Teaching children digital literacy through design-based learning with digital toolkits in schools

Citation for published version (APA):

Bekker, T., Bakker, S., Douma, I., van der Poel, J. E. C., & Scheltenaar, K. J. (2015). Teaching children digital literacy through design-based learning with digital toolkits in schools. *International Journal of Child-Computer Interaction*, 5, 29-38. <https://doi.org/10.1016/j.ijcci.2015.12.001>

Document license:
TAVERNE

DOI:
[10.1016/j.ijcci.2015.12.001](https://doi.org/10.1016/j.ijcci.2015.12.001)

Document status and date:
Published: 01/01/2015

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Teaching children digital literacy through design-based learning with digital toolkits in schools

Tilde Bekker*, Saskia Bakker, Iris Douma, Janneke van der Poel, Koen Scheltenaar

Department of Industrial Design, Eindhoven University of Technology, P.O. Box 513, 5600 MB, The Netherlands

ARTICLE INFO

Article history:

Available online 3 December 2015

Keywords:

Design thinking
Digital literacy
Schools
Children digital toolkits
Design-based learning

ABSTRACT

The paper presents our work on how to teach digital literacy and design thinking to children at primary and secondary schools, with a particular focus on exploring the tools that may support children's learning in these domains. We have conducted design explorations with input from diverse stakeholders, such as teachers, children, publishers and educational scientists to examine how to develop an integrated design-based learning approach for the school context. Based on the design explorations insights are described about requirements for digital toolkits and the design-based learning process. Based on this work a Reflective Design-based Learning (RDBL) framework is presented that describes the challenges of developing an integrated process that is doable at school, matching teachers abilities, appealing for children and fitting to the knowledge presented in the publisher's materials, that support teaching learning goals as requested by the government.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

How can we teach children about the value of technology through a design-based learning approach with digital toolkits? How can we teach them a problem-solving attitude to life through digital fabrication and design thinking embedded in an educational approach for schools?

The role of digital technologies in everyday life has been increasing over the past decades. As a result, society is changing and it is thus important to appropriately prepare today's children for tomorrow's everyday life. This has resulted in debate about the kinds of skills that children need to be taught. These 21st century skills include critical thinking, creativity, communication, team work, and ICT and information literacy [1]. Different frameworks for 21st century skills have been described, including the KSAVE (Knowledge, Skills, Attitudes, Values and Ethics) framework by Binkley et al. [2]. Binkley et al. [2] distinguish ten skills or competency areas, related to the 21st century skills, grouped into four main categories: *Ways of Thinking* (creativity and innovation, critical thinking, problem solving and decision making, learning to learn/ metacognition), *Ways of Working* (communication, collaboration), *Tools for Working* (information literacy, ICT literacy) and

Living in the World (citizenship, life and career, personal and social responsibility).

The debate discusses the need for development of both new skills and competencies and emphasizes the importance of life-long learning, showing that education needs to change to facilitate this. One of these 21st century skills involves **digital literacy**. We broadly interpret digital literacy as the ability to use, understand and evaluate technology, and also to understand technological principles and strategies required to *develop solutions* and realize specific goals [3,4]. This includes providing children with an understanding of the use of various digital technologies, including social media, digital fabrication techniques, sensors, actuators and computing technologies. In our work we have interpreted digital fabrication as a process of designing tangible solutions with digital toolkits.

With the increasing presence of technology in everyday life, we argue it is important for children to get a sense of the value of technology for issues in society. For example, modern communication technologies have the potential to decrease social isolation of elderly, or sensing systems can support people in reducing energy usage in the home. To understand such values of technology, children should not only learn the 'hard' technology skills (e.g. programming and building electronic circuits), but they should also gain insights in how such technologies can impact society. Research has shown that teenagers have different kinds of interest in science, technology, engineering and mathematics (STEM) subjects. A study conducted in the Netherlands in 2010 [5] distinguishes four different profiles of interest in technology: teenagers

* Corresponding author.

E-mail addresses: m.m.bekker@tue.nl (T. Bekker), s.bakker@tue.nl (S. Bakker), i.douma@tue.nl (I. Douma), j.e.c.v.d.poel@student.tue.nl (J. van der Poel), k.j.scheltenaar@student.tue.nl (K. Scheltenaar).

<http://dx.doi.org/10.1016/j.ijcci.2015.12.001>

2212-8689/© 2015 Elsevier B.V. All rights reserved.

who are (1) fundamentally interested in STEM, and teenagers with interests in STEM from a (2) career-oriented or (3) human-oriented perspective and those with (4) little or no interest in STEM subjects. These youngsters can be triggered to be interested in technology in different ways, ranging from more fundamental approaches to showing more applied approaches of technology. Gaining an understanding of the value of technology for society, at an early age, is expected to help attract a larger group of youngsters to gain interest in STEM subjects in their future education and career choices, a target that is of increasing importance worldwide (e.g. in European research agenda, Horizon [6] call: SEAC-1-2015). While the concept of digital literacy could also be related to topics other than STEM, we examine it in relation to STEM topics, because within our network of stakeholders (including publishers of educational material, teachers, and educational scientists) that is where it seems to be most easily integrated, providing us with a responsive design research context.

Various developments have already facilitated the introduction of digital tools in the school context to teach children about digital literacy. These include FabLab equipment, such as 3D printers and laser-cutters, but also digital toolkits that support low-threshold ‘making’ of diverse digital solutions for various problems [7,8]. Examples of digital toolkits, which enable children to engage in digital fabrication of various applications using electronics and programming, include littleBits, lego WeDo and MakeyMakey. Thus, providing digital toolkits with design-based learning opportunities can also be seen as a form of digital fabrication.

However, little is yet known about the requirements for embedding design-based learning of digital literacy skills in a school’s curriculum.

In the department of Industrial Design at the University of Eindhoven University of Technology, students develop knowledge, skills and attitude in design related subjects through a design-based learning process of interactive products and systems with societal relevance. Students are taught through various learning activities, which include lectures, but a large part of the learning activities contain design-based learning components. For example, students learn how to apply theories about behaviour change in designing solutions to help people lead a healthier life style. Applying this approach over the last 10 years, we have experienced it supports the development of various 21st century skills; next to digital literacy the approach also enhances collaboration, problem solving, creativity and critical thinking. Therefore we have been exploring whether this approach can also be used in a primary and secondary school context to serve the purpose of increasing children’s understanding of the societal relevance of modern technologies, with the ultimate target to increasing children’s interests in STEM subjects and careers. Since pupils of primary and secondary school are younger than university level students, one of the challenges in translating this approach is adjusting it to the appropriate level, matching the appropriate learning goals.

To explore how to teach **digital literacy** and **design thinking** to children through a **design-based learning** approach we have conducted various design explorations. Based on both a literature study and these designs explorations, we have developed the **Reflective Design-based Learning (RDBL) framework**. RDBL describes various factors which play a role in developing design-based learning solutions for the school context, taking into account the challenges that come with this formal learning setting. RDBL can be applied to understand the relationships between the various requirements and can be used to create and evaluate solutions for a school context. This paper presents the RDBL framework and illustrate it through three design case studies, which focused on upper primary school (children aged 11–12 years), and lower secondary school (children aged 13–14 years).

The aim of the work presented in this paper is to examine how to integrate elements of instructional settings of design-based

learning that teach digital literacy and design thinking in real-life primary and secondary school contexts. Furthermore, it aims to develop a framework for supporting a structured consideration of future RDBL activities for teaching digital literacy and design thinking to children. We focus on the following research question: *How to provide a reflective design-based learning process that supports relevant learning goals from a course specific (e.g. English, Maths and Science) and from 21st century skills perspective (including digital literacy, design thinking and value of technology) in a school context?*

2. The Reflective Design-based Learning (RDBL) framework: overview and grounding in literature

In this section we lay out the motivation for the Reflective Design-based Learning (RDBL) framework, which extends the existing Design-based Learning (DBL) model presented by Gomez et al. [9] by adding a specific Reflective learning component (The ‘R’ in RDBL) and more attention to the digital properties of the learning environment.

The RDBL framework extends earlier work by Gomez et al. [9], who developed a set of critical elements of instructional settings in Design-based Learning (DBL) in higher engineering education. Their framework, which includes project characteristics, design elements, teacher’s role, assessment and social context, was based on an extensive literature review with a focus mostly on engineering disciplines, such as mechanical engineering and electrical engineering. It was used, among other things, to analyse existing DBL activities at engineering level, and to suggest ideas for improving professional development of DBL teachers to redesign their projects using the DBL framework [10]. We examine how it can be extended and applied to a primary and secondary school context.

Based on our experience with design-based learning for industrial design students at the University of Technology, where we apply the Reflective Transformative Design Process (RTDP, Hummels and Frens [11]), the activity of **reflection** forms an important part of the learning process. Therefore, we propose to add this component to the DBL framework for primary and secondary education. The Reflective Transformative Design Process has been developed to combine a flexible design process, with a learning-through-reflection process. It promotes frequently switching between design activities, and to reflect on action when switching between activities. This is in line with the assumption that design processes are not so much rational problem solving processes [12], but rather reflection-on-action processes, as described by Schön [13].

The RTDP is intended for university-level students, and provides a high degree of freedom in how they go through the design process. More structure is needed for younger pupils, at least at first, to guide them through the design process.

2.1. The Reflective Design-based Learning framework

The RDBL framework has been developed by combining input and thoughts from stakeholders (such as teachers, educational scientists, policy makers and publishers) with theoretical grounding in literature. At the start of our research on technology toolkits to teach children digital literacy skills, we organized four workshop-sessions, of roughly two hours each, with various stakeholders (a total of 14 stakeholders were involved). These sessions made us realize that design-based learning in the classroom can only be successful when integrating various criteria coherently into the entire process. For example, digital tools developed as learning materials should be child-friendly and easy-to-use, but also need to be linked to specific learning goals (decided on by governmental policy makers), and the teachers can facilitate the process.

Fig. 1. Overview of Reflective Design-based Learning dimensions and characteristics, with reframing based on our own experiences, i.e. different terminology for dimensions, and with the added digital toolkit dimension (Item F).
Source: Adapted and extended from Gomez et al. [9].

The various criteria for design-based learning in the classroom and their mutual dependences were discussed at length in our stakeholder workshops and underpinned with literature. This led to the development of the RDBL framework (see Fig. 1), aimed to outline the complex web of stakeholders and criteria that need to be considered for design-based learning in the classroom, particularly when using technology tools such as electronics toolkits, programming environments and digital fabrication techniques. This particular focus is chosen because physically creating solutions enables children to experience the value of technology first-hand, which we believe is crucial to encourage children's interest in STEM education and careers.

Furthermore, we also added a category for '**learning materials**' to the RDBL framework, because of our particular focus on the role of digital toolkits and other materials on supporting design-based learning. Fig. 1 depicts the RDBL framework, showing both the components of Gomez' BDL model and the elements we added our specific purpose of teaching **digital literacy and design thinking**: (1) the learning environment in terms of *materials and the digital toolkit* (Section 2.7, Item F), and (2) the *learning through reflection process related to the design process* (Section 2.3, Item B).

In the coming subsections we separately address and motivate each of the components of the RDBL framework through a literature review and a discussion of the outcomes of our stakeholder workshops. An earlier version of the framework was presented in [14]. The first version of the framework was based on an initial reflection of two design explorations, whereas the present framework is based on a more extensive literature study and on a third design exploration.

2.2. The elements of a design process (dimension A in Fig. 1)

Various design processes have been described in literature, some of which target children specifically. Design-a-thon [15], for example, describes a process that includes introducing the theme, research, idea time, sketch and prototype, present and reflect. The d.school group at Stanford described a design process using the steps empathizing, defining, ideating, prototyping and testing (The [16]). They provided clear suggestions for design process steps. This process should be combined with the facilitation of the learning process (see Section 2.3).

In contrast to these more generic approaches, the RDBL approach has a few specific characteristics, which require a specific approach. Different from engineering design challenges, such as often used in DBL activities in engineering departments (e.g. [10]), the RDBL approach focuses on more **open-ended design problems**. For example, the RDBL might be used to design a solution to

the societal challenge of aiming to reduce energy usage in the home environment, which might include multiple engineering problems such as redesigning a showerhead that reduces water usage.

The reasoning required for such open-ended design problems is described by Dorst [17] who considers the WHAT (the thing) and the HOW (the working principle) which together lead to the VALUE (that which is aspired). Often, design is creating a solution (the WHAT) that uses a known working principle (the HOW) to lead to an intended VALUE. However, sometimes both the HOW and the WHAT are unclear at the start of the process, and only the intended VALUE is determined. The challenge for designers then is to come up with a good combination of both the WHAT and the HOW to solve a problem and create VALUE.

Various stakeholders mentioned that children can go through a design process when provided with a clear structure.

In summary, the reflective design process is an iterative process that combines learning with designing, that follows steps that support diverging and converging and getting an understanding of the context of use, and that examines open-ended design problems that require coming up with a good combination of a product with specific working principles that has value for the user.

2.3. Collaborative learning and reflection process (dimension B in Fig. 1)

In the reflective transformative design process (RTDP, Hummels and Frens [11]), developed as a method for design education at universities, reflection plays a central role. Design students conducting RTDP reflect on their actions both during the process and in between various steps, to support and facilitate the students' learning process.

This practice is also common in other approaches. For example, in Kolodner's [18] *learning-by-design* approach, learners create *design diaries* to reflect on their learning activities, and use *whiteboarding* to collectively reflect on the progress and key learning insights of a group of learners. Similar to RTDP, Stables and Kimbell [19] describe the *learning process* as switching between 'imagining and modelling in the head' and 'confronting reality outside of head'. They furthermore describe the use of a learning environment with a digital portfolio, where children record their ideas and reflections with diverse tools, such as photo's, videos and voice recording tools.

Some stakeholders had experience with teaching university level pupils in a reflective process. Others mentioned that supporting children with good reflection questions, helped them in their learning process.

2.4. Learning goals and assessment (dimension C in Fig. 1)

Learning goals can be phrased both in relation to 21st century skills – such as problem solving and digital literacy – and in relation to course specific goals. **Digital literacy**, one of the 21st century skills, includes basic knowledge of ICT, media literacy, and information skills [1]. Digital or *Technology literacy* can be defined as the ability to use, understand and evaluate technology, and also to understand technological principles and strategies required to *develop solutions* and realize specific goals (NAEP, 2010; [3], in [4]). A slightly different scope describes requirements for learning about technological literacy [20].

Furthermore, learning goals can be defined in terms of course-specific goals, for e.g. Science, Technology, Engineering, and Mathematics (STEM). By combining digital literacy skills with design-based learning activities, we can also address teaching children to be critical about how and when to apply digital solutions. This is related to teaching critical reflection on digital literacy (e.g. [21]).

During a number of stakeholder workshops, we noticed that even though most involved stakeholders were enthusiastic about design-based learning, many were hesitant about its suitability in schools, because it is often unclear which particular learning goals (usually set by the government) are targeted. In fact, design-based learning usually targets a number of learning goals at the same time, for example a group working on designing an energy-awareness lamp might learn about energy usage and properties of light, while at the same time improving meta-level skills such as collaboration and problem-solving.

The learning goals we targeted in our research, from which the RDBL framework resulted, are digital literacy and design thinking.

2.5. Design brief and project characteristics (dimension D in Fig. 1)

As described by Gomez et al. [9], design briefs in higher education usually deliberately describe ill-defined problems, to which there can be numerous solutions. This enhances creativity and problem-solving skills. Additionally such briefs are often connected to industry, enhancing the authenticity of the described problem and enabling engagement of real stakeholders (role models for the students) in the process [9].

As an additional factor that may specifically apply to a younger target group, Resnick and Silverman [22] illustrate how the design brief should be appealing and meaningful for the child. Also, children should be able to understand the context of the design challenge and the importance of finding a solution [23]. It should provide diverse opportunities in terms of learning goals and should have the right balance between being open, but still providing some scoping and direction [23].

Aligning with our overall aim to enable children to understand and gain first-hand experience of the value of technology for societal issues (thereby enthusing children for STEM subjects and careers), we argue that design briefs need to have a societally relevant aim. For example, a design brief asking children to design a lamp that helps people become aware of their energy usage, leaves enough degrees of freedom e.g. in form, or technology used to come up with different kinds of solutions.

2.6. Teacher's and children's role (dimension E in Fig. 1)

In DBL processes, traditional forms of teaching (such as whole-class instructions) form only a minor part of the teacher's tasks. The major role of the teacher in DBL is to 'coach' [18] the student by scaffolding the process, asking questions [9], inspiring the student, guiding reflection [18].

During stakeholder workshops, we also realized that an important challenge of realizing design-based learning in the context of a classroom is the role of the teacher. The stakeholder workshops pointed out that since most teachers are trained to use traditional methods of teaching, this new role of the teacher must explicitly be taken into account and supported through tools designed for teaching design-based learning.

Pupils can be interested in technology for different reasons, e.g. they might be fundamentally interested or have a career-oriented or human-oriented interest [5]. These different children should be targeted in different manners when providing them with learning activities. In a reflective design-based learning approach with the right tools and materials, children of these different categories can all find an angle that fits their interest.

2.7. Properties of the learning environment including the digital toolkit (dimension F in Fig. 1)

Digital toolkits have been used as a support for children to quickly develop solutions for various problems and thereby support digital fabrication. Such toolkits are essential in the RDBL approach. Resnick and Silverman [22] state the importance of construction kits being easy to understand (which they call low floor), but also general enough so that they can be used for diverse things (which they call wide walls). Simple tools to support basic programming can provide children with the opportunity to create interesting designs, without having to know the details of programming. Furthermore, they mention it is important to decide on the basic building block of the toolkit, as this influences what is explored and learned. For example, having a building block that contains a motor, children do not have to learn how the motor itself works, but can create things with the motor as one of the components. The kits should also support different styles of learning, e.g. the more disciplined and structured way, and the more trial and error kind of way. Additionally, as described by Douma et al. [24], such kits should take into account varying interests children may have. Some children are more interested in applying technological solutions to conceptual design decisions, while others are more interested in understanding details about the fundamental concepts of programming or electronics. It is important to examine how the learning environment provides support for these different levels of learning goals.

Blikstein [25] describes that what you show and expose in a digital toolkit influences where the learning challenges are. This is called selective exposure and is related to Resnick and Silverman's [22] suggestion to choose your building blocks (or black boxes) carefully. Blikstein [25] analyses the affordances of different generations of construction toolkits and programmable tangibles. He argues that to allow children to create powerful ideas, rather than focusing only on learning to program, construction toolkits have to consider what the basic building blocks are that allow children to create tangible solutions.

In their discussion on how tinkering can support a combination of making and learning, Resnick and Rosenbaum [26] state that 'just making things is not enough'. They mention three core principles in construction kits that support learning: immediate feedback, fluid experimentation and open exploration.

In summary, the RDBL approach needs to address and consider the relationships between a wide variety of elements (see Fig. 1) in a school context in order to be successfully applied. Design explorations were conducted to explore how to embed a RDBL approach in schools that teaches design thinking and digital literacy to pupils in schools.

3. Method

To understand how to create a reflective design-based learning approach to teach **digital literacy and design thinking** to

Fig. 2. (a) The Dolly 2.0 toolkit in use, (b) and example worksheet, and (c) the teacher's manual and children's workbook. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

children we followed a research through design approach [27]. To generate knowledge we went through a reflection, articulation and abstraction process in examining the designs created, to uncover elements or principles that may be valuable for other designs [28]. We took a holistic approach in understanding how to develop a RDBL for schools. We examined the relationships between different components of the context of use and the design decisions for creating integrated learning activities.

We focused on the following research question:

How can a reflective design-based learning process support relevant learning goals from a course-specific (e.g. English, Maths and Science) and from a 21st century skills perspective (including digital literacy, design thinking and value of technology) in a school context?

To answer this research question, we conducted three design explorations. In these design explorations, we iteratively developed tools that can be used by teachers and children to support RDBL activities, aimed to support developing design thinking and digital literacy skills, in the school context. Two of these design explorations ('Dolly 2.0' and 'Spark!') were conducted in parallel by two of the authors. Building on the results of these two, the third exploration ('ID-Box') was subsequently conducted by a third author.

During the process of conducting these three design explorations, a total of six (four during the explorations 1 and 2, and two more during design exploration 3) stakeholder workshops were held, in which teachers, policy makers, educational scientists and publishers provided input and gave feedback on the developed design concepts.

3.1. First and second design explorations of creating integrated design-based learning activities with focus on design of digital toolkit

The first two design explorations, conducted by design students, examined how to design an integrated design-based learning activity with a focus on also developing components for a digital toolkit.

In the first two stakeholder workshops (one for primary education (PE) with two curriculum developers, one teacher at a department of education, a teacher and a publisher and one for secondary education (SE), with 2 teachers, 1 support person) design students presented initial concepts in a scenario format, and received input in relation to the components of the framework and on the needs from a teacher and a child perspective. Observations of children participating in a technology education class were conducted to better understand the needs of the children. Expert meetings were held with two schoolteachers to better understand the children's and teachers needs. Furthermore, the design students conducted usability tests with children to determine whether the learning activities had appeal for the pupils, whether they were doable in the given context. For example, they examined whether children understood the digital toolkit components that were developed, and

whether the design brief and process explanation was manageable in the course of a lesson. More details about the user tests can be found in [14]. During the course of the work we uncovered specific properties of the context that lead to design challenges for a RDBL approach for primary and secondary education.

3.2. Third design exploration to create design-based learning activities with an off-the-shelf digital toolkit

The third design exploration focused on developing an integrated RDBL activity that could be handed over to schools. Therefore, it was built around an off-the-shelf toolkit.

Activities by the design researcher who worked on the third design exploration included trying out various existing toolkits, such as Makey Makey, Circuit Scribe, PicoBoard, Lego WeDo and littleBits. The try-out session with various toolkits, included an informal Lab session (2 h, 2 children), a session at a primary school (90 min, 45 children), and another session at school (primary education: 90 min, 60 children; and secondary education: 50 min, 6 children). Two further stakeholder workshops were held where teachers, educational experts, learning researchers provided input on the ideas behind the solution, again discussing the different components of the framework, and the needs of the children and the teacher. Finally, the solution was evaluated at a primary school and a secondary school to verify whether the learning activity was fun and understandable for the children, and whether the intended learning goals were addressed.

Through reflection on these design explorations, using our RDBL framework (Fig. 1) as a basis for analysis, we uncovered generic design requirements for RDBL tools. In this paper, we first describe the three design explorations and subsequently discuss the generic insights gained and design guidelines formulated.

4. Design explorations

4.1. Design exploration "Dolly 2.0": RDBL for primary education

In this design exploration, a learning activity was designed for children in primary school (aged 10–12) to develop a fantasy animal in groups of four. In this activity, children were encouraged to think about the abilities that they wanted the animal to have and why it should have these abilities. In a subsequent phase, children were also asked to consider how their animal would live together with other animals.

To facilitate this learning activity, a toolkit, called 'Dolly 2.0', was developed that contained transparent objects, each with some electronics components that demonstrated an action–reaction principle (such as sound, temperature, colour and vibration). These objects were called Sensor Actuator (SA) modules. One of the SA modules for example contained a colour-sensor and an RGB led that showed the sensed colour (see Fig. 2). A teacher guide,

Fig. 3. (a) The Spark! Toolbox, (b) the Arduino-based Spark! Module, and (c) the outcome of a design-based learning activity with the toolkit.

that described the process, and provided activity cards, showed connected learning goals and the kind of materials (digital and physical) needed for the learning activity. Furthermore, Dolly 2.0 contained worksheets for pupils that guided them through the design and reflection steps. For example, children had to write down why they gave the fantasy animals certain characteristics. Finally, it contained evaluation sheets that supported the teacher in assessing the knowledge and skills children had acquired during the activities.

In the first sessions, children were introduced to the different SA modules, and explore the functionality of these modules. In following sessions the children were guided through an iterative design process, which involves different design activities. These included examining extra requirements for the design of the animal by considering the context (environment and other animals) in which it lived. In the final sessions, the children worked together, and had to negotiate and think about the decision making together.

A teacher manual described the design-based learning process for the teacher. During the sessions, the teacher provided design process support and explanations about the SA modules. The worksheets which children used during the sessions also helped the teachers in examining the children's progress. Furthermore, the earlier mentioned evaluation sheets could be used by the teacher to assess children's acquired digital literacy skills and reflection skills.

4.2. Design exploration 'Spark!': RDBL for secondary education

In this design exploration, a learning activity was developed in which secondary school children worked in pairs to find a solution for a design problem with societal relevance to which children can relate: combating street litter. The learning activity aimed to support the development of the following 21st century skills: digital literacy, problem solving, critical thinking, creativity and collaboration and communication skills.

To reach these learning goals, the children made use of a dedicatedly designed toolkit called the Spark! Box, see Fig. 3. The Spark! Box contained diverse materials including conductive ink, Snap4Arduino programming software, a selection of crafting materials, such as straws, cardboard and paperclips (see Fig. 3) and a 'Spark! Module'. This module was an Arduino tailored to have limited, but specific functionality for the purpose of the learning activity.

The Spark! Box can be used for various learning exercises. In this design exploration, one such learning exercise was worked out in detail. In this exercise, which lasted for at least 150 min, children linked a (touch) sensor to a LED actuator using conductive ink as part of creating a solution. At the start of the exercise, children

received a manual that included the design brief and a description of a six-step process, including the steps (1) problem exploration, (2) idea generation, (3) concept sketching, (4) prototyping, (5) testing and improving and (6) presentation and reflection. For each step the manual clearly describes the goal of the step and a practical hint. At the presentation and reflection step, specific reflection questions were provided. The manual also explained the basic functionality of the Spark! Module and the Snap4Arduino programming environment.

Children could do a Spark! lesson in a fairly independent manner using the design brief. The teacher was the facilitator of learning, stepping in whenever necessary by providing children with the help they needed to continue with the design process or achieve a higher level of learning.

4.3. Design exploration 'ID box': RDBL approach for primary and secondary education

In this design exploration we examined how a similar toolkit could be used in two different learning contexts: last two classes of primary (or elementary) school (PE), and first two classes in secondary school. We developed a learning activity in which children were asked to design a new interactive lamp that supported a healthier lifestyle, or is more sustainable, compared to existing lamps. This activity was designed such that it helped children in practising the 21st century skill critical reflection, problem solving, presentation skills and digital literacy. Additionally, by conducting the activity, children learned about properties of sensors and actuators and about the concept of light.

To conduct the developed learning activity, children make use of the 'ID toolbox', which was developed for the purpose of this activity. The ID toolbox is a physical box consisting of littleBits (including a light sensor, and a colour Led, infrared sensor and remote control), and various materials that are transparent and semi-transparent to explore shadow effects and refraction and support tinkering (see Fig. 4).

The ID toolbox learning activity was conducted in two sessions of 60 min. The activity consisted of a 4 step process: (1) imagine and discover, (2) make and prototype, and (3) test and present and (4) reflect. In step 1, children, who worked in groups of 4, were presented with inspirational material, including a video that explained how light influences our mood. They were encouraged to discuss the aspects of the functioning of light that they find, and to make a mind-map around what they knew about light. In step 2, the children came up with ideas of interactive lamps and used paper and pencils to make sketches of their ideas and use littleBits to create interactive prototypes (see Fig. 5). When building these prototypes, the children could use diverse materials with varying

Fig. 4. (a) The ID toolbox. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Children designing an interactive and sustainable lamp with littleBits (a) primary education and (b) secondary education.

transparency to play with the properties of light. As support for the design process, the ID toolbox included a number of prompting cards that provided suggestions on how to conduct the design process, and how to use the technology. In step 3, the children tried out their design within their own group, and reflected on whether it did what they wanted it to do. After trying it out, the children gave a one-minute presentation to their peers, who were asked to play the role of client belonging to a lamp company, and ask questions and give feedback. In step 4, children reflected on their design by taking a picture of their prototype and discussed whether they would like to make changes to their design-based on the feedback from the other children.

Because the ID toolbox was designed to be useable in both primary education (PE) and secondary education (SE), we developed two versions of the learning activity. Firstly, these two versions differ in the framing of the design challenge. In the PE version, the challenge was rather concrete, as it emphasized on different colours of light and provided predefined design requirements (e.g. using LEDs for sustainability and colours to influence people's health). In the SE version, the challenge was more abstract focused on the design of interactive lamps, and no predefined requirements were given. Instead children were challenged to determine these requirements themselves. Secondly, in the PE version, children were steered more by instructions and suggestions from the teacher or *facilitator*, whereas the SE children were expected to work mostly independently, using the ID toolbox's contents and instruction forms. Thirdly, the learning goals were adjusted to the appropriate level. The PE learning goals were related to colours of light whereas the SE learning goals were related to shadows and refraction.

5. Insights from design explorations

5.1. Insights on teaching digital literacy using digital toolkits at school

By conducting and reflecting on our three design explorations, we uncovered a number of challenges specific to teaching *digital literacy* (learning goal) with *digital toolkits* in schools. In this section, we describe the conclusions, illustrate them with the most salient insights from the design explorations, and link them to the different items of the RDBL framework (see Fig. 1).

Reflecting on particularly Spark! and ID toolbox, we realized that it is important to map the learning goals (Item C) to the properties of the digital toolkit (Item F) and vice versa.

- The design intention in the Spark! Toolkit was to support both conceptual design and to learn about concrete technology. Spark! combines high level learning (the design process; e.g. implications of technology in modern life) with aspects of lower level issues, such as getting the plus and minus right of connecting a led or learning Snap4Arduino visual programming. The Spark! toolkit facilitates a connection between conceptual design and learning about concrete technology. In the usability tests with children it was observed children were challenged both on the conceptual design level and in learning about lower level topics. This was also observed by the teacher in the third usability test.

Furthermore, it is important to support different learning styles and interests [5] (Item E) by thinking carefully about the properties of the digital toolkit (Item F).

- During the try-out sessions with ID toolbox, we discovered that the properties of the digital materials need to be related to the intended learning goals and learning styles (see also, [24]). For example, littleBits supports creating conceptual designs in a short amount of time, and also teaches some aspects of digital literacy, linked to learning goals of Science and Technology. Makey Makey is less modular, e.g. it only has one input sensor to link to concepts of learning goals. Arduino is more modular, but more difficult to use to quickly create a conceptual design.

We furthermore found that the toolkit (Item F) has to be age appropriate and tinkerable, enabling a balance between providing the right learning opportunity (Item C) with enough flexibility in the design process (Item A).

- Based on the second usability test with the Spark! Toolkit it was concluded that the current design process may be too pre-defined for more experienced older children. On the other hand, the simplified Arduino-based solution that Spark! uses was too complex for it to be really tinkerable for younger children with less experience. The Led, for example, can only be connected in one way, leaving little room for tinkering.

Finally, our design explorations made us understand that the digital literacy topics (Item C) have to be linked to relevant and meaningful topics to children (Item D).

- It was stated by a teacher and a curriculum developer at a stakeholder workshop, that it is important to have children apply digital literacy topics to design challenges that are relevant to children's world. This helps to increase their intrinsic motivation to understand about technology.

5.2. Insights on teaching design thinking through design-based learning at school

We additionally reflected on our design explorations to uncover challenges that related to teaching *design thinking* through a *design-based learning process* at schools.

Through this reflection we realized that the design activity (Item A) has to be structured and built up in such a way that children can relate digital literacy topics (Item C) to design considerations.

- When trying out the Dolly 2.0 concept, children were asked to first sketch a solution and then write characteristics of their fantasy animal. This was included to support thinking about whether the solution has value for the animal, and to empathize with the animal. It was observed in the usability test that making a link to an appealing context and environment and building up how to think about it helped children go through the process more smoothly.
- A teacher, participating in a stakeholder workshop, who also has a design background, stated that teachers need to be a dungeon master, facilitator of learning for the pupils, with enough understanding of the toolkit. *Teachers* need to guide the learning process and motivate the student, without taking away the ownership of the pupil.

Additionally, we concluded that children need support for reflection (item B) in different formats for the various phases of the design process (item A).

- In the usability test during the Dolly 2.0 design exploration children had to first draw an animal individually and then create one animal as a group. Examining the worksheets used in the usability test showed that the worksheets support children in *reflecting* at different levels, e.g. about more simple or more complex issues. Subsequently, working together had them practice discussion about design considerations and

negotiating about contributions from all children. During the usability tests of the Spark! Design exploration, variations with and without prompt questions were examined. To support children's reflection process, the manual needed prompt questions for *reflection*.

Teachers (item E) need support to develop and adapt design challenges (item D) with relevant and feasible learning goals (item C). Of course some learning lines already have design exercises embedded, however teachers may want to adjust and tailor them to their own considerations.

- It is important to provide examples to teachers of bridges between *learning goals* related to *digital literacy* of different sorts, such as content specific learning goals for topics such as teaching about the concept of light, sound, energy and electricity. Both a teacher and a publisher, who reflected on his discussions with teachers, mentioned this requirement in a stakeholder workshop.

It is important to help children (item E) understand the phases of the design process (item B), and how to manage the process, so they can be confident creators.

- It is important to be explicit about the phases of the design process, because it helps pupils to move on to the next phase of design, e.g. moving from diverging in brainstorming to converging in deciding on criteria. This was seen in the usability with children trying out the Spark! Toolkit.

6. Discussion

If we want children to become proficient in creating solutions for societal problems, we believe that one way to achieve this is to have them practice digital fabrication skills, with appropriate materials in an appealing design-based learning process. Teaching children these skills in a school context requires a good understanding of this complex context of use. While related research has examined how to embed FabLab like constructions in schools (e.g. [7,8]), we decided to take a slightly different approach, where we have interpreted digital fabrication as a process of designing tangible solutions with digital toolkits.

The three case studies presented were first explorations of RDBL in schools using such digital toolkits. While these have posed a number of insights that can inform future research, these explorations naturally also have limitations. In this section we discuss a number of issues relevant for RDBL which we were not able to explore in our present research, but which deserve future exploration.

Firstly, our cases explored only fairly short design-based activities. Further research is needed to examine requirements for longer learning activities, embedded in complete learning lines. We have already seen that the properties of the digital toolkits should be appropriate to support learning goals that need to be met at schools, and that they should support different learning styles of children. However, further research is needed to provide more guidance to teachers in how to select the right toolkit for their purposes, and how to adjust the design-based learning activities for different learning styles.

As presented in our RDBL framework, one important requirement for learning activities that are to become part of a school's curriculum is to support measuring children's progress of competencies such as design thinking and digital literacy. We have neither been able to explore in detail what the best manner in which to teach design thinking, nor what different levels of design thinking skills for different years in the schools need to be assessed. The Stanford d-school has developed a set of design thinking rubrics; these might be developed further to match our

purpose, e.g. the rubrics do not contain process management skills, or framing skills [17]. This would provide a basis for how to define design challenges for children engaging in digital fabrication activities.

Through our explorations we furthermore found that it is also important to support teachers in creating design challenges that are related to school related learning goals and in creating learning activities related to the steps of the design process and the level of design thinking of the children. While we were not able to develop concrete support tools for teachers yet, this will be part of our future research as well.

Another challenge is to select and design flexible toolkits that can be used for different course-based learning goals that are not too expensive, easy to use, and need little support. While existing platforms such as LittleBits and Makey Makey provide support for sharing lessons, it is difficult for teachers and schools to get started and plan a process for how to adopt and integrate an extensive RDBL approach in schools.

Finally, in our design research exploration, our view might have been subject to bias: Many of the stakeholders involved were already interested in this approach. However, in teaching practice there is a large diversity in how open people are to such an approach. Thus, we need to develop further examples of the benefits of following this approach.

7. Conclusions

Based on a research through design approach, in which we analysed the process and outcome of three design explorations, we have developed a basic framework, called RDBL, for describing important elements to consider when implementing design thinking and digital literacy through a design-based learning approach in primary and secondary education.

7.1. A framework for RDBL for primary and secondary education

We have adapted the model provided by Gomez et al. [9] to describing design-based learning at *primary and secondary school level*, and added components that are specific to the *role of digital materials* in a design-based learning approach. Some differences can be seen when applying it to the last two classes of the primary school and the first two classes at secondary schools.

- The manner in which support for learning is provided differs: at primary school there is more structure and more class-activities, while in secondary school we see a shift to self-directed learning.
- The complexity of the design problem, and thus the design thinking skills practised need to be adjusted to the appropriate level.
- The learning goals have to be adjusted to the appropriate level for the children.

Other researchers and teachers working on digital making and digital literacy can use the framework to reflect on how the choices they make fit into the context of the learning activity, e.g. do the digital making materials have the right affordances (or selective exposure) for the intended learning goals of the activity? Or, how are the learning activities in a fablab context related to the course specific learning goals?

7.2. Challenges in applying design-based learning using digital toolkits at school

In summary, creating good design-based learning solution to teach digital literacy and design thinking at schools requires

considering a wide range of issues described in the RDBL framework. The digital toolkits need to support learning goals at different levels to appeal to children with different motivations for learning about technology. Furthermore, good support needs to be provided about how to plan, manage and assess the progress in design-based learning processes for teachers.

Acknowledgements

We want to thank the following people for their input to the project: the various stakeholders (the teachers, the publishers, and the educational experts) and the other Industrial Design students, including Nina Maaden, who designed the SA modules used in design exploration 3 and Sam Janssen for help with the third design exploration. The 'Design-based learning of 21st century skills with technology toolkits at schools' project was supported by the Municipality of Eindhoven under a grant (2014/00881) for examining Eindhoven Education 2030.

References

- [1] A. Thijs, P. Fisser, M. van der Hoeven, Digitale geletterdheid en 21e eeuwse vaardigheden in het funderend onderwijs: een conceptueel kader, Digital literacy and 21st century skills in primary and secondary education: a conceptual framework, SLO nationaal expertisecentrum leerplanontwikkeling, Enschede, 2014.
- [2] M. Binkley, O. Erstad, J. Herman, S. Raizen, M. Ripley, M. Rumble, Defining 21st Century Skills, The University of Melbourne, Melbourne, 2010.
- [3] J. Voogt, N. Pareja Roblin, 21st Century Skills. Een Discussienota, Universiteit Twente, Hengelo, 2010.
- [4] L. Boswinkel, E. Schram, De toekomst telt, Report by Dutch National Centre of Curriculum development (SLO) and Ververs Foundation, 2011.
- [5] Youngworks Motivation, BetaMentality 2011–2016 Jongeren boeien voor bèta en techniek, BetaMentality 2011–2016 Getting children interested in science and technology, November 2010.
- [6] Horizon 2020: SEAC-1-2015, call for research. Retrieved 8th of June 2015 from: <http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/2426-seac-1-2015.html>.
- [7] P. Blikstein, Digital fabrication and making in education—the democratization of invention, in: J. Walter-Hermann, C. Büchling (Eds.), Fablab, of Machines, Makers and Inventors, Verlag, Bielefeld, 2013, pp. 203–222.
- [8] N. Dittert, D. Krannich, Digital fabrication in educational contexts—ideas for a constructionist workshop setting, in: J. Walter-Hermann, C. Büchling (Eds.), Fablab, of Machines, Makers and Inventors, Verlag, Bielefeld, 2013, pp. 173–180.
- [9] S.M. Gómez Puente, M.W. Eijck, W.M.G. van & Jochems, Empirical validation of characteristics of design-based learning in higher education, Int. J. Eng. Educ. 29 (2) (2013) 491–503.
- [10] S.M. Gómez Puente, M. van Eijck, W. Jochems, Professional development for design-based learning in engineering education: a case study, vol. 40, no. 1, 2015.
- [11] C.C.M. Hummels, J.W. Frens, Designing for the unknown : a design process for the future generation of highly interactive systems and products, in: Proceedings of the 10th International Conference on Engineering and Product Design Education, Ideo 2015, Definition of design thinking; Retrieved April 2015, 2008, pp. 204–209. <http://www.ideo.com/about/>.
- [12] H.A. Simon, The Sciences of the Artificial, MIT Press, Cambridge, MA, 1969.
- [13] D.A. Schön, The Reflective Practitioner, Basic Books, New York, 1983.
- [14] K. Scheltenaar, J. van der Poel, T. Bekker, Design-based learning in classrooms using digital toolkits, in: Proceedings of International Conference on Entertainment Computing, ICEC 2015—International Conference on Entertainment Computing, Norway, 2015, pp. 126–139.
- [15] E. Beamer, Why you should use design thinking approaches in education! [blog post] in April 2015, 2013. Retrieved from: <https://emerbeamer.wordpress.com>.
- [16] K12 Lab wiki, Process [blog post] (2010). Retrieved on 10th of June from https://dschool.stanford.edu/groups/k12/wiki/606dd/Process_.html.
- [17] K. Dorst, The core of 'design thinking' and its application, Des. Stud. 32 (2011) 521–532.
- [18] J.L. Kolodner, Learning by design™: Iterations of design challenges for better learning of science skills, Jpn. Bull. Cognit. Sci. (2002).
- [19] K. Stables, R. Kimbell, Evidence through the looking glass: developing performance and assessing capability, in: 13th International Conference on Thinking: Curious Minds Think and Learn by Exploring the Unknown, Norrköping, Sweden, June 17–21, 2007.
- [20] International Technology Education Association (ITEA), Standards for technological literacy: Content for the study of technology, Reston, VA: Author, 2000.
- [21] J. Hinrichsen, A. Coombs, The five resources of critical digital literacy: a framework for curriculum integration, Res. Learn. Technol. 21 (2014) [S.I.].

- [22] M. Resnick, B. Silverman, Some reflections on designing construction kits for kids, in: *Proceedings of Interaction Design and Children Conference*, ACM, Boulder, CO, New York, NY, USA, 2005, pp. 117–122.
- [23] J.E. Frederik, W. Sonneveld, *Ontwerpen onderwijzen (Teaching design)*, NVOX 33 (1) (2008) 19–21.
- [24] I. Douma, T. Bekker, P. Rijnbout, Design-based learning with 'digital making toolkits' at dutch schools, 2015, unpublished manuscript.
- [25] P. Blikstein, Gears of our childhood: Constructionist toolkits, robotics, and physical computing, past and future, in: *Conf. IDC 2013*, New York, NY, USA, 2013, pp. 173–182.
- [26] M. Resnick, E. Rosenbaum, Designing for tinkability, in: M. Honey, D.E. Kanter (Eds.), *Design, Make, Play*, Routledge, London, 2013, pp. 163–181 (Chapter 10).
- [27] J. Zimmerman, J. Forlizzi, S. Evenson, Research through design as a method for interaction design research in HCI, in: *Proceedings of SIGCHI Conference on Human Factors in Computing Systems*, San Jose, California, 2007, pp. 493–502.
- [28] Kristina Höök, Jonas Löwgren, Strong concepts: Intermediate-level knowledge in interaction design research, *ACM Trans. Comput.-Hum. Interact.* 19 (3) (2012) 18. <http://dx.doi.org/10.1145/2362364.2362371>. Article 23 (October 2012).