics, and engineering; science knowledge is often obtained through an inquiry approach.

Within their LBD approach, Hmelo et al. (2000) introduced a project whereby 6th-grade students studied the human respiratory system by designing artificial lungs and building partial working models. In the LBD project developed by Kolodner et al. (2003), students (7-8th grade) were challenged to design a parachute, a miniature car able to go over hills, and a device that can lift objects within their physical science modules. Within an earth science module, students were expected to design a way to manage the erosion on a hill and in another unit to design underground transportation tunnels. In a DBSL study conducted by Apedoe and Schunn (2013), 9–12th grade students were required to design earthquake-proof structures within a regional design competition. In a DBS project (Fortus et al., 2005), students (9–10th grade) were expected to develop structures for extreme environmental conditions, and in a DBL project, 8th graders were invited to design electrical alarm systems (Mehalik et al., 2008). Nevertheless, there have been only a few studies where chemistry knowledge is needed for, or developed by, students to enable them to accomplish a design task. The rare exceptions were studies conducted by Apedoe et al. (2008), where design activities were built on the knowledge of thermal effects of chemical reactions and a study conducted by Fortus et al. (2004), where 9–10th graders were asked to develop environmentally safe batteries using some basic knowledge from electrochemistry.

A number of studies have proven the benefits of DBSL approaches as a means for developing positive attitudes toward learning science (Mamlok et al., 2001), improving students' problem-solving (Fortus et al., 2005) and inquiry skills (Silk et al., 2009), helping them to obtain better science knowledge compared to more traditional science classrooms (Hmelo et al., 2000; Kolodner et al., 2003) and increasing students' interest in technology and engineering careers (Apedoe et al., 2008; Vaino et al., 2015). The existing studies, though, have mostly used a pre-post type study design.

The other problem that was addressed by the current study was the concern that students tended to have difficulties in understanding scientific principles underlying their design projects (Fortus et al., 2004). This difficulty is also known as the "design-science gap," and it has been attributed to students' poor ability to transfer knowledge from one context to another (Vattam and Kolodner, 2008). The extent of knowledge transfer, in turn, is found to be related to the students':

a. Ability to access intellectual resources in situations where those resources are relevant;
b. Ability to recognize an appropriate transfer opportunity;
c. Ability to apply knowledge flexibly when the opportunity arises;
d. Motivation to take advantage of transfer opportunities (Marini and Genereux, 1995; Prawat, 1989; Kolodner et al., 2003).

The design-science gap, therefore, can result from a combination of subproblems. Certainly, more insights are needed about the type of difficulties that students may face when prompted to apply their science knowledge in a somewhat new, i.e. design situation. Another reason for the gap can lie within the contemporary assessment practice. Jonassen (2011) claims that student assessment is currently the weakest link in teaching students to solve complex problems; teachers and educators far too often rely on a single type, such as recall-oriented assessment, though, in principle, recognizing the need for developing higher-order problem-solving skills by students. Therefore, student assessment methods (both formative and summative) needed to be more aligned with contemporary learning goals and implemented learning methods (such as DBSL).

Based on the ideas above, three research questions were guiding this study:

1. Within the design phase, what are the processes used and difficulties faced by students?
2. How do students make use of science knowledge in the design situation?
3. How can the student design processes and products be characterized and assessed?

THEORETICAL FOUNDATION

In most DBSL approaches, design is mostly seen as a means through which scientific knowledge is constructed; however, in the current case, there is also an attempt to develop the students' understanding of design processes *per se*. A few design concepts and principles are applied when (1) developing a DBSL module and (2) describing and analyzing the processes and products of student design within the module. Some of the concepts are directly introduced to students to support their understanding of design processes, while the others mostly play a role in conceptualizing the approach.

According to Vincenti (1990), a designed artifact can be characterized by its *operational principle* and by its *normal configuration*. The operational principle (the concept was first introduced by Michael Polanyi) describes the working principle that enables the artifact to fulfill its expected function (Vincenti, 1990). For example, the operational principle of an internal combustion engine can be explained as follows: In a combustion engine, fuel, and air are led into a cylinder and ignited; the expansion of produced gases applies force to a component of the engine (e.g. turbine blades), which, as a result, moves the component. As complex artifacts consist of a number of different constituents, specific operational principles can be found for each constituent. The normal configuration, on the other hand, is the way in which the main components of the artifact are structured, or as defined by Vincenti (1990), *the general shape and arrangement which are commonly agreed to best embody the operational principle* (p. 209). However, one operational principle may afford generating different normal configurations.

Design criteria (also known as *design objectives*) refer to criteria that designer need to meet in designing some system or device (Farlex, 2018). Criteria may involve:

- The function of a given artifact (what it should be able to do);
- Structure (how its parts should be arranged);
- Appearance and esthetics (what it should look like);
- Production technology (how it should be made - what methods and materials need to be used) as well as the technology of recycling and disposal;
- User requirements (e.g. is it easy to use);
- Regulatory considerations (does it meet government rules), and so forth (Cross, 2000; ITEA, 2007; National Institute of Building Sciences, 2016).

Design limitations (also known as *design constraints*) refer to market, regulatory, economic, and engineering limits placed on a design (ITEA, 2007). The last two, design criteria and design limitations are closely related to another important concept in design, which is the *trade-off*. It is a situation that involves choosing between or balancing two desirable, but opposing qualities. The concept also implies that a decision is to be made, based on an analysis of both pros and cons of a particular choice.

System is a group of interacting, or interdependent component parts (*subsystems*) forming a complex whole (Merriam-Webster, 2018). To understand a system, one has to consider the causal interactions and functional relations between parts of the system as well as with other systems (Hmelo et al., 2000).

Design cycle. The design process is similar to general problem-solving processes and includes stages such as: Defining the problem and specifying the need, determining design criteria and limitations, searching for information, developing a range of alternative design ideas, choosing the optimal solution, designing and constructing a prototype, and evaluation, and further improvement of the prototype (Figure 1) (Doppelt et al., 2008; Vaino and Vaino, 2014).

THE STUDY

In the current study, three different data sources: Students' written reports, both individual and collective, classroom video records, and teachers' oral feedback were used to explore the processes of student design when implementing the DBSL module "Designing an ice cream making device" in the classroom. The module was taught within five ordinary science lessons (45 min each) by the science teacher, while the technology teacher assisted in providing materials and consulting about practical aspects of the students' design. Lessons were recorded by two cameras, one placed in the front, and the other in the back of the classroom. While written reports were used as the primary data source, additional classroom video-data and the teachers' feedback on the implementation of the module, including a member check (Creswell, 1994) of the selected data, helped by providing further insights into the processes of student design and thereby, validating the main data**.** In this way, an attempt was made to capture multiple perspectives on the phenomenon (Patton, 2002), rather than just one.

Participants

The participants of this study were 8th-grade students (13 girls, 11 boys) and their science (female) and technology (male) teachers at one Estonian city school in 2016. The teachers were volunteers in a sense that they agreed to participate in the project through taking part in joint meetings together with the first author during a school year and carry out the module in their classroom. Consent to carry out the study was asked from school authorities who followed the normal routine practiced in such cases. Privacy and data protection were taken into account. Before teaching the module, the science teacher informed students that in place of their actual names, pseudonyms would be used in study reports and none other than the researchers would analyze the videotapes and students' written reports. No additional ethical review was needed from the Research Ethics Committee of the University of Tartu, as the study was part of the school's normal teaching plan.

Both teachers were quite experienced, having taught for more than 20 years. The science teacher had previous experience with teaching context-based and design-based science modules. The technology teacher did not have previous experience with DBSL specifically, though he was knowledgeable and skilled in supervising student design projects. The students did not have any experience with DBSL nor similar approaches beforehand.

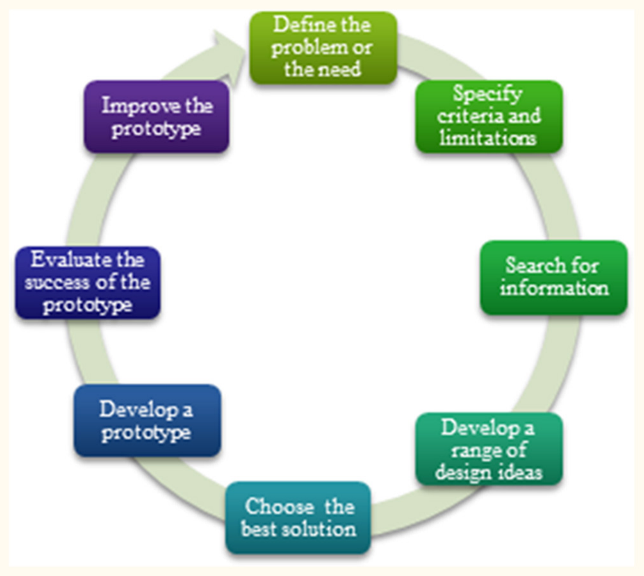

Figure 1: Design cycle

Design and Implementation of the Module

A DBSL module was developed by the research team within which the students were expected to design an ice cream making device from simple and easily available materials. It was expected that students collaboratively define a problem, examine the underlying scientific principles through a number of experiments, develop a range of possible design solutions, pick up the best solution, and build and test a prototype. The developed materials consisted of two parts: Student worksheets and a teacher's guide and the latter including the most important aspects of the module, such as learning goals, methods, and guidelines for the assessment of learning outcomes.

The learning module consists of four stages. It starts from a **scenario** (Stage I), which gives a short overview of the history of ice cream making technology, beginning with ancient China and ending with current high-tech solutions. Among the historical passages and details, the operational principle of the ancient ice cream making technology is revealed to students - the secret behind the invention lay in ordinary table salt, or saltpetre; namely, the salt is mixed with snow or ice to obtain a temperature, much lower than is possible with the use of snow or ice alone. This mixture is then used for freezing the flavored milk. The exact structure (normal configuration) of ancient ice cream making devices is not entirely revealed, although the given pictures indicate clearly that the process of endothermic dissolution of salt (the cooling subsystem) is separated from the edible substances by a septum.

After the introduction, students in groups (4–5 students per group) were asked to discuss the scenario and put forward as many ideas and questions as they could. In addition, they were asked to think of requirements that should be met to make a good ice cream, such as, for example, that cream or juice, together with flavorings, should be mixed; that edible material (no matter whether from cream or juice or both) needed to become frozen; that frothing and freezing needed to be performed simultaneously to avoid a stone-like texture of ice cream. This activity could also be regarded as a preliminary determination of design criteria (which actually would be followed by a more precise specification afterward). At the end of Stage I, students were asked to design an ice cream making device and make an "old-fashioned" "ice cream."

The discussion is followed by an **inquiry session** (Stage II) which is expected to provide students with relevant science knowledge needed for their subsequent designing. Through inquiry learning, students propose hypotheses, based on a given problem, and carry out three experiments on:

- Heat of dissolution: Students find out which substances can absorb and which substances can produce heat when dissolved in water; this experiment is expected to provide students with the knowledge needed for developing their cooling subsystem[1];
- Thermal conductivity/insulation properties of different substances: This experiment is expected to make students think about how different container materials impact on the transfer of heat from one subsystem (cooling mixture) to another (cream with flavorings);
- Students find out how the salt/ice ratio impacts on the amount of heat absorbed; this activity is expected to provide students with a rough understanding of how much salt, compared to ice, needs to be added to achieve the desired temperature.

Based on the data gathered, groups make their conclusions and report their results to the whole class. In addition to the knowledge gained through experimenting, students are provided with additional information about the same substances and materials such as their chemical properties, uses, and costs.

Based on their knowledge gained from Stage II, students **design their device** for making ice cream (Stage III). For that purpose, students are provided with different substances, materials, and equipment (Figure 2).

Students are expected to elaborate on their design criteria further and think about potential design constraints. Second, students need to make a decision on the choice of substances and material for their design and draw initial drafts of their device. This particular task is done individually but is later continued as group work. An attempt to maximize everyone's input into the final design is made by this shift (from individual to group work). In groups, every student is required to present his/her ideas to the other members, after which this is followed by a group discussion, consolidation of ideas and the development of a group draft and finally, a prototype. Accordingly, students in groups make a prototype and test it while making ice cream from cream and various flavorings. This stage is finalized by tasting the ice cream produced. Students are also encouraged to think whether their design meets their proposed design criteria, where they can improve their design and to what extent their device is environmentally sustainable.

In the very last stage (Stage IV), students **apply for a patent** and defend it in front of their classmates. For this activity, information about patenting is provided for students, including, as an example, an original patent of an ice cream machine from the 19th century. The idea of applying for a patent as a part of student design is taken from a design-based module introduced by Apedoe et al. (2008), who suggests that patent application allows students to connect their science and engineering knowledge, providing them with an opportunity to think about their design in more theoretical terms. The last stage may not

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[1] The temperature drops because the melting of ice is an additional endothermic process that consumes energy in the case of mixing salt with snow as was foreseen in performing this project. However, it was recognized by the authors, that middle school students may have problems with understanding the complex effect. Therefore, other aspects of the cooling effect, except the heat of dissolution, were omitted from the module.


Figure 2: Available substances and equipment

be entirely possible in a direct design situation, as students are often overwhelmed with many practical concerns. However, the last activity is also expected to maximize the similarity between classroom learning and real engineering practice.

Teacher Support

Two months before the actual implementation of the module, a 4-h face-to-face meeting between the first author and the participating teachers was organized, within which the participants "played" through the whole module. The most important aspects of the module, such as learning goals, basic concepts of design, the operational principle behind the ice cream making technology, and potential design ideas were also thoroughly discussed during the meeting. Two follow-ups were organized through Skype, one during and one after the implementation of the module. The first Skype meeting served to consult teachers about practical aspects of the module, especially for discussing the details of the upcoming design activities, such as general logistics and material resources. The researcher also asked for the teachers' feedback on the previous module activities, student involvement, difficulties encountered and aspects that the teachers themselves considered important to share. The last Skype meeting focused entirely on the teachers' feedback on the implementation of the module.

RESEARCH INSTRUMENTS AND DATA ANALYSIS

In the current paper, data analysis is focused only on Stages III and IV of the module, within which the students developed and executed their design ideas, evaluated the prototype and applied for a patent. This choice was made because these stages, more than the others, produce data that reveal students' individual and group level problem-solving processes. The science experiments conducted, although essential for further design activities, show little individual or group differences, as all steps were performed following the worksheet guidelines and conclusions from each experiment were discussed together under the guidance of their science teacher.

Students' individual and group reports were analyzed using a set of criteria as given later in the findings (Tables 1 and 2). The explanations of student decisions on substances and materials needed for their design were analyzed according to their accuracy and logic and then classified as *correct*, *partially correct*, or *incorrect*. A statement was classified as correct when it was generally logical and scientifically valid. Still, certain reservations were made in this regard, keeping in mind the early age of the students. Not all statements that were classified as correct were scientifically perfect; in many cases, they were just close and/or on the right track. Statements were classified as partially correct when a student gave an argument which was generally logical but was rather poorly explained, or was lacking correct scientific language. The explanation was considered as incorrect when it was scientifically incorrect, or illogical, or irrelevant to a given situation. Moreover, the explanations were also classified according to their context - whether a reference was made to heat of dissolution, thermal conductivity, chemical properties, or safety. Finally, the categorization schema and selected sample of student statements were peer-examined (Lincoln and Guba, 1985) with a group of science and technology education researchers for seeking a common agreement. This process resulted in a few changes in categorization decisions, but not in the schema itself which basically remained the same.

Criteria development for the analysis of the earlier individual and the latter group design drafts (as given in their patent applications) took place together with data analysis and was conducted in three rounds. During the first round, an attempt to operationalize the theoretical knowledge about design and design criteria (Vincenti, 1990; Cross, 2000) into more specific descriptors suitable for the current study was made. Some initial ideas were received from Fortus et al. (2004), where the authors had developed a set of criteria for analyzing student-built models of houses designed for extreme environmental conditions. In the current study, the review of the students' design drafts itself gave multiple insights about which criteria should be added. Moreover, it was the mutual interaction between theoretical knowledge on the one hand and empirical data from the other that helped to derive the criteria and develop the descriptors.

After the first version of criteria was randomly tested on the students' design drafts (on ~1/2 of all design projects), the ratings of first two authors were compared with each other, and the wording of the criteria or descriptors was modified to better represent the raters' common understanding. Furthermore, a need was felt for an additional criterion that would encompass the design as a whole (not only its single aspects), keeping in mind the ultimate purpose of the device - it should be able to produce edible ice cream, while the design process should be in compliance with a given timeframe and available equipment. Therefore, in the second round, the feasibility criterion was added, and again, the student drafts were roughly analyzed against this criterion, after which the descriptor was improved to be more concrete. Comparing to student-proposed design criteria (which could be seen as design objectives), the assessment criteria for analysis were more fine-grained and specific, as these were meant to rate the design outcomes. As a result of the process described, the final list of criteria encompassed functional, structural, safety, and feasibility aspects of the device, plus the choice of materials. Due to the limited material resources and therefore, relatively low level of freedom, the appearance and economical aspects were not included in the list of assessment criteria. At the end of this stage, the existing criteria and descriptors were peer-examined with a group of science and technology education researchers. Based on their suggestions, a new descriptor *The distance between two containers is optimal* and was added to the list as it, indeed, was seen to reflect the common problem, that some designs had - that is, there was not enough space between two vessels (bags) for placing an adequate amount of ice and salt.

In the third round, students' drafts were analyzed independently by the first two authors according to the criteria in Tables 1 and 2. In the case of disagreement, the two researchers discussed their opinions until reaching consensus. There was only one case, where researchers' ratings differed from each other: The disagreement was related to the safety aspect of a design project questioning whether the leakage of salty water into the cream would be possible or not. Still, after some consideration, the solution was rated as generally safe, and no additional changes were made to the list of descriptors. The evolution of two final designs (Groups 2 and 4), from single individual designs based on data from student reports, was illustrated in Figures 6 and 7.

Video data were used as background information when interpreting the findings from student reports. Although it was not directly aimed to gather video data from all student groups separately, more evidence was gathered about the discussion that took place in Group 5, because it was placed closest to the first camera and there was a microphone on the desk of Group 5. From this discussion, a meaningful episode was chosen so as to clarify and illustrate the results from student reports. The stages in the module when students developed their design criteria and, at the end, suggested ways how their designs could be improved were not analyzed in detail, and only a short overview of the activities and discussions that took place in the classroom while being triangulated by the corresponding responses in the students' reports is provided in the findings to illustrate the main findings and provide a richer context for the reader.

Several findings found in student reports and video records were checked with the participating teachers through the last Skype meeting to ensure their credibility which, according to Lincoln and Guba (1985), meant that the findings were credible and made sense to the participants. Mostly, they were related to the stages where students started to develop design criteria, a group draft and finally, build a prototype.

FINDINGS

The implementation of the module "Designing an ice cream making device" in a middle school science and technology classroom was explored in the current study. An attempt was made to develop an understanding of the processes of student design within a given setting as well as how students applied their newly learned science knowledge when designing an artifact. In addition, an attempt was made to find ways for characterizing and assessing student design processes and products (drafts and prototypes).

Defining Design Criteria

The establishment of design criteria was organized by the science teacher as a whole-class activity. The rationality behind her decision (as explained by the teacher herself) was that the students had never practiced proposing design criteria before. Therefore, the process at this stage was led more by the teacher's ideas than the students'. As a result, the criteria in students' reports were quite uniformly copied down from the criteria written on the class board. Hence, this section in students' reports was not used for further analysis. Still, based on video data, a short description of the course of events was as outlined below.

First, the teacher used a car design as an example to explain the meaning of design criteria and design constraints to the whole class, after which she asked the students (in groups) to think about and write down their own criteria for their ice cream making device. The teacher wrote out all suggested criteria on the whiteboard, and afterward there was a class discussion and collective consideration of each criterion. In the beginning, the students tended to suggest criteria which were rather related to the taste of the ice cream than the ice cream making device itself. In this aspect, students tended to go into details. Practically all groups arrived at the idea that the device should be able to make ice cream that was sweet (flavored with sugar and other flavorings). After some consideration, three groups (1, 3, and 4) out of five came to quite similar ideas which could be summarized by the expression of a boy from the third group: *Crystals were nasty*; it [ice cream] *should be smooth and whipped*. As a solution, it was suggested by some other students that cream must be foamed and cooled simultaneously to avoid the formation of crystals: *Once we made ice cream ourselves - whipped the cream and put it in the freezer, but it was difficult to eat as it was hard like a stone* (a girl from Group 4). Keeping the costs of the device down was also not difficult for students to put forward, as it was presented and illustrated by the teacher beforehand. However, the students had more problems with understanding the other aspects of their design, such as the structure and limiting factors. Still, with a little help from their teacher, the rest of the criteria were outlined as:

- The project must be doable with the given equipment (substances, materials, vessels, and tools) and within the next three lessons;
- The device must consist of a part that can cool down (freeze), and of another part containing the edible components; the two parts must be separated by a material able to conduct heat (in students' wording it was actually *conducted cold*);
- The device must be safe for the people who are going to use it.

Explanation of the Choice of Substances and Materials

As the next step in their design process, students, individually, needed to make decisions on substances and materials required for their ice cream making devices. In addition, students were asked to explain their decisions from different points of view - why they would, or would not, choose the substances/materials from a given list. The third research goal was to find out whether, and how, science knowledge was used by students in a design situation; this aspect only focused on their explanations.

Based on the data, it was found that most of the students were able to find a suitable substance for the cooling mixture (22 of 24 students), or a good thermal conductor (19 of 24); however, there was a smaller number of students (17 and 16, respectively) who were actually able to reflect on, or use, this knowledge when explaining the choice of substances/materials relevant to their designs (Table 1). Five students did not give any reference to dissolution heat, thermal conductivity, chemical properties, safety, or a particular experiment they had conducted when asked to explain their choice. In two cases, the explanation was simply because it was the best or similar, and in three other cases, the explanation headings were just left empty. In summary, 58 science-related statements (including 34 correct) were made by the 24 students, with an average score of 2.4 statements per student (minimum score was 0 and maximum was 6).

Most of the students (17) used explanations that were related to **dissolution heat**, while 12 of them used scientifically valid and logical arguments, such as *I would choose table salt for my cooling mixture because dissolution of salt in water can absorb heat* (classified as correct). A common misconception came out from the students' responses, too. Four students were writing about warm and cold substances (e.g. *ammonium nitrate is...a cold substance*) as if the change in temperature was an intrinsic characteristic of a given substance not as a result of an interaction between the substance and water. Or in some other cases, it was explained that in their experiment, *ammonium nitrate became coolest* (not mentioning the role of water or ice in the process). Therefore, their explanations were classified only as partially correct.

Altogether, 16 students mentioned **thermal conductivity** in one way or another when explaining their choice of the material for separating the edible components (whether plastic, aluminum, or glass) from the cooling mixture. In 10 cases, the explanation was classified as correct (example in Table 1), but still there was a lack of clarity in the explanation in three other cases, which were classified as partially correct. For example, a student from this subgroup explained: *Cold comes through the metal, but does not go through the plastic*. Here, the student used language which people often use in every-day situations, but which was not considered as sufficiently scientific - we should expect more from a student, based on their previously taught science content in Grades 7 and 8. Three other explanations were classified as incorrect, as they seemed to share a common misunderstanding: Good thermal conductors ought to conduct heat, and bad thermal conductors, cold, and therefore, glass or plastic would be

Table 1: Type of students' explanations based on students' individual reports while explaining their choice of substances/materials

Reference made to.....	Number of statements (Number of correct/partially correct/incorrect statements)	Excerpts from students' written explanations (Correct - C; Partially correct - PC; Incorrect - IC)
Heat of dissolution	12/4/1	I would choose table salt for my cooling mixture because the dissolution of salt in water is able to absorb heat (C) Ammonium nitrate is good for a cooling mixture because it's a cold substance (PC)
Thermal conductivity	10/3/3	I used plastic for my outer bowl because it stopped the ice from melting, and steel for my inner bowl to easily cool down the cream (C) Steel is a bad conductor and keeps things, which are placed in the bowl, cold (IC)
Chemical properties	7/4/3	Salt is OK because it does not decompose when mixed with water (C) Ammonium nitrate is good for making a cooling mixture because it's moderately acidic (PC) Calcium chloride cannot be used since it reduces the formation of ice (IC)
Safety	5/4/2	Salt is not poisonous for humans, and so there's no risk when using it for making an ice cream making device (C) I do not want to use ammonium nitrate since it can explode and ruin my device (PC) Ammonium nitrate can also be used for making narcotics; some criminals may try to do that if this kind of device is available (C)

needed for keeping the cream in the inner vessel cool. Or the other way around - metals were considered to be bad thermal conductors (as they seemed to be often cold to the touch), and, therefore, were found to be applicable for holding ice cream (example in Table 1). In these cases, again, an understanding of the operational principle and the purpose of the cooling mixture seemed to be lacking - that good conductivity for a material separating cream from the cooling mixture was needed to allow the latter to do its job - freeze the cream in the other vessel. In six cases (three classified as correct and three as partially correct), students directly referred to the experiments conducted as evidence using the argument that, for example, *because the experiment showed that…*; in four cases, the reference was made toward the dissolution experiment, and in two cases the thermal conductivity experiment.

Regarding the **chemical properties**, students were mostly using the acidity or neutrality argument when explaining their choices. The neutrality in aqueous solutions was seen as a positive factor (four cases, all explanations classified as correct), claiming that *if it's neutral in water, it does not corrode the steel*, for example. The chemical stability of a "cooling agent" was cited in three cases as an argument supporting the use of table salt. All of these were classified as correct, as stability indeed, enabled maintaining the components of the device if needed and, second, no smelly gases were produced (as might be the case with urea, e.g.). However, the latter arguments were not suggested by the students but were only theorized by the research team. In two cases, acidity was referred to but insufficiently explained regarding how it might interfere with the device by explaining, for example, that *ammonium nitrate was good for making a cooling mixture because it was moderately acidic*. With the last comment, the student probably referred to mild acidity not being an obstacle for using it as part of the cooling mixture, as well as not being harmful to the metal parts of the device. As it was not clearly explained (what was exactly meant by *moderately acidic*), this explanation was categorized as partially correct. Based on the science teacher's comments, the properties of acids were studied immediately before the start of the module, so students' prior knowledge about the corrosive properties of acids probably had some positive influence on their decision making here. In three cases where sugar was chosen for the cooling mixture, but the explanation was considered irrelevant to the current situation and therefore, incorrect. One student explained: *I would choose sugar because it is chemically stable; it can only caramelize, which is good and gives a good taste*. What was common to all three of these students and was that they actually thought all the components would be mixed together and only sugar could satisfy this situation (as it did not spoil the taste of the ice cream). However, they missed the fact that sugar did not practically absorb heat when dissolved in water. Therefore, here they actually made two misjudgments when explaining their choices.

Regarding the **safety** aspect - there were basically two types of arguments that were used: (1) Ammonium nitrate could not be used as it could explode and (2) table salt could be used as it was known to be non-toxic, and there was no risk when using it in an ice cream making device. The first type of argument (four cases) was not classified as correct, but rather as partially correct, because it was particularly explained in the given text that ammonium nitrate might explode, only in a solid state and such certain circumstances, the risk in the current case was practically non-existent. The statements of the second type (three cases) were all classified as correct. One student mentioned that when using ammonium nitrate for building an ice cream making device, there was a possibility that somebody could use it for making narcotics (a hint was given in the text about this). As students were encouraged to imagine, as if their device was meant to be produced as a large-scale product, the last explanation was considered relevant, and therefore classified as correct. Two statements were found to be irrelevant (e.g. *urea is used as a fertilizer and is [therefore] poisonous for humans*) and these were classified as incorrect.

Characteristics of Students' Individual and Group Design Solutions

As a next task, the students were required to develop their first design draft individually as a homework assignment. In the previous lesson, after choosing and explaining the choice of materials, the teacher urged students not to neglect their homework while stressing how important it was to contribute to the group work with their own unique ideas. As a result, 23 individual design drafts (one student was missing from the first two lessons) were produced for the next lesson. The earlier individual design drafts, as well as the latter group designs as presented in their patent applications, were analyzed according to the assessment criteria given (Table 2). The design solution of two groups, Groups 2 and 4 are described in detail in the following paragraphs. The first could be considered as a representative example of a typical design developed by the students in this study, while the other represented a design which most deviated from the others and from a *normal design* (Vincenti, 1990), which was modeled for students during the introduction stage.

Earlier Individual Designs

As mentioned earlier, most of the students (22 out of 24) were able to find a suitable substance able to absorb heat when dissolved in water, but only 17 actually used it as a part of the cooling mixture (e.g. table salt + ice) in their design drafts. Three students indicated only ice for cooling down the cream, notwithstanding the fact that ice on its own was not capable of freezing the cream, at least not in the case where the procedure was conducted at room temperature (this aspect was also explained by the teacher at the beginning of the module). Four students did not indicate cooling agents on their design drafts. 14 students were able to choose a good thermal conductor (aluminum or steel) for separating the two mixtures - the cooling mixture and the cream with flavorings from each other (Figure 3) - while three students chose a glass or plastic bowl for the same purpose. Only 10 students paid attention to the fact

Table 2: Assessment criteria for student design solutions

Design aspects	Assessment criterion	Individual design n=23	Group design n=5
Choice of substances and materials	Cooling system		
	The mixture of the substance able to absorb heat while dissolved in water and ice is used for cooling (yes/no)	17	5
	Container system		
	A good thermal conductor such as aluminum or steel is chosen for the vessel separating cream and flavorings from a cooling mixture (yes/no)	12	4
	A bad thermal conductor such as plastic or glass is chosen for the outer vessel helping to keep substances inside the vessel cool (yes/no)	10	3
Configuration of subsystems	Cooling mixture is separated from the edible components by a septum (yes/no)	15	5
	Cream can be whipped up/foamed at the same time while cooling it down (yes/no)	8	5
	The distance between two containers is optimal (yes/no)	14	5
Safety	Device seems to be safe when used as intended (yes/no)	17	5
Feasibility	Design project seems applicable for making edible ice cream within the given time frame and equipment		
	Realistic	8	4
	Realistic with reservations	7	1
	Unrealistic	9	0

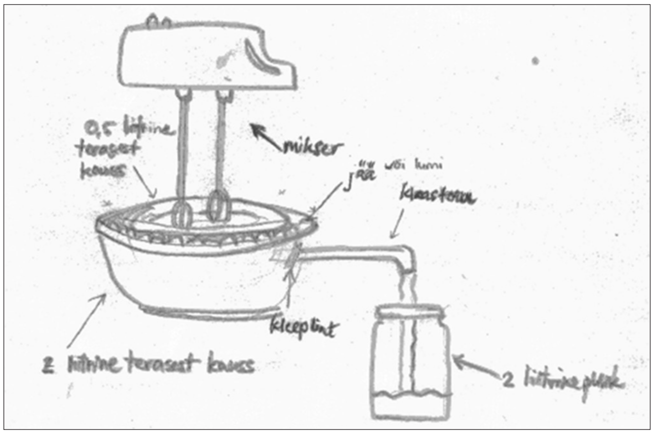

Figure 3: Example of an individual design

that to keep the cooling mixture and ice cream from melting away; the outer vessel should be made from a bad thermal conductor. Although the material of the outer vessel did not play an important role, compared to the inner vessel where good thermal conductivity was really crucial to ensure the cream became frozen, this aspect was still included in the list of assessment criteria (Table 2), since this factor additionally helped to improve the device's functionality.

Although the authors admitted that the criterion, *cooling mixture is separated from the edible components by a septum* partially overlapped with the earlier criterion, *a good thermal conductor such as aluminum or steel is chosen for the vessel separating cream and flavorings from a cooling mixture*, it was still found to be a necessary criterion that should be added as it helped to include the cases where indeed, bad thermal conductors were used, but the configuration itself seemed to be pretty reasonable. There were also some exceptions where the material played a lesser role. In two cases, when cream was sealed into a plastic bottle or a plastic bag, both having pretty thin walls, heat could still be conducted through the plastic wall reasonably well, allowing a device to fulfill its expected function.

A total of five students from 23 wanted to mix all substances, such as salt and ice as well as cream and flavorings, together (Figure 4). This misconception could also be illustrated by several student statements when asked to explain the choice of substances, for example, *salt will spoil the taste of ice cream; I'll use sugar for a cooling agent because it's tasty and does not spoil the taste of ice cream*. Simultaneous foaming and cooling were indicated on eight drafts: In six cases, foaming was presented by means of whisks (including a case where the whisk was placed into a narrow-neck bottle - actually quite difficult to realise if not cutting and resealing the bottle with tape); in two other cases, manual shaking of plastic bag/plastic bottle by free hand was noted. Six drafts did not show any reference to foaming devices or methods. In five cases, foaming and cooling processes were separated; cream was first whisked, and after that cooled down (in one case even a refrigerator was indicated for this final step). It seemed that these 11 students who did not indicate foaming or simultaneous

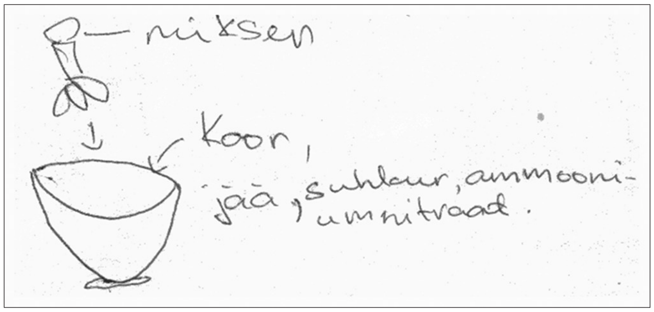

Figure 4: Example of an individual design

foaming and cooling, had, either forgotten this particular design criterion (cream should be foamed and frozen simultaneously) or were not able to operationalize it.

In 14 cases, the distance between containers was considered as optimal, which meant that there was enough room between vessels, enabling placement of about 1 L of the cooling mixture. The designs that failed to meet this criterion were those that had also ignored the simultaneous cooling and foaming criterion (two processes were performed separately and one after another) and therefore, evaluating the distance between the containers was meaningless, though it was rated as not meeting the criterion. The same criterion was also not met by the designs where the cooling mixture and edible matter were all mixed together. That last solution was also classified as unsafe, as that type of design could only have produced inedible ice cream. In one case, leakage of cooling mixture into the vessel holding the cream was seen as far too probable. All the other 17 designs were assessed as potentially safe.

Regarding the feasibility aspect, all designs were classified as *realistic*, *realistic with reservations*, or *unrealistic*. The design in Figure 5 was classified as unrealistic, as it was not clear why and how cream or "cooling liquid" should flow from the jars into the bowl and why they should be mixed together. The example given in Figure 3 was classified as realistic with reservations, as the tap as indicated was first, difficult to construct with the given equipment and second, its purpose remained unclear. Actually, many individually developed solutions (nine) could be considered quite original, yet at the same time, by and large unrealistic as they were not able to produce edible ice cream.

Group Designs

As not all students seemed to understand the scientific principles behind the experiments (as evidenced from their choice of substances and materials), it made their knowledge transfer from an experiment situation to a design situation almost impossible. Still, after consolidating their individual design ideas within their groups, at least some misconceptions were gradually resolved as their group mates (evidenced at least in Groups 2 and 5) started to criticize and question their suggested ideas.

The following discussion in Group 5 consisting of two boys and two girls and is presented here as an example. The situation took place after the first student (Kristel) had shown and commented briefly on her draft to her group mates while the others tended to accept her ideas without much questions or criticism. When the second student (Sven) started to show his draft, the following discussion took place:

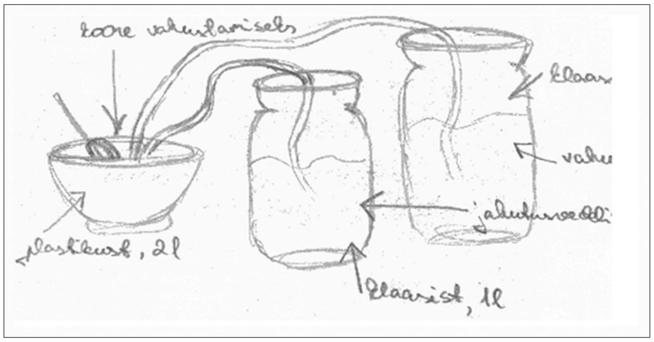

Figure 5: Example of an unrealistic individual design

> Karl: (Putting his finger on Sven's draft) *Are you really going to eat it? You know - this* [ice-cream] *will be salty and sweet simultaneously! Ugh!* (with a face expressing disgust)
>
> Sven: *But I thought that it won't be poisonous, it's just salt, not like chemicals …*
>
> Karl: *There is no need to mix them, you have to separate them, cold comes through the wall… Like in the experiment that we had* [he probably meant here that the cooling effect was felt through the beaker's wall when doing experiment].
>
> Kristel: *Only the material must be right such as metal or something...*
>
> Karl: *Yeah! Exactly!*
>
> Sven: (impatiently) *Okay, okay, I got the point. Just leave it and let's take some other.*

From the given discussion Sven's preliminary and quite unreasoned ideas were juxtaposed with ideas from the more knowledgeable others. After the first remark from Karl, Sven kept defending his ideas by pointing to the need for an edible cooling agent. However, after Karl's further argument (reminding the experience from their experiment) and Kristel's reference to metal, it seemed he started to understand his misconception.

In another group (Group 1), the students asked the teacher to be a judge and help them to decide whose design was the best based on her opinion. The teacher reflected their request back, asking them to look over their design criteria and indicate whether salty ice cream would satisfy these, after which the group collectively decided to separate the cooling mixture from the edible substances with a separate container. After a short "a-ha moment," when realizing finally the working principle behind it, they started to act fairly independently and, as a result, developed a viable design.

As shown in Table 2, the last group designs satisfied most of the suggested criteria. Only the criterion concerning the material for the outer vessel was not met by two of the groups (Groups 1 and 3); though as explained earlier, it was not a decisive, but rather a supportive aspect for determining the success or failure of the design. In summary, four groups fulfilled the feasibility criterion and were classified as realistic, while one group design (Group 3) was classified as realistic with reservations as they had added a tube for removing ice cream from a bowl. Although the group was not able to realize their tube idea in practice, they retained this detail until their patent proposal, the last step included.

Different from the quite original - yet likely non-viable - individual solutions, the group solutions bore a strong resemblance to each other (such as shown in Figure 6 [Group 4]). This last finding was understandable as there was a limited number of potential realistic solutions, whereas the number of potential unrealistic designs was unlimited.

The group solution, as shown in Figure 6, which gained a maximum score according to the criteria in Table 2 and was categorized as realistic, evolved from two earlier individual solutions quite similar to the final design (except that whisks, instead of electric mixer, in one case and ammonium nitrate instead of sodium chloride, in another case, were used), plus two individual designs classified as unrealistic. One of these last individual designs was given in Figure 4, according to which all the substances should be mixed together. In the other case, the processes of foaming and cooling were separated in time (after foaming, the cream was frozen in a fridge). In both, the latter cases, the lack of understanding of the proposed design criteria and operational principle as demonstrated earlier, could be recognized. It seemed that the impact of the last two design ideas to the final solution tended to remain rather modest. The group choice of using sodium chloride, instead of ammonium nitrate, probably originated from a student with an earlier unrealistic design (*sodium chloride can be even eaten in small amounts, it does not make much harm*). In their group patent application, their choice was afterwards explained as *sodium chloride is safe for humans and* [chemically] *neutral and it is able to freeze the cream when mixed with ice cubes*. Reference to neutrality was also found from an earlier individual report of another group member with a realistic design.

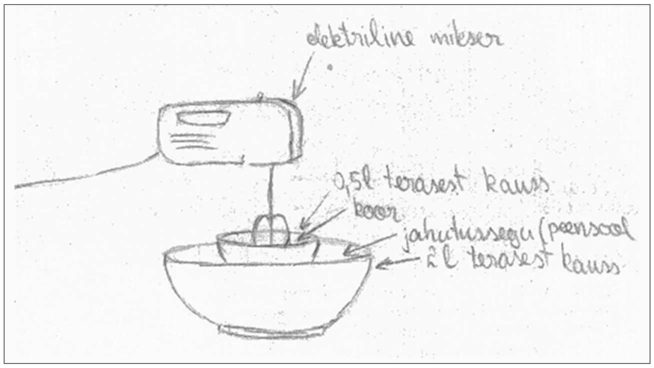

Figure 6: Example of a group design

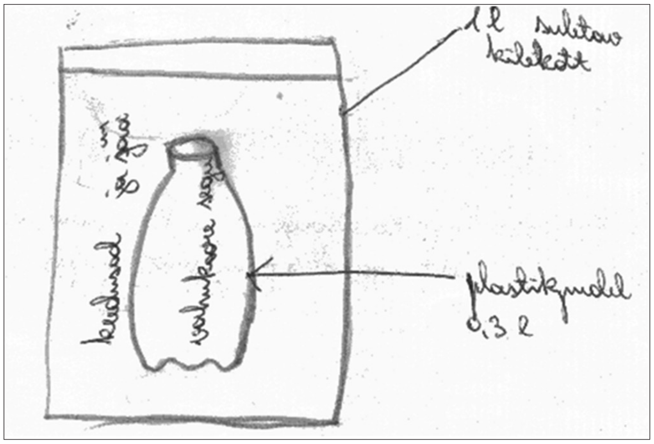

Figure 7: Example of a group design

Only one group's solution (Group 2 and Figure 7), among the five, diverged from the configuration demonstrated to the students during the introduction stage (overview of the historical developments in ice cream making technology). In their latter group design, no whisks or other beaters were used for foaming the cream. In its place, only manual shaking was proposed. The container system consisted of a zipped plastic bag containing a sealed plastic bottle. The plastic bag holding the mixture of ice and salt functioned as a "cooling system" and the plastic bottle with cream and flavoring as an "edible subsystem." The design fulfilled all but one of the suggested assessment criteria (Table 2) and was classified as realistic. That not fulfilled was related to the fact that a bad thermal conductor, such as plastic instead of metal, was chosen for separating cream from a cooling mixture. In the current case, the walls of the bottle were quite thin and still enabled the cream to freeze. The whole design basically seemed to evolve from an individual design which was pretty similar to the final group design, thus making the contribution from the other students in this group difficult to detect (from their individual designs, two were actually classified as realistic, one realistic with reservations, and one as unrealistic). Probably, the author of this idea was persuasive enough to "push through" his distinctive design as he had, in his science teacher opinion, a "smart guy image" among his classmates.

Suggested Design Improvements

After building the prototype and making ice cream, students in groups were required to evaluate their prototypes. As a result, a number of suggestions were made about how prototypes could be improved. Similar to the proposing of design criteria, all groups first and foremost focused on the taste and the texture of the ice cream. Regarding the device, Group 3 recognized that plastic instead of metal would have been better for an outer vessel to prevent ice from melting. Group 2 (their design is shown in Figure 7) suggested that next time they would put cream into a different, smaller plastic bag that enabled taking ice cream out more easily, compared to a plastic bottle. Group 1 found that they could have added more ice and salt to freeze the cream than they did in their experiment, as their ice cream was only partially frozen.

Regarding the sustainability aspect, the students needed to think whether their device was environmentally friendly or whether they could suggest ways in which it could be improved. However, for this effort, the groups suggested few ideas. Group 4 suggested that in winter, snow instead of industrial ice could be used to save costs and energy spent on producing ice. Two Groups (1 and 5) shared the idea that plastic bowls could be replaced with more sustainable material because *plastic is harmful to our environment* (Group 1). Group 1 suggested wood instead of plastic, Group 5 did not specify the material. None of the groups came up with an idea of recycling the cooling mixture - for "this run," it was safely disposed of after its single use, though it could potentially be recycled by evaporating the water from the salt solution.

DISCUSSION, CONCLUSIONS, AND SUGGESTIONS

In the current paper, the framework of engineering design (Vincenti, 1990; Cross, 2000) was used to explain the theoretical, as well as the practical aspects of the DBSL module "Designing an ice cream making device." An explanation of some essential engineering concepts (operational principle, normal configuration, and design cycle) helped to develop the learning module, as well as to analyze the students' design processes and design products.

Based on the findings, it was found that the crucial aspects for the success of the design were the students' understanding of (1) the science phenomena, (2) the operational principle behind the ice cream making device, and (3) the design criteria. These claims needed to be further explained.

Design-related activities in the module started with suggesting design criteria for an ice cream making device. The students' initial difficulties with it were partially overcome with the help of their science teacher. This teacher-led activity resulted in a list of jointly posed design criteria covering the artifact's function, structure, social demands (safety of use), and limitations of the designing process (time frame, materials, and cost). Hypothetically, criteria could also be proposed regarding the appearance, ease of use, production technology and so on, although it could also be claimed that the proposed criteria covered the most crucial aspects of the designed artifact to enable it (potentially) to fulfill its function. At this stage, no conclusion could be made to what extent every single student understood the meaning of the criteria, as it mostly took place as a whole-class activity. Some students were clearly more active in suggesting their ideas, while others probably only copied the final list from the whiteboard without conceptualization. Therefore, it could be proposed that a teacher should ensure that students' proposed criteria were indeed relevant for the current design and that students understood their meaning, irrespective of the particular way they were proposed (whether individually, in groups, or as a whole-class discussion).

While the majority of the students were already able to develop a realistic, or almost realistic, design as a result of their individual work, the others, however, seemed to struggle with significant difficulties which, in turn, resulted in unrealistic design ideas. The problems that they encountered were in different areas, described below.

Some students from the unrealistic ideas group seemed to have problems with understanding, at least one of the scientific phenomena illustrated by the experiments. This was evidenced by the fact that they were not able to choose proper substances from a given list needed to absorb heat when dissolved in water, or a good thermal conductor when it was directly asked. The last situation arose where students actually could use their experimental data on their worksheets and recall the information if needed. Probably, the purpose of the experiments itself remained unclear for these students and their prior knowledge was also not sufficient.

The other students who also created unrealistic individual design ideas were those who, although choosing the proper substances or materials, did not recognize how this knowledge could be useful for solving a particular design task. Students might even have understood subprocesses but were not able to incorporate these processes into a single device. An alternative explanation, using the Cognitive Load Theory (Sweller, 1988), could be that these students had working memory overload when trying to incorporate their newly gained, as well as earlier, knowledge into the development of a single design product. In addition to recalling the information and applying it in a new situation, the students needed to use their higher-order thinking skills, such as analysis, evaluation, and creative thinking, to solve a given design task. These types of problems definitely put a higher demand on students' cognitive abilities that could usually be expected for solving "normal" problems in a science classroom.

A number of scientific misconceptions and partial understandings were found from the students' explanations on their choice of substances and materials. Two recurring misconceptions were also detected. Regarding the dissolution heat, some students seemed to neglect the fact that the strong cooling effect was achieved by means of interaction between water and salt, not from a single subject (salt or ice) alone. Concerning thermal conductivity, a few students seemed to confuse what "good" or "bad" thermal conductivity meant, which could result from the fact that they did not understand the phenomenon of thermal conductivity itself. Some other students only lacked the ability to use correct scientific language when explaining the phenomenon. As both science topics were known to be "rich" with various forms of scientific misconceptions among students of different ages (Lewis and Linn, 2003; Calyk et al., 2005; Lee, 2014; Özalp and Kahveci, 2015), it was no wonder that alternative ideas were found in the current study. At the same time, the awareness of these specific difficulties could help the researchers to anticipate their potential existence for a future study and convey this knowledge to teachers in advance.

Where all, or part, of the earlier problems were compounded with a poor understanding of the operational principle and design criteria (or being just a result of the earlier ones), the unrealistic individual design was practically guaranteed. Complete lack of understanding of the modeled operational principle and some crucial design criteria was clearly evident in drafts where both edible and non-edible substances were mixed together. Although there was a need for at least four subsystems to produce ice cream: (1) A cooling (reaction) subsystem, (2) a container subsystem responsible for the transfer of energy, (3) a subsystem with edible components (cream with flavorings), and (4) a subsystem responsible for whisking the cream, it seemed that these students were lacking in understanding that all systems could be broken down to subsystems, each having a special function (Apedoe et al. 2008). This happened notwithstanding the fact that the operational principles of the first two subsystems were particularly and separately modeled for the students through scenario and inquiry session.

Based on the earlier discussion, it could be concluded that the shortage of at least two abilities needed for successful knowledge transfer (Prawat, 1989; Marini and Genereux, 1995; Kolodner et al., 2003) was evidenced by the unrealistic-design-group students': (1) ability to access intellectual resources (previously learned science knowledge) in situations where those resources were relevant and (2) ability to recognise an appropriate transfer opportunity while designing a device. Therefore, the existence of the so-called design-science gap (Vattam and Kolodner, 2008) was indeed confirmed by the current study, although it seemed that the transference problem as demonstrated here was not only characteristic of DBL approaches but also to any learning where knowledge transfer from one situation to another was required. During the course of the module, it was also seen how this gap was gradually narrowing through peer support, teacher guidance, and some trial and error experiences, right up through the development of the final patent application. Similar progress was also shown in a DBS study conducted by Fortus et al. (2004), where students' science knowledge grew together with their successively improving models. In the current study, it could not be determined exactly to what extent individual students improved their science knowledge as a result of the module, as no pre- or post-test was taken. Still, it could be stated that the design process, as presented, enabled revelation of a number of scientific misconceptions, knowledge gaps, and transference problems, which some students might have had and therefore, allowed them to be operatively addressed by a teacher to avoid a potential design failure due to incorrect scientific assumptions. The lesson learned from this was that throughout the whole module, the teacher should put great effort into ensuring that students really understand the operational principle of the device and the scientific phenomena behind it. This might happen in different ways: Using students' worksheets as evidence of their learning, questioning and interacting frequently with individual students, as well as with groups. Even if a device did not work as expected, this could be taken as valuable feedback rather than failure. As was seen from the students' suggestions on design improvement, the students indeed were able to learn from their practice.

When tracking the evolution of individual designs toward the final group design solutions, by means of students' individual and group reports, it was found in one selected case how this resulted in a synthesis of different individual ideas (Group 4) while in the other case (Group 2), the final design was rather a solo project of a single student. In the last case, it seemed to be uncertain whether all students really introduced their ideas and whether the ideas of all students were considered and discussed before arriving at a consensus for the final design. Next time, teachers, for example, could create a special procedure for helping individual students to present their ideas and, also, how to find a consensus in a group and make a best decision.

A set of criteria were established for characterizing students' design products encompassing their functional, structural, safety and feasibility aspects, and the choice of materials. These criteria could not be seen as mutually exclusive. Rather, they were geared to supplement each other while trying to capture the most crucial aspects of the designed artifact and enabled assessment of whether the device was able to fulfill its expected function. It should be admitted that the list of criteria was neither universal nor easily transferable to any other student design product, yet it might still provide curriculum developers and teachers with a working example and further insights into how student-designed artifacts could be assessed. Rather than being an ultimate "judgment list" for summative assessment purposes, it might help teachers to guide students during their design process, or it could be a tool for both students and teachers, helping them to analyze together the prototypes already developed. Still, among the criteria, the most problematic for students to self-assess could be the safety criterion. The defined descriptor *device seems to be safe when used as intended* could cover a whole array of safety risks. Although it was quite uniformly assessed by the raters (except one case when consensus was sought through the discussion), it seemed to be too general for the purposes of learning. For that case, safety criterion could be further breaken down into more detailed descriptors relevant to a given design project.

ACKNOWLEDGMENTS

This study was supported by a research grant from Umeå University, Sweden, Dnr 103-435-07. The authors wish to thank the teachers and their students who participated in the project**.**

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