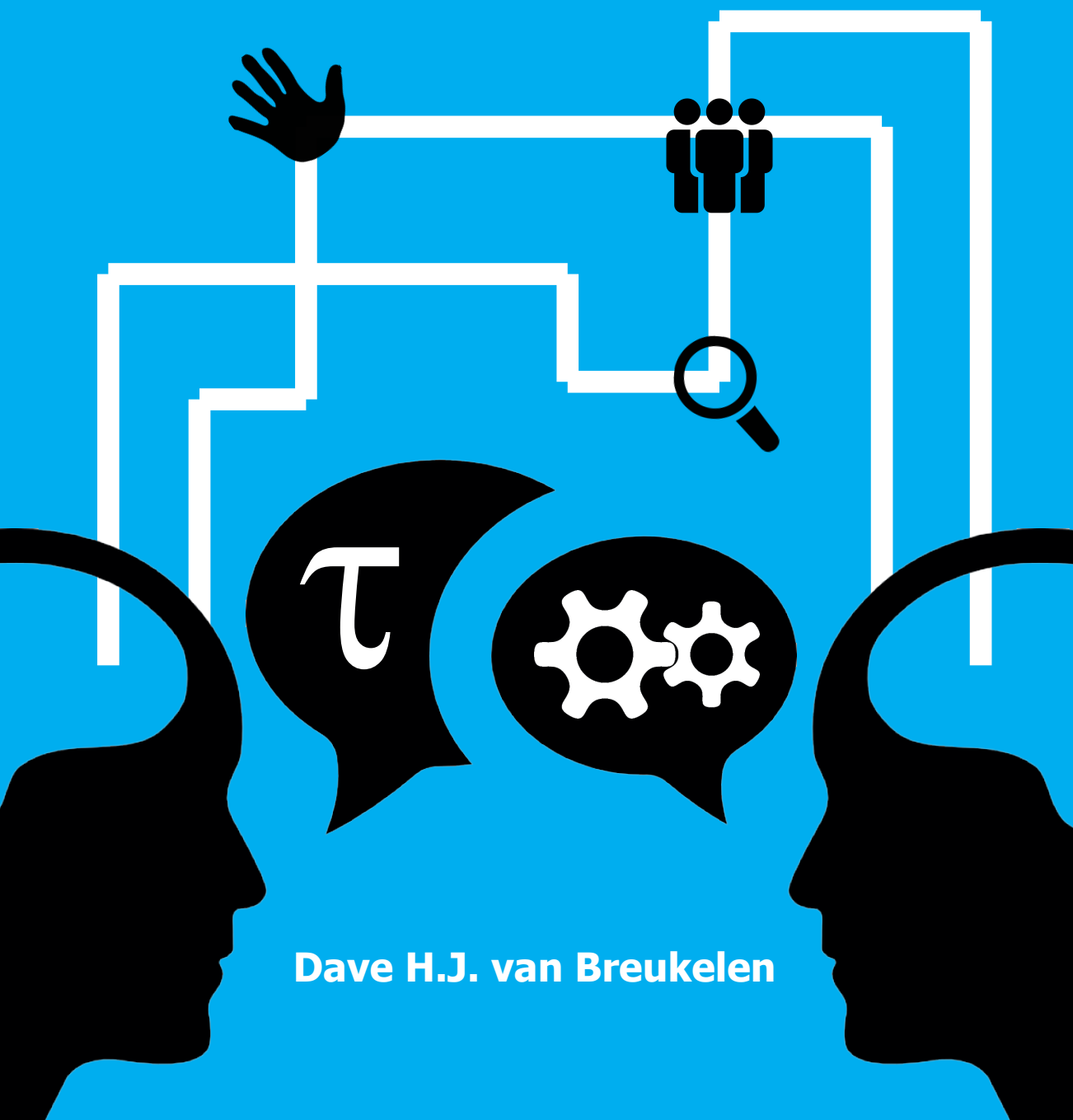
Teaching and learning science through design activities

A revision of design-based learning



Dave H.J. van Breukelen

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Proefschrift

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"Education is not the learning of facts,
but the training of the mind to think."

Albert Einstein

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Summary

Juveniles nowadays encounter a dynamic and complex world, inter alia, because science and technology have become strongly entangled and have grown denser in our personal lives (Lelas, 1993). Studies also indicate that interest in and understanding of both disciplines is decreasing (Sjöberg & Schreiner, 2010) where the opposite is needed to face modern societies. In response to this, other studies suggest that interdisciplinary teaching may improve students' motivation and understanding (Lustig et al., 2009; Osborne & Dillon, 2008; Rennie, Venville, & Wallace, 2012). Many national governments therefore whish for interdisciplinary STEM education (science, technology, engineering and mathematics).

Multiple approaches that try to grant this wish use project-based design challenges to unite a broad range of science- and technology-related content (e.g. skills, practices and knowledge). Nearly all design-based learning (DBL) approaches accomplish a meaningful and stimulating learning environment (Wendell, 2008) and improve the learning of skills and practices. For example, the Learning by Design (LBD) approach, which is the bedrock of this PhD study, delivered students who were highly involved and who achieved, compared with non-LBD students, high skill levels (e.g. collaboration, metacognitive and science skills) (Kolodner, Camp, Crismond, Fasse, Gray, et al., 2003; Kolodner, Gray, & Fasse, 2003). However, as in case of LBD, nearly all approaches suffer from limitations in (scientific) concept learning (Sidawi, 2009; Wendell, 2008), despite the fact, this kind of learning is often theoretically facilitated by the pedagogical foundations of DBL. In a nutshell, this topic is the central research theme, which feeds the central research question: Why the current practice of design-based learning not yet leads to an expected high level of concept learning, and how learning can be enhanced resulting in an educational strategy where the learning of concepts and skills both are strongly represented?

Four cohesive studies were conducted to answer the central research question where the emphasis shifted from qualitative to quantitative data. The first study (Chapter 2) investigated how and when scientific content was addressed and learned by 77 general secondary education students during a traditional LBD challenge and what limitations in understanding were present. To provide the study with an important research focus, a hypothesis was formulated based on theoretical insights and previous research. This hypothesis states that the complex nature of design-based learning, due to many objects of integration and a strong process focus, forces

students to overlook conceptual knowledge and to focus on doing rather than knowing (Berlin & White, 1994; Popovic, 2004; Wendell, 2008). In general, the study seemed to confirm the hypothesis. Students were mainly process focused and strongly interested in what to do and deliver. This behaviour was primarily provoked by the complexity and extensiveness of the challenge. As a result, students mainly learned science concepts, in an ad hoc way, that came available from activities that strongly determined a successful design outcome, which induced implicit learning of isolated facts and a lack of deeper understanding. This, for example, became visible when students failed to demonstrate proper scientific reasoning when they were encouraged to explain science used.

The second study (Chapter 3) mainly focused on teacher handling because literature claims that (concept) learning is highly teacher dependent (Bamberger & Cahill, 2013; Van der Veen & Van der Wal, 2012) and teachers involved in the first study described task guidance as intensive and complex. The following sub-questions were leading: What teaching strategies dominate and (directly) affect the learning of science content and, by analysing all teaching interventions during LBD, what is the relative number of interventions that directly appeal to these strategies? Which teaching strategies should get more attention to enhance concept learning? To provide answers a traditional LBD task was developed for student teachers where they had to design a high-efficient solar power system for a model house. The challenge was guided by two experienced teacher trainers and video and sound recordings enabled the detailed study of teacher behaviour. Data analysis showed that detailed task analysis is necessary to predict (conceptual) learning outcomes and to unravel task-driven concepts that are addressed strongly by the task. Additional, less directive concepts, complementing the knowledge domain, should be addressed otherwise (teacher-driven). For learning concepts, explicit teaching strategies, teacher feedback and process-related issues (e.g. solar cell measurements) were highly appreciated by students. Especially, when interventions directly appealed to underlying science or when an ongoing learning process was stimulated. Unfortunately, only 13 percent of all interventions concerned these topics, which offers room for improvement.

Chapter 4 (third study) describes the first experiences with modifications for enhanced concept learning. For this, the LBD challenge developed for the second study was enriched by explicit teaching and scaffolding strategies in response to the findings of Studies 1 and 2: backward design (Wiggins & McTighe, 2006), guided discussion (Carpenter, Fennema, & Franke, 1996), informed design (Burghardt &

Hacker, 2004), explicit instruction and scaffolding (Archer & Hughes, 2011), and an adjustment of administrative activities. Studying assessment results, it was fair to state that the level of concept learning significantly increased. Students were able to equal achievements found in some of the most successful physics-related courses (Hake, 1998). This conceptual performance was accompanied by significant increases in achievement levels among seven skill dimensions. Achievements that were fairly comparable to results found by Kolodner, Camp, Crismond, Fasse, Gray, et al. (2003) in traditional LBD studies. Furthermore, the study revealed strong positive correlations between concept learning and three skill dimensions: use and adequacy of prior knowledge and scientific reasoning. Although the findings of the study were promising, the study revealed two more areas for improvement: too little coherence and assimilation of addressed science and the large number of individual stages and accompanying administration that were disruptive to the ongoing learning process.

The final study (Chapter 5) confirmed the enhanced level of concept learning, found in the third study, statistically by modifying and testing the task developed for the first study. Also the effect of further remodifications, based on the outcomes of the third study, were studied. Remodifications concerned a reduction of separate stages and associated administration, and an addition of two science lectures to merge and assimilate conceptual knowledge. Test results revealed a small, but significant, additional increase on top of the large gain enabled by the initial modifications. Together, all (re)modifications seem to provide a promising design-based learning strategy, expressed as the acronym FITS, where students learn through providing a proper task **F**ocus, **I**nvestigating scientifically what has to be learned, informed application of content during **T**echnological design activities, and creating and explicating **S**ynergy regarding science and technology.

In Chapter 6 the main findings and conclusions per study are described with the aim of providing an answer to the central research question mentioned before. In short, this answer includes the fact that indeed the complexity and extensiveness of design challenges mask the potentially rich learning environment for conceptual learning. Furthermore, the FITS model is presented as a promising strategy to enhance concept learning through design challenges. The FITS model includes all traditional LBD activities, however, depending on the task and based on the strategies of backward design and informed design, several activities are enriched by pre-planned elements (e.g. additional experimentation, class discussions, information seeking, etc.). Mainly to complement strongly task-related knowledge

by weakly task-related content and to guarantee design creation from a more knowledgeable base. Furthermore, all science content is explicated (teacher-driven) during the task through explicit teaching strategies. This explication is enriched by examples of de- and recontextualisation to facilitate knowledge transfer. Science explication is done through anticipating the process and during pre-planned moments of class discussion. For class discussions, the strategy of guided discussion helps to address students' thinking constructively and to become clear about what students know and what they need to learn for proper understanding. To deepen (scientific) knowledge, two traditional science lectures provide a complete and coherent picture of science involved where especially at the end it becomes explicit how science and (design) technology complement and enrich each other. Beside a lot more science focus, the FITS model contains only four individual stages and two moments of administration (instead of LBD's seven stages and moments of administration). By doing this, more coherence is offered and administration is limited to the amount necessary to move on. All in all, the ongoing learning process is stimulated where guidance and scaffolding is shifted towards the ongoing process itself rather than breaking it down into parts.

The sixth chapter ends with summarising limitations of the study, suggestions for further research and implications for educational practice. In broad terms, some of these closely linked topics are: ensuring credibility and generalisability, (a limited) focus on knowledge retention, the use of rubrics and concept maps as assessment strategy, ambiguities regarding teacher education in case of design-based learning, a curriculum approach for design challenges, and transferability of results to other educational settings.

Samenvatting

Jongeren worden tegenwoordig geconfronteerd met een dynamische en complexe wereld, onder andere omdat wetenschap en techniek een belangrijke plaats hebben ingenomen binnen ons leven en beide sterk verstrengeld zijn geraakt (Lelas, 1993). Studies tonen verder aan dat de interesse in en het begrip van beide disciplines afneemt (Sjöberg & Schreiner, 2010), terwijl het tegenovergestelde nodig is om jongeren klaar te stomen voor de maatschappij. Andere studies suggereren dat interdisciplinair onderwijs een positief effect kan hebben op de motivatie en het begrip van leerlingen (Lustig et al., 2009; Osborne & Dillon, 2008; Rennie et al., 2012). Mede daarom hebben veel beleidsbepalers de wens om integratief STEM-onderwijs (science, technology, engineering en mathematics) op de kaart te zetten.

Veel pogingen die deze wens proberen te vervullen, zijn projectgestuurde ontwerptaken, onder de noemer van design-based learning (DBL), die een variëteit aan wetenschappelijke en technische inhouden aandoen, waaronder kennis en vaardigheden. Bijna al deze benaderingen resulteren in een betekenisvolle en motiverende leeromgeving (Wendell, 2008) en een sterke verbetering van het vaardigheidsleren. De strategie van Learning by Design (LBD), welke aan de basis ligt van deze dissertatie, levert bijvoorbeeld zeer betrokken studenten af met een, vergeleken met niet-LBD studenten, hoog vaardigheidsniveau op het gebied van samenwerken, metacognitie en natuurwetenschappelijke vaardigheden (Kolodner, Camp, Crismond, Fasse, Gray, et al., 2003; Kolodner, Gray, et al., 2003). Echter, zoals ook in het geval van LBD, kampen vrijwel alle benaderingen met achterblijvende conceptuele leeropbrengsten (Sidawi, 2009; Wendell, 2008), terwijl deze opbrengsten vaak wel in potentie gefaciliteerd worden door de pedagogische en didactische basis van DBL. Samengevat zal dit het centrale onderzoeksthema zijn van deze dissertatie, waarbij de volgende hoofdvraag centraal staat: Waarom leidt de huidige onderwijspraktijk van design-based learning niet tot de in potentie haalbare hoge conceptuele leeropbrengsten en hoe kan dit verbeterd worden, zodat er een educatieve strategie ontstaat waarbij het leren van concepten en vaardigheden allebei sterk vertegenwoordigd zijn?

Vier studies zijn uiteindelijk uitgevoerd, waarbij de nadruk verschoof van kwalitatieve naar kwantitatieve data. De eerste studie (Hoofdstuk 2) onderzocht hoe en wanneer wetenschappelijke kennis door 77 leerlingen werd gebruikt en geleerd tijdens een traditionele LBD-taak en welke beperkingen in het uiteindelijke begrip

aanwezig waren. De studie werd, op basis van literatuur, voorzien van een initiële focus en een hypothese die stelt dat de complexe aard van ontwerptaken, als gevolg van veel integratieve elementen en een complexe procesgang, leerlingen dwingt om te focussen op doen, waardoor het begrijpen van onderliggende concepten een bijzaak wordt (Berlin & White, 1994; Popovic, 2004; Wendell, 2008). Deze hypothese lijkt door de studie bevestigd te worden, omdat leerlingen veelal geïnteresseerd waren in wat er gedaan en gemaakt moest worden. Deze houding lijkt getriggerd te worden door complexiteit en taakomvang, met als gevolg het ad hoc vergaren van kennis op momenten dat bepaalde (conceptuele) inzichten van onmiskenbaar belang blijken voor een succesvol ontwerp. Het gevolg was het impliciet leren van losstaande feiten en een gebrek aan dieper inzicht. Dit werd bijvoorbeeld duidelijk omdat leerlingen niet goed in staat waren om genomen (ontwerp)beslissingen op basis van natuurwetenschappelijke inzichten te onderbouwen.

Tijdens de tweede studie (Hoofdstuk 3) stond de docentvaardigheid centraal. Enerzijds, omdat literatuur suggereert dat (concept)leren sterk docentafhankelijk is (Bamberger & Cahill, 2013; Van der Veen & Van der Wal, 2012) en anderzijds, omdat docenten tijdens de eerste studie de begeleiding als complex en intensief beschreven. De volgende deelvragen waren leidend: Welke docentvaardigheden domineren en beïnvloeden het leren van wetenschappelijke inhouden en, op basis van analyse van docentinterventies tijdens LBD, wat is de frequentie van interventies die betrekking hebben op deze vaardigheden? Welke docentvaardigheden zouden meer aandacht moeten krijgen om conceptueel leren te versterken? Om de vragen te kunnen beantwoorden, werd een traditionele LBD-taak ontwikkeld voor leraren in opleiding, waarbij een hoogefficiënt zonne-energienetwerk voor een modelhuis ontworpen moest worden. De taak werd begeleid door twee ervaren leraren(opleiders), waarbij het proces werd vastgelegd middels beeld- en geluidsopnamen. Uit de data-analyse bleek dat een gedetailleerde analyse van de leertaak nodig is om (conceptuele) leeropbrengsten te voorspellen en te zien welke concepten sterk (direct) of zwak (indirect) taakgerelateerd zijn. Indirecte concepten dienen, om het kennisdomein te completeren, anders aangesproken te worden (docentgestuurd en aanvullend aan de taak). Tijdens het proces bleken het expliciteren van kennis, feedback van de docent en specifieke taakelementen (bijvoorbeeld zonnecelmetingen) sterk door de leerlingen gewaardeerd te worden met betrekking tot het leren van concepten, vooral wanneer er een directe koppeling was met onderliggende kennis of het stimuleren van de procesgang. Slechts 13 procent van alle waargenomen docentinterventies hadden echter betrekking hierop.

Hoofdstuk 4 (derde studie) beschrijft de eerste ervaringen met betrekking tot het verbeteren van conceptueel leren. Hiervoor werd de LBD-taak van de tweede studie verrijkt, op basis van de resultaten van Studies 1 en 2, met strategieën rondom *explicit teaching* (expliciet laten leren) en *scaffolding* (uitdagen en ondersteunen): *backward design*, ofwel omgekeerd ontwerpen (Wiggins & McTighe, 2006); *guided discussion*, ofwel geleide discussie (Carpenter et al., 1996); *informed design*, ofwel geïnformeerd ontwerpen (Burghardt & Hacker, 2004); *explicit instruction*, ofwel expliciete instructie; *scaffolding* (Archer & Hughes, 2011) en een aanpassing van administratieve handelingen. Resultaten lieten zien dat studenten een (veel) hogere leerwinst boekten in het geval van de kennistoets. Zelfs vergelijkbaar met de hoogste leerwinsten gemeten in het verleden (Hake, 1998). Ook realiseerden de studenten een significante verbetering van hun vaardigheidsniveau betreffende zeven vaardigheidsdimensies. Een progressie die redelijk vergelijkbaar is met eerder LBD-onderzoek, uitgevoerd door Kolodner, Camp, Crismond, Fasse, Gray, et al. (2003). Verder werden er sterke positieve correlaties gevonden tussen conceptueel leren en drie vaardigheidsdimensies: het gebruik en de adequaatheid van voorkennis en wetenschappelijk redeneren. Hoewel de resultaten van de studie veelbelovend leken, bleken er nog twee belangrijke verbeterpunten te zijn: te weinig coherentie en verdieping met betrekking tot onderliggende natuurwetenschappelijke kennis en de grote hoeveelheid van separate procesfasen en administratieve momenten, wat een procesverstorende werking bleek te hebben.

De laatste studie (Hoofdstuk 5) bevestigde het verbeterde kennisniveau van de derde studie op grotere schaal. Hiervoor werd de LBD-taak van de eerste studie aangepast en uitgevoerd. Eerst door de modificaties van de derde studie opnieuw uit te proberen en vervolgens door aanvullende modificaties te implementeren op basis van de uitkomsten van de derde studie. Aanvullende modificaties betroffen een reductie van separate fases en administratie en een toevoeging van twee traditionele colleges om kennis samen te brengen en te verdiepen. De hermodificaties bleken in een kleine, maar significante, verbetering te resulteren, bovenop de grote winst veroorzaakt door de initiële verbeteringen. Alle aanpassingen samen lijken te resulteren in een veelbelovende strategie, onder het acroniem FITS, voor het leren door ontwerpen, waarbij studenten leren door een juiste **F**ocus binnen de taak, onderzoek (**I**nvestigation) naar wat geleerd moet worden, expliciete toepassing van kennis tijdens **T**echnisch ontwerpen en het creëren en expliciteren van **S**ynergie tussen natuurwetenschap en techniek.

Hoofdstuk 6 beschrijft de opbrengsten en conclusies per studie met als doel het beantwoorden van de eerder genoemde hoofdvraag. Dit antwoord bevat onder andere de opmerking dat de complexiteit en omvang van ontwerptaken maskerend werkt met betrekking tot de potentieel rijke conceptuele leeromgeving. Verder wordt het FITS-model uitgediept als strategie voor het leren door ontwerpen. Het FITS-model bevat alle traditionele LBD-elementen maar, taakafhankelijk, zijn bepaalde activiteiten verrijkt door vooraf geplande interventies, zoals aanvullend onderzoek, groepsdiscussies en informatie zoeken, die worden ingegeven door het toepassen van *backward design* en *informed design*. Beide strategieën zorgen voor een volledig beeld van (natuurwetenschappelijke) kennis en een expliciete toepassing van deze kennis tijdens ontwerpen. Verder wordt alle natuurwetenschappelijke kennis die tijdens de taak aan orde komt geëxpliciteerd (docentgestuurd), waarbij aandacht besteed wordt aan voorbeelden van de- en recontextualisatie om kennistransfer te stimuleren. Deze explicitatie vindt plaats door tijdens het proces te anticiperen op door de situatie ingegeven momenten en op vaste momenten tijdens groepsdiscussies. Tijdens vaste momenten helpt de strategie van *guided discussion* om zicht te krijgen op het denken en doen van de studenten en deze informatie te gebruiken als basis voor het toewerken naar juiste natuurwetenschappelijke inzichten. Verder zorgen twee colleges voor het verder verdiepen en samenbrengen van kennis die centraal staat tijdens de taak, waarbij het laatste college expliciet aandacht besteedt aan hoe technisch ontwerpen en natuurwetenschap elkaar versterken (synergie). Naast meer focus op natuurwetenschappelijke kennis bevat het FITS-model slechts vier fysiek gescheiden fasen en twee administratieve momenten. Dit in tegenstelling tot de zeven fasen en administratieve momenten van LBD. Hierdoor wordt een doorlopend leerproces gecreëerd met meer nadruk op sturing tijdens het proces, waarbij administratieve handelingen beperkt worden tot een hoeveelheid die noodzakelijk is om vooruitgang te boeken.

Hoofdstuk 6 eindigt met een beschouwing van de beperkingen van het onderzoek, suggesties voor vervolgonderzoek en de implicaties voor de beroepspraktijk. Enkele, sterk samenhangende, aspecten die besproken worden zijn de betrouwbaarheid, validiteit en generaliseerbaarheid van het onderzoek; (de beperkte) focus op kennisretentie; het gebruik van rubrics en concept maps als assessmentstrategie; vragen met betrekking tot het opleiden van leraren; de curriculaire aanpak voor ontwerpgestuurd leren en de transfereerbaarheid van onderzoeksresultaten naar andere educatieve settingen.

1

General introduction

1.1 Relevance and aim of the research

The world around us is constantly changing and getting more complex. Partly because science and technology have grown progressively denser in our personal lives where most of the world's issues ask for an interdisciplinary approach to meet humans' needs (Lustig et al., 2009). We might expect that school systems respond accordingly by delivering juveniles ready to face these issues. Unfortunately, many curricula are traditionally dominated by separate disciplines (Scott, 2008) where international studies, e.g. ROSE (Sjöberg & Schreiner, 2010), demonstrate a decreasing interest in and understanding of science and technology. Aikenhead (2006) states that unidisciplinary science curricula result in sterile, dehumanised science content that has little appeal to students and is often perceived by them to be irrelevant. Several studies indicate that a holistic understanding of science and technology, through interdisciplinary teaching, may improve students' motivation and understanding (Lustig et al., 2009; Osborne & Dillon, 2008; Rennie et al., 2012). If we want students to learn how to apply knowledge and skills in daily life, their educational experiences must involve them in learning and applying knowledge and skills of related disciplines in recognisable contexts (Bybee, 2013). Therefore, many national governments aim for interdisciplinary science, technology, engineering, and mathematics (STEM) education (National Science and Technology Council, 2013; Office of the Chief Scientist, 2013; Parliamentary Office of Science & Technology, 2013). In this context, technology should be seen as purposeful and goal-directed activities where knowledge (e.g. conceptual, procedural) and skills (e.g. design, experimentation, craft) are used to solve practical problems and to meet needs (International Technology Education Association, 2007).

A lot of integrative approaches use design contexts to learn knowledge, skills and practices: Design-Based Modeling (Penner, Giles, Lehrer, & Schauble, 1997), Engineering for Children (Roth, 2001), Engineering Competitions (Sadler, Coyle, & Schwartz, 2000), Project-Based Science (Krajcik, Blumenfeld, Marx, Bass, & Fredricks, 1998), Informed Design (Burghardt & Hacker, 2004), Design-Based Science (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004) and Learning by Design (Kolodner, 2002b). Nearly all approaches apply similar strategies to accomplish learning goals by centralising design-related problems (Lewis, 2006). First, students address the design problem by exploration and identifying what they need to learn or know. Second, students investigate the problem by finding answers to design-related research questions coming from the exploration. Third, those

answers help students to develop and optimise possible design solutions after which prototyping takes place. Fourth, through testing and evaluation a final design solution is realised often by iteration and redesign. Taking research results on learning outcomes into account, it becomes clear that all approaches create a meaningful and stimulating learning environment (Wendell, 2008). Furthermore, process-orientated learning is highly stimulated due to a strong focus on procedural requirements for offering guidance and heading for successful design outcomes; resulting in a significant improvement of students' skills and practices (e.g. experimental skills, design-related skills, collaboration and checking work). Unfortunately, supported by a review of literature on design-based science teaching (Sidawi, 2009), nearly all approaches, to a greater or lesser extent, experience difficulties with respect to conceptual learning. For example, Design-Based Modeling students made no transition from summarising patterns of artifact performance to understanding of underlying science principles, and students involved in Project-Based Science and Learning by Design showed limited conceptual learning gains that also were highly teacher dependent. Students in Engineering Competitions showed little rationale for how to connect design content to scientific concepts.

To study the topic of concept learning by design challenges the Learning by Design (LBD) approach was chosen as the bedrock of this dissertation. This, because LBD has been studied extensively in the past, more than other approaches, and those studies offer a solid starting point to move forward. On the one hand because LBD for a number of reasons appeared to be quite successful, and on the other hand because previous LBD research provided a rich amount of data on student learning, accompanied by a transparent description of data collection and analysis.

From 1999 until 2003 over 3500 American middle school students (aged 12-14; grades 6-8) took part in studies that compared achievements of LBD classes to non-LBD classes (Kolodner, Camp, Crismond, Fasse, Gray, et al., 2003; Kolodner, Gray, et al., 2003). Validated performance tasks revealed high student involvement and, compared with non-LBD classes, significantly better collaboration skills, metacognitive skills (e.g. checking work, reflection) and science skills (e.g. fair testing, using prior knowledge). Unfortunately, the results of validated pre- and post-exams, mostly containing multiple choice questions, were less promising and showed no significant difference with respect to concept learning (Kolodner, 2002b; Kolodner, Camp, Crismond, Fasse, Gray, et al., 2003; Kolodner, Gray, et al., 2003), despite the fact, which will be discussed later on, LBD theoretically provides a sound basis for this. So it seems LBD makes students more skilful, but does not care for

better concept learning; as discussed before, a finding that is symptomatic of nearly all design-based science approaches. Therefore, this PhD study aims to investigate why this limitation in concept learning occurs and how concept learning can be enhanced. The series of studies will provide more insight in how students learn within design-based contexts and, strongly intertwined, how teaching affects students' performances. Finally, by investigating improvements, a sophisticated educational strategy for design-based learning environments can by developed.

1.2 The development towards design-based learning

According to Childs (2015), based on a literature review of curriculum development in science, there are three main emphases or themes in school science education: content (What to teach?), process (How science is done?) and context (Why science is done?). A brief description of how science education developed from the early twentieth century until now, can be done on the basis of these emphases where there is nowadays a general recognition that all three emphases are needed to create rich and useful science curricula.

Until the 1960/70s science education in Europe and Anglophone countries concerned mono-disciplinary subjects and was dominated by content: education in science (Childs, 2015). Science was seen as a subject for the higher social classes whit the aim for preparing students for university education and careers in science (Osborne & Dillon, 2008). Science education mainly focused on facts, concepts, principles and laboratory skills where content was dictated from above (top-down). This behaviourist mode of education equates science learning with changes in either the form or frequency of observable performance (Ertmer & Newby, 1993).

In the 1980/90s the attention was shifted towards scientific literacy and science for all. Mainly to increase students' understanding and motivation towards science. This, in respond to the increasing worldwide demand for citizens ready to face a more and more science-dominated world. Education in science became education about science, and context-based science education emphasised the application and relevance of science by learning in and through authentic contexts (Ratcliffe, 2001). According to the pedagogical methodology of context-based learning, there is the belief that both the social context of the learning environment (e.g. collaboration and collective knowledge building) and the real, concrete context of knowing are pivotal to the acquisition and processing of knowledge (Seel, 2012).This corresponds to Platteel, Hulshof, Van Driel, and Verloop (2013) that concept-context rich

education stresses the relevance of science, enhances deep processing and student performance, enhances transfer of knowledge and skills in students, and builds connections among subjects. In general, science education shifted towards cognitivism with a stronger emphasis on conceptualisation of students' learning processes and the way information is received, organised, stored and retrieved by the mind (Ertmer & Newby, 1993).

Since the start of the twenty-first century there has been an emphasis on twenty-first century skills, mainly because the modern world and economy are complex and much success lies in dealing with a wide-ranging and amorphous body of knowledge and skills (Pacific Policy Research Center, 2010). Knowledge and skills that are necessary to deal with multidisciplinary topics like global awareness, human health, environmental literacy, etc. Although it is difficult to provide an uniform list of those skills it is obvious that some of these skills correspond to science skills: e.g. critical thinking, problem solving, (scientific) reasoning, inquiry, communication and collaboration (Guest, 2005). This connection provoked an inquiry-based science curriculum where inquiry has the potential to be an important medium for centralising conceptual and procedural knowledge and skills in science (Hofstein & Lunetta, 2004). In general, inquiry-based learning includes problem-based learning and has the following characteristics: contextualised, problem-based, creating questions (by students), obtaining supporting evidence to answer questions, explaining the evidence collected, making knowledge-connections, and creating an argument and justification for an explanation (Krajcik et al., 1998; The Centre for Excellence in Enquiry-Based Learning, 2010). Thus, in brief, science education more and more embraced constructivism by associating learning with creating meaning from experiences (Ertmer & Newby, 1993).

Together with the entry of inquiry-based learning (IBL), more or less for the same reasons but particularly in the light of often multidisciplinary real-world contexts, interdisciplinary teaching came to the attention of curriculum developers (Commissie Vernieuwing Natuurkundeonderwijs, 2006). Especially in the case of science and technology education where already in the 1970s there was a vigorous international movement to promote integration (Geraedts, Boersma, & Eijkelhof, 2006). Science and technology often address the same real-world problems (contexts) and both disciplines share important content knowledge, skills and practices (Roth, 2001). Where both disciplines differ from each other they nowadays engage in a two-way interaction and learn from each other in mutually beneficial ways (Gardner, 1994; Murphy & McCormick, 1997; Roth, 2001). Historically, design technology frequently

preceded science because design realisations, like tools, instruments and artefacts, often were created without the explicit use of scientific content knowledge (Davies, 1997). Many technological creations more and more were used or even created by scientists to investigate scientific phenomena and therefore increased and improved scientific insights. In turn, those insights were used to produce more sophisticated artefacts. This interaction contributed to the development of the contemporary modern world where science and (design) technology are strongly interwoven.

This entanglement is used, inter alia by Kolodner, Camp, Crismond, Fasse, Hyser, et al. (2003), as a basis for nearly all design-based learning approaches where students have to explore and learn design-related skills and concepts that are needed for success by identifying a need to learn them, trying them out, questioning their handling and thinking, and iteration. An educational movement that also tries to provide design technology with a more conceptual basis, which is a necessity that has arisen since the 1980s when design as a learning context gained increasing momentum (Mawson, 2003). Back then, technology started to develop as a school subject (Ginns, Norton, McRobbie, & Davis, 2007) and design became, logically, the primary problem solving approach (International Technology Education Association, 2007). Literature gives a few main reasons, partly overlapping reasons why to choose inquiry as a learning context, why to choose design as a learning context.

- Collaborative learning (social aspect of learning): Design activities provide a rich context for practicing collaborative learning (Johnson, 1997). This takes into account that learning is not an individual process. In fact, students go through a collective knowledge building process by sharing experiences and ideas (Scardamalia & Bereiter, 1994). This is more or less similar to how engineers engage with peers and clients (Kolodner, Gray, et al., 2003).
- Reflective learning, feedback and iteration (focus on the learner): Successful design realisations arise by a process of continuous reflection on and evaluation of decisions taken based on heads- and hands-on activities. For example, by design drawings and presentations students externalise ideas and open them for critique and inspection (Roth, 1995), which makes students aware of their own thinking and doing (Johnson, 1997). Furthermore, failures are opportunities for testing and revising (new) ideas and insights, and therefore stimulate reflection. Design technology naturally involves iterations, which can contribute to iterative refinement in conceptual understanding and the learning of skills (Roth, 2001).

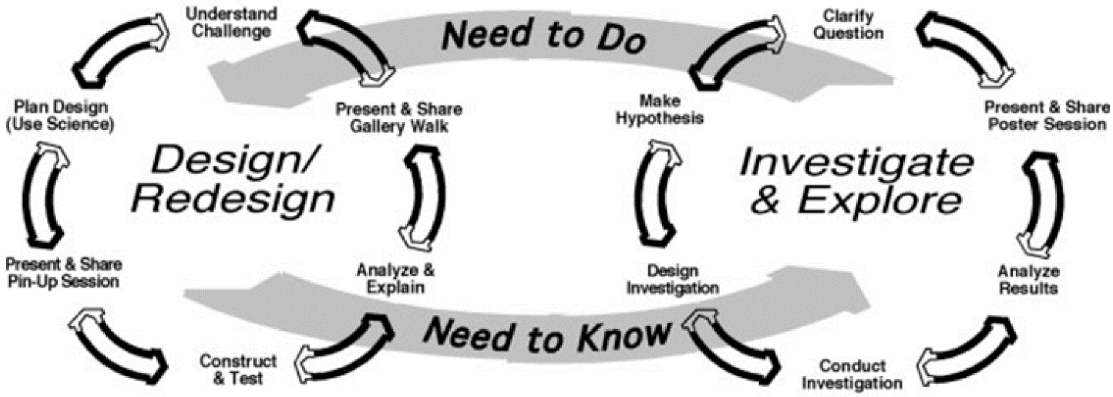
- Contextual learning (focus on the environment): Design outcomes are often based on and explainable by scientific principles, which implies that, nowadays, science and technology are strongly entangled in real-life (Commissie Vernieuwing Natuurkundeonderwijs, 2006; Rennie et al., 2012). Those contexts stimulate learning because people in their everyday are used to holistic problem solving and learning within the framework of real contexts (Lave, 1988).
- Learning by doing (focus on the task): Design builds the learning around an activity and students are deeply involved in the performative aspects of knowledge (Roth, 2001). A connection between knowing (concepts) and doing (skills) is provided, which is essential for learning (J. S. Brown, Collins, & Duguid, 1989; Jones, 1997). Design affords, just like IBL, the learning of communication, collaboration, (re)presentation and informed reasoning, but design offers more than that. Scientific inquiry is largely based upon carefully controlled tasks to ensure predictable conceptual knowledge (Murphy & McCormick, 1997). Design challenges are more open-ended, which emphasises the importance of divergent thinking (to find multiple solutions) and informed decision-making. By combining inquiry and design a large number of twenty-first century skills are addressed that is critical to innovation and in creating a competitive edge in modern complex economies (ICF & Cedefop for the European Commission, 2015).

Supplementary to the previous, design-based learning reflects the wish of the ITEEA, formerly ITEA, to stop using design mostly as an instructional strategy for product realisation (International Technology Education Association, 2007) where trial and error dominates the process (Burghardt & Hacker, 2004): the present standards for technological literacy emphasise and demand a conceptual design approach where, among others, science and mathematics are used explicitly for (improved) design realisation. This corresponds to Ginns et al. (2007) who state that since the birth of technology curricula there is a continuous struggle to conceptualise (design) technology and to facilitate conceptual learning, which is, as stated before, still a problem in case of design-based science curricula. To tackle this, students have to notice that, for example, procedural and conceptual knowledge and design activities cannot be divorced (Jones, 1997). One of the goals is to produce students with a conceptual understanding of (design) technology (International Technology Education Association, 2007). For example, students should focus on concepts behind design realisations such as properties of materials, construction techniques and knowledge of electric circuits, where the latter concerns this dissertation.

1.3 A description of LBD

LBD is, as mentioned before, a project-based inquiry approach where students learn, beside skills and practices, conceptual knowledge through achieving design challenges (Kolodner, 2002b). It combines two educational pedagogies that try to bring deeper learning into practice. First, problem-based learning (PBL): a task-centred cognitive apprenticeship approach that stimulates learning by collaboration, solving real-world problems and reflection (Norman & Schmidt, 1992). Second, case-based reasoning (CBR): a constructivist model of learning that refers to solving new problems by adapting old solutions or interpreting new situations in light of similar situations (Kolodner, Hmelo, & Narayanan, 1996).

Figure 1.1 Learning by Design's cycles



Reprinted from Kolodner (2002b).

Figure 1.1 shows that LBD is based on two interacting cycles of activities: "(re)design" and "investigate & explore". To achieve a design challenge students (operating in design groups) first have to explore and **understand the challenge**, inter alia, by gathering examples, studying underlying content, identifying learning issues, activating prior knowledge, and exploring criteria, constraints and design specifications. After exploration, each design group prepares a whiteboarding session for sharing things they need to know and learn for succeeding. During the teacher-guided whiteboarding session students **clarify questions** for investigation (science practice) and afterwards the scientifically formulated research questions enable design groups to **make hypothesis** by using (prior) knowledge. Then,

design investigation takes place by identifying important variables and creating fair tests for finding answers to the research questions, whereupon design groups will **conduct investigation** and collect data. Based on collected data, students try to provide answers to the research questions. For this, they **analyse results** and apply scientific reasoning to compare predictions, provide explanations and to make design recommendations. To share research results with other design groups a poster is created for a teacher-guided **poster session**. During the poster session procedures, results and conclusions are discussed and used for creating (scientifically formulated) design rules of thumb by taking into account design principles and specifications. Thus, by carrying out investigations students learn things they "need to know" in order to notice what they "need to do". During the next stage **design planning** takes place by generating ideas (divergent thinking), sketching ideas, predicting functionalities and trying things out. This results in a provisional design solution that is presented during a teacher-guided **pin-up session**. After this session, the provisional design solution is revised by taking (peer) feedback into account, after which the **construct and test** stage begins. During this stage the design solution is transformed into a tangible artefact that is tested according to the design specifications. This is done by running tests, collecting data and interpreting results. These results are necessary to **analyse and explain** the artefact's functionality and to establish shortcomings, which offers input for redesign and improvement. During a teacher-guided **gallery walk** the final design is presented and discussed. This activity is also used to explain the design's functionality scientifically and to establish further topics for redesign and reinvestigation.

In summary, teacher-guided activities (whiteboarding, poster session, pin-up session and gallery walk) are crucial to incentivise the understanding of design-related concepts. During these activities experiences and insights are shared among groups, feedback is being given and science is being discussed. In short, students learn concepts and skills needed for success by identifying a need to learn them, trying them out, questioning their handling and thinking, and acting again (iteration). A detailed description, which can also be found in Kolodner, Camp, Crismond, Fasse, Gray, et al. (2003), will be given in the next chapters by discussing the LBD challenges developed for the research.

1.4 Knowledge transfer

Because concept learning is central to this research, it is important to explain how LBD aims for this. LBD is a constructivist approach where students experience the necessity to learn (Kolodner et al., 1996). This necessity is driven by the fact that students' pre-task conceptions are not sufficient for succeeding: design challenges deliberately address cognitive conflicts. Students need to develop a more scientific knowledge framework to tackle conflicts and reach conceptual change (Abdul Gafoor & Akhilesh, 2013; Cobern, 1994). In compliance with Nussbaum and Novick (1982) and Cosgrove and Osborne (1985), LBD contains four main elements for conceptual change. First, students explore their pre-task conceptions (preliminary phase). Second, students become aware of their own and other's conceptual shortcomings (focus phase). Third, students investigate and explain the conceptual conflict (challenging phase) and, fourth, students adopt the new conceptual model (application phase). Based on literature, e.g. Brandsford, Brown, Donovan, and Pellegrino (2003), LBD contains several elements that promote conceptual change: collaboration, reflection, contextual learning, applying what is learned, learning from failures and iteration, and connecting skills, practices and concepts.

When students reach a certain level of conceptual change, this is managed within the design context where the presence of this context enhanced the learning process and strongly determines the level of conceptual performance (Murphy & McCormick, 1997). In that way, the newly adopted conceptual framework is contextualised, which hinders students to de- and recontextualise conceptual knowledge with respect to different contexts (Lin, Hu, & Tsai, 2010; Murphy & McCormick, 1997; Sidawi, 2009). This process of mastering task-related knowledge, decontextualising knowledge, recognising transfer opportunities and making an effective knowledge transfer (recontextualising) corresponds with the higher levels of Bloom's taxonomy (Krathwohl, 2002) and represents deep conceptual understanding. LBD tries to foster knowledge transfer in several ways, listed below, that are all consistent with what studies of human cognition tell us about promoting transfer (Kolodner, Gray, et al., 2003).

- Encoding: LBD students learn by acquiring experiences (cases) and encoding them actively. During encoding students extract, supported by the teacher, essential design-related concepts. By intentionally interpreting experiences to extract lessons from it, students will be able to recall and apply knowledge-based

experiences later on. For this, sharing and refining ideas publicly with peers is a key feature (Lewis, 2006). In general, we can say that students will learn those things they focus on.

- Failures: LBD students are allowed to make failures, which is critical to learning (Kolodner, Gray, et al., 2003; Lewis, 2006). Failure has the affordance of focussing a student on what is need to learn. Provided with proper feedback it will allow students to understand underlying principles, to recognise future failures and to make more sophisticated decisions.
- Iteration: LBD students never learn on the basis of an one-time experience, but encounter an iterative learning cycle (Kolodner, 2002a). Students periodically recall prior (encoded) concepts and skills. By doing this, students are afforded to deepen encoded knowledge and to extend their focus and understanding.
- Teacher guidance: during teacher-guided LBD rituals students are assisted to turn experiences into well-encoded and well-interpreted cases in their memories.
- Reflection: By fixed moments of deep reflection students are stimulated to intensify their learning. Reflection strengthens the effect of all previous aspects.

1.5 Research questions

According to the previous, the main goal of this research concerns an enhancement of concept learning through design-based learning activities. This leads to the following central research question:

Why the current practice of design-based learning not yet leads to an expected high level of concept learning, and how learning can be enhanced resulting in an educational strategy where the learning of concepts and skills both are strongly represented?

Furthermore, in the longer term the research serves a higher purpose. Improving the pedagogy of design-based learning only makes sense when (future) teachers are able to adjust to the new kind of classroom control. According to Kolodner (2002a), a first important step towards this purpose is to let teachers experience design-based learning as their students will, after which teachers and experts concurrently reflect on experiences to extract what is important and to move forward. To facilitate this, beside general secondary education students (from now referred to as "students"), student teachers are involved in the series of studies; initially as study population and gradually as (participating) research assistants.

As discussed in section 1.1, addressing LBD offers a solid starting point for the research. A first step will be a detailed analysis of the LBD practice. The results of previous LBD studies were based upon validated assessment tasks, conducted before and after the learning intervention. A detailed analysis of the LBD practice itself, studying why and when students learn conceptual knowledge during LBD, had less attention, despite the fact it could provide more insight into the process of concept learning. This point of interest leads to a first set of sub-questions.

1. When and how, during LBD, students use science for design purposes and how students demonstrate an understanding of scientific concepts?
2. What learning strategies, which can enhance deeper learning of science, are yet missing and how this absence affects learning?

A second set of research questions follows from educational literature that claims conceptual learning is highly teacher dependent (Bamberger & Cahill, 2013; Van der Veen & Van der Wal, 2012). Using design faces teachers with an open-ended nature where teachers must relinquish directive control (Burghardt & Hacker, 2004). As a result, teachers leave or undermine LBD activities because they cannot adjust to the new classroom control (Wendell, 2008). Thus, it is worthwhile to study the interplay of teaching and concept learning in depth to help teachers to develop proper pedagogical strategies. For this, the following sub-questions are leading:

3. What teaching strategies dominate and (directly) affect the learning of science content and, by analysing all teaching interventions during LBD, what is the relative number of interventions that directly appeal to these strategies?
4. Which teaching strategies, based on the answer to the third question, should get more attention to enhance concept learning?

Based on the answers to questions 1 to 4 it will be possible to adapt LBD for better concept learning. Then, by implementing improvements and trying them out, it becomes clear to what extent concept learning is enhanced. This matter leads to the third, and final, set of research questions.

5. How the pedagogical structure of design-based learning activities can be improved based on the research?
6. By how many the students' conceptual learning gain will (further) increase due to application of improvements and how the learning of skills is affected?

1.6 Research design and method

The development of a sophisticated educational strategy for design-based learning activities is central to the research. Based on previous educational research there are several approaches that can be taken into consideration: experimental research, action research, formative research, developmental research and design-based research (Wang & Hannafin, 2005).

Experimental research usually focuses on a single set of variables where other variables are controlled in a laboratory setting. This control is hard to realise in educational settings since variables cannot be clearly distinguished (The Design-Based Research Collective, 2003). Moreover, this control is not always desirable because insight in distracting effects, which are often present in learning contexts and sometimes critical to the results of learning experiences, may enrich the research (Abdallah & Wegerif, 2014). Ruling them out can cause quasi valid outcomes that are only valid within a standardised experimental setting (Sandoval & Bell, 2004).

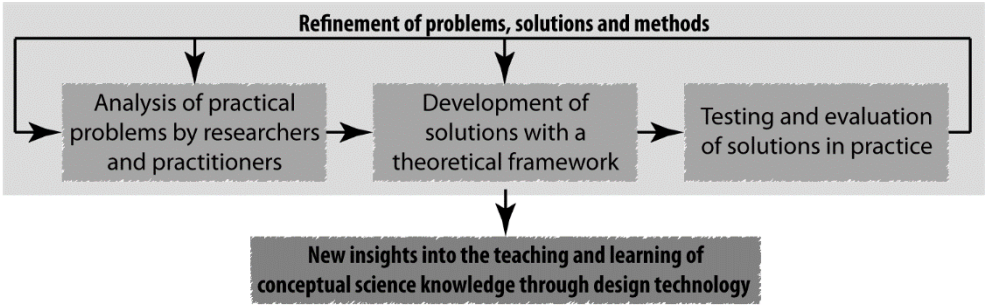
Action research seems to be a more suitable approach because it identifies educational problems accompanied by subsequent actions for improvement. The research itself is immersed in the context of educational practice, and therefore exposed to the wide range of interactions education includes (Stringer, 1999). However, action research primarily focuses, just like formative research, on solving practical problems where practitioners, and not researchers, take the leading role (Anderson & Shattuck, 2012). In that way, action research and formative research can be categorised as evaluation methods rather than research paradigms (Barab & Squire, 2004). The research topic central to this dissertation also asks for the development of (new) educational design principles and corresponding theoretical insights where both practitioners and researchers are involved.

That brings developmental research into the scope of the dissertation. This approach is known as the systematic study of educational processes where the creation of knowledge, grounded in data systematically derived from practice, is of primary importance (Richey & Klein, 2005). It offers a pragmatic way to test theory and to validate practice. However, according to Richey and Klein (2005) and Van den Akker (1999), it not specifically aims for designing (instructional) interventions to improve a specific kind of educational practice. The purpose of developmental research is rather to assess changes (e.g. in learning outcomes) over an extended period of time for generating theoretical insights. Therefore it is worthwhile to search for a method that combines elements of action research, formative research and

developmental research in order to improve educational practice, to generate specific educational design rules and to complement educational theory.

Design-based research (DBR) is a research method that responds to this wish because it aims to improve educational practices through systematic, flexible and iterative review, complemented by design, implementation, analysis and development. All based upon collaboration among researchers and practitioners in real-world settings where the development of (new) design principles and theories is an end in itself (Wang & Hannafin, 2004). See Figure 1.2. No less importantly, DBR has been proven to be successful in delivering on the objectives it sets (Hake, 2004; Sandoval & Bell, 2004) and therefore the methodology of DBR was leading for the dissertation's research design. Deciding for DBR has some important implications for the research design. Those implications directly arise from limitations associated with DBR, which can be categorised in three major aspects.

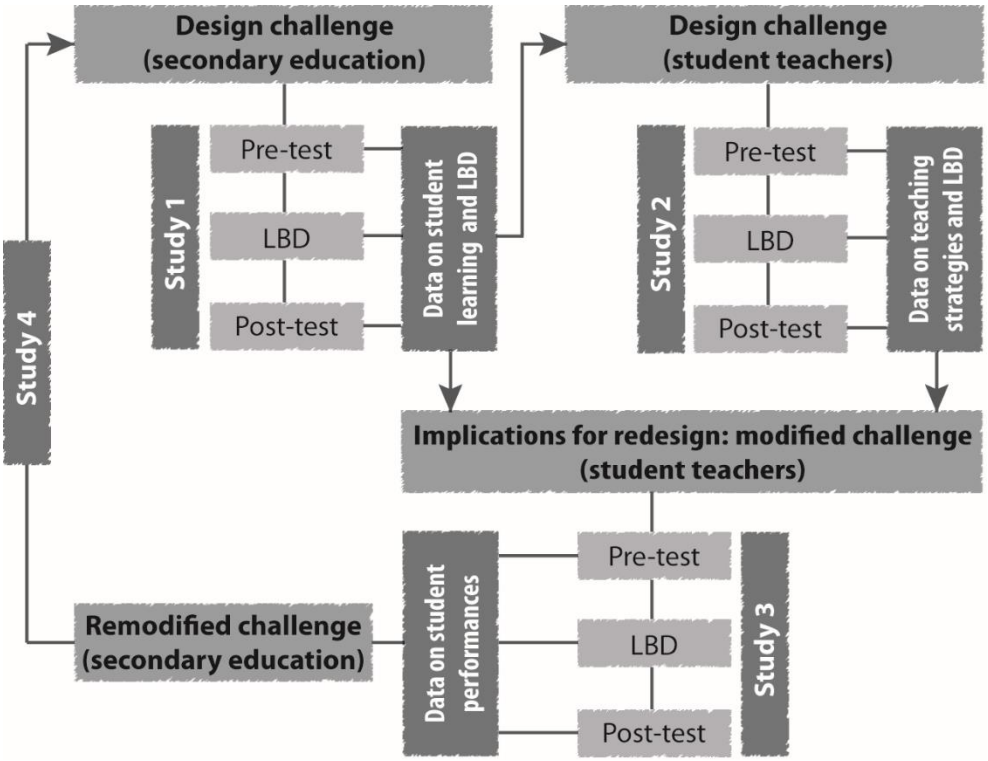
Figure 1.2 DBR approach



1.6.1 Time constraints

DBR involves a long-term and intensive period of research where the number of interacting studies and the amount of data collected is large and analysis requires extended time (Herrington, McKenney, Reeves, & Oliver, 2007; Wang & Hannafin, 2004). Therefore, many avoid DBR as a research approach for PhD studies where completion is desired in four to five years. To make DBR workable for PhD studies a research design is suggested by Abdallah and Wegerif (2014) and Herrington et al. (2007), which has proven to be successful. This approach, which is directive for the research discussed in this dissertation, resulted in the iterative research design in Figure 1.3 that shows how the individual studies need to interact, as a variant to traditional time-consuming longitudinal approaches, to provide meaningful results.

Figure 1.3 Iterative research design



During the preliminary research phase an exploration of the educational context takes place. Initially through review of literature and the development of a conceptual or theoretical framework for the research. This framework is leading for making hypotheses (and providing a certain amount of focus) and planning data collection and analysis. Then, preliminary empirical data is collected through one or more (related) exploratory studies within the educational context, and with a strong emphasis on qualitative analysis of the learning and teaching process. During this phase pre- and post-testing has a subordinate role and is, for example, just used to explore learning outcomes. In our case Studies 1 and 2 reflect this phase. These strongly related studies unravel the teaching and learning process of LBD, based on a theoretical framework, which results in possible design rules for improvement of the educational setting. The next phase (prototyping), the third study in Figure 1.3, is a first step in improving and refining the intervention. Suggested improvements are implemented in the educational strategy and tried out. For collecting and

analysing data, methods used during the preliminary studies are (partly) adopted and refined or complemented. During this stage qualitative data again is of major importance to find out how modifications work out in practice and what remodifications are left over. Also pre- and post-testing becomes increasingly important to supplement qualitative data with quantitative data on (improved) student performance. Finally, during the assessment or reflective phase (Study 4), a final set of improvements is tried out with a stronger emphasis on quantitative data on students' performances, whereupon final recommendations for the improvement of the educational strategy and corresponding (new) theoretical insights are established. In general, changes in data collection and analysis during Studies 1 to 4 correspond to Hake (2004) who suggests that a mixed methods approach is fundamental to DBR where the emphasis moves from qualitative to quantitative data. Also Abdul Gafoor and Akhilesh (2013) state that pre- and post-testing is eventually a useful tool to verify effects of an adapted intervention.

1.6.2 Credibility

According to Anderson and Shattuck (2012) objectivity, reliability and validity are important criteria for ensuring research credibility. Because DBR researchers are emerged in the research practice, it is difficult to guaranty objectivity and to avoid subjective interpretations of phenomena (The Design-Based Research Collective, 2003). This latter directly interferes with the reliability of the research because, for example, the analysis of qualitative data, although based on clear agreements, entails a certain amount of interpretation and therefore is not completely objective. Furthermore, reliability is affected because it is difficult, if not impossible, to collect and interpret data under exactly the same circumstances (Wang & Hannafin, 2004). This is, of course, partly due to the complex educational context the research takes place in, which also can cause validity problems. Despite the fact it is possible to select and use valid instruments and methods for data collection and analysis, it remains difficult to determine causality between multiple kinds of quantitative and qualitative data (The Design-Based Research Collective, 2003).

In response to the credibility issues discussed, literature provides several ways to deal with them and to eliminate bias and subjectivity. We will briefly discuss some of these aspects, which will be addressed in Chapters 2 to 5 in detail. First, as discussed before, a solid theoretical basis was used to inform the research, to design and improve interventions and to prepare data collection and analysis. In general,

validity was strengthened by the alignment of theory, design, practice and measurement (The Design-Based Research Collective, 2003). Second, to enhance reliability and validity we used several types of triangulation: e.g. multiple researchers and practitioners, coherent data collection methods, multiple theoretical resources, and an iterative research design. Third, based on Wang and Hannafin (2004), conclusions derived from data analysis were, at times, complemented with retrospective verification (focus group, member check, and peer review). Fourth, co-researchers, practitioners and participating students were to a limited extent informed about hypotheses, expectations and research objectives. Mainly to prevent, as mentioned in A. L. Brown (1992), research bias (confirmation or observer bias) and response bias (demand characteristics and social desirability).

1.6.3 Generalisability

Maybe the biggest challenge for DBR, mainly because DBR is strongly contextualised, concerns generalisability: the extent to which results, coming from a particular situation or sample, are transferable to a wider population or other settings, contexts or times (Maxwell, 2002). According to Van den Akker, Bannan, Kelly, Nieveen, and Plomp (2013) generalisability of DBR not directly comes from results that are generally true. DBR has to invest in analytical forms of generalisation. What is generalised is a way of developing, conducting, analysing, interpreting and understanding specific cases. In general, heuristic statements have to be given (both substantive and methodological) to enable researchers and practitioners to investigate their own educational context and to distract credible conclusions. In other words, generalisability of results is in some way ignored in favour of enriching the local understanding of multiple different situations. Then, by combining results across multiple studies and iterations, it is possible to make generalisations with respect to (new) theoretical insights and design rules and how they have to interact in a broad range of educational settings (Anderson & Shattuck, 2012; The Design-Based Research Collective, 2003).

According to the previous, the research central to this dissertation is still in its infancy and will especially focus on analytic generalisability. Nevertheless, it will reveal important learning- and teaching-related ingredients and a promising educational strategy for design-based learning units. Altogether, which will be discussed in detail in Chapter 6, it offers the opportunity to expand the research to other educational contexts and to distract general results.

1.7 Dissertation outline

As shown in Table 1.1, this dissertation is made up of six chapters where Chapters 2 to 5 are adapted from journal articles. Therefore, they may show some overlap with each other and the general introduction. For example, the introduction discusses the relevance and aim of the research, research questions and the foundations of LBD. Of course these items are also addressed by the individual chapters. Furthermore, the introduction gives a brief description of the historical development towards design-based learning and an overview of how the different studies form an entity necessary to obtain answers to the research questions.

Chapter 2 presents the first study that concerned general secondary school students. Those students were challenged by a traditional LBD task to design a battery-operated dance pad that let them use their feet to sound a buzzer or flash lights. Insight is given in how the scientific objectives are linked to the design challenge and how students are facilitated to learn scientific design principles. Based on a developed theoretical framework of coherent aspects important for concept learning, data on the LDB process is analysed. The results reveal why a limited conceptual learning gain was sufficient for successful design realisation. Finally, the discussion describes how students address and learn science during LBD and, allied to that, what important learning-related limitations can be deduced from the data.

Chapter 3 complements the framework for learning, developed for the first study, by teaching skills important for facilitating concept learning. Furthermore, the design of a LBD challenge for student teachers is discussed where students had to design a highly efficient solar power system for a model house. Based on the framework of teaching skills, data is presented that shows how the skills were addressed by two teacher trainers during the challenge. Finally, it is revealed which teacher behaviour is naturally excited by the LBD approach and which strategies should get more attention to enhance concept learning.

Chapter 4 presents the third study that is built upon the challenge of the second study where the solar power challenge is improved, based on the findings of the first and second study, for better concept learning. After an explanation of the modifications, the chapter reveals to what extent concept learning was enhanced and whether the improvements affected the learning of skills. For the sake of completeness, it is revealed which skills strongly interact with concept learning. Furthermore, the chapter discusses experiences with concept mapping as an alternative way to measure conceptual learning gains.

Chapter 5 brings together the results of all previous studies. For this, the dance pad challenge, developed for the first study, was adapted for better concept learning based on (re)modifications that concerned the third study. By presenting the conceptual learning gains for 110 secondary school students, it is revealed how the adjustments act on a larger scale. A second group of 127 students were exposed to the same but, based on the results of the third study, slightly further improved challenge. Those improvements mainly tackled problems that were left with respect to fragmentation of the task and science addressed. Finally, the chapter presents a revised educational strategy for design-based learning activities where the learning of skills and concepts both are of fundamental importance.

Chapter 6 provides an overview of the main findings per study including the answers to the research questions. A vital part of this chapter is also the discussion of the implications for educational practice, the limitations of the research and suggestions for further research.

Table 1.1 Overview of the chapters and studies

Chap.	Study	Title	Quest.	Participants				Data collection					
				S	ST	TT	T	Ass	Que	Int	Obs	Lit	Foc
1		General introduction											
2	1	Concept learning by direct current design challenges in secondary education	1,2	●	●		●	●	●	●	●	●	
3	2	Teaching strategies to promote concept learning by design challenges	3,4		●	●		●	●	●	●	●	
4	3	Explicit teaching and scaffolding to enhance concept learning by design challenges	5,6		●	●		●	●		●	●	●
5	4	The FITS model: an improved Learning by Design approach	5,6	●	●	●	●	●					
6		General conclusion and discussion											

Chap. = chapter; Quest. = research question number (according to section 1.5); S = student (secondary education); ST = student teacher; TT = teacher trainer; T = teacher (secondary education); Ass = performance assessment; Que = questionnaire; Int = interview; Obs = observation; Lit = literature; Foc = focus group.

2

Concept learning by direct current design challenges in secondary education

This chapter has been published in adapted form as:
van Breukelen, D. H. J., de Vries, M. J., & Schure, F. A. (2016). Concept learning by direct current design challenges in secondary education. *International Journal of Technology and Design Education*. Advance online publication. doi:10.1007/s10798-016-9357-0

2.1 Introduction

As discussed in Chapter 1 science and technology play an important role in our modern world and international studies indicate this is not followed by an increasing interest in and understanding of science and technology among juveniles. To counter this, more meaningful and motivating teaching methods based on interdisciplinary teaching are necessary (Lustig et al., 2009; Osborne & Dillon, 2008). In response to this, the integration of science, technology, engineering and mathematics (STEM) has become a main topic within educational systems (Rennie et al., 2012) where (designing) technology, due to its wide contexts and informative activities, has the means of becoming the catalyst for integration (Clark & Ernst, 2007).

Based on Roth (2001), design is described as the entire set of activities that leads initial vague ideas through construction and testing of prototypes to a final model. The potential of teaching science through design is that the design task provides the context for applying science knowledge, and science provides content needed for design realisation. Many attempts to respond to this strong interplay appear to be unsuccessful (Lustig et al., 2009; Osborne & Dillon, 2008). Nevertheless, LBD shows that integration can bring significantly better collaboration skills, metacognitive skills and science skills. As discussed in Chapter 1, previous studies showed that LBD students learn scientific concepts as well or slightly better (not significant), compared with non-LBD students, with respect to knowledge transfer. However, LBD students performed significantly better at a wide range of skills. So it seems LBD makes students more skilful but does not care for better concept learning.

This is notable because, as described in Chapter 1, LDB theoretically provides a sound basis for concept learning. Thus, what factors impede concept learning? The results of previous LBD studies were based on a set of validated performance tasks and multiple choice tests conducted before and after the learning intervention. A detailed analysis of the LBD practice itself had less attention, despite the fact it could provide more insight into the process of concept learning. Therefore, this will be the main objective of this study.

To gain insight into a hypothesis that states why concept learning is limited and to provide the study with important points of interest, literature upon design-based learning is helpful. Nearly all design-based science approaches are complex because many objects of integration (e.g. skills, practices, attitudes and content) are combined and remain under-exposed (Berlin & White, 1994). Various studies give similar focus-related explanations for this. For example, expert designers focus on

content because skills, practices and activities are familiar. Novices mainly focus on process-related issues, needed for success, in which content is largely overlooked (Popovic, 2004). Wendell (2008) states that scientific content may not emerge because students focus on doing. For this, they try to avoid unknown content areas because of complexity and diversity of hands-on activities that mainly dominate the process. Students rather rely on prior knowledge and assumptions (trial and error). Thus, a lack of focus on content and a dominant process focus might cause limitations in concept learning. Therefore, this study investigates where students (senior general education) focus on during LBD and, more specific, how and when scientific content is addressed and what students learn from it. Eventually, implications can be deduced for better concept learning and further research.

2.2 Method

For this study the methodology of design-based mixed methods research was chosen. Beside quantitative data about learned science, qualitative data is necessary to investigate the learning process by a thorough analysis of events. The study took place in the second grade of general secondary education. 77 students (aged 13 - 14; 33 females and 44 males), spread over three adjacent classrooms, were involved accompanied by three teachers. All students and teachers had prior experiences regarding characteristic LBD components, but the students had no specific prior knowledge with respect to the scientific design-related content.

2.2.1 Design of the challenge

The LBD task "Back to the Nineties" was related to the physics domain "direct current electric circuits" and design groups (three students per group, randomly chosen) were challenged to build a battery-operated dance pad that let them use their feet to sound a buzzer or flash lights. The dance pad had to consist of four operating floor pads and one main power switch. The entire activity took five to six class periods of 100 minutes and was guided by an instructive presentation and a student's and teacher's guide. To accomplish the task, design specifications were formulated, shown in Table 2.1, that stimulated the use of underlying science (A to D) and the process of decision-making and creative thinking (E to G).

Table 2.1 Design specifications and materials

Design specifications			
A. The readily available push button serves as main power switch.			
B. One self-designed floor pad, circular shaped, should flash a light by being stepped on it.			
C. One self-designed floor pad, triangular shaped, should flash a second light by being stepped on it.			
D. To sound the buzzer, two self-designed floor pads, cross and rectangular shaped, must be pushed on simultaneously (with two feet).			
E. It is not allowed to use more design materials than available.			
F. The dance pad consists of one piece and can be used frequently without failure.			
G. The dance pad has a nice design (an eye candy) and is easy to use.			
Material	Quantity	Material	Quantity
1,5-volt AA battery (and holder)	2 (1 holder)	Push button	1
Aluminium foil	1 roll	Light bulb (and holder)	2
Coloured cardboard (40 x70 cm)	4 sheets	Buzzer	1
Tape (one- and double-sided)	2 rolls	Electrical wire	500 cm

Regarding specifications A to D, the most fundamental (scientific) design principles concerned proper wiring (combining series and parallel parts) and a proper use of conducting and insulating materials for floor pad creation. Figure 2.1 shows an example of a design outcome and wiring. To investigate and design electric circuits, students used real experiments and an interactive simulation (PhET™ DC-circuit construction kit). Beside proper circuit creation, the design challenge sets for more scientific objectives. Table 2.2 shows all objectives and their initial appearance.

Furthermore, Table 2.3 shows, which LBD stages and activities took place to guide the process and to help students to understand underlying principles. In addition, the modifications listed below, mainly concerning the usage of modern learning resources, were implemented to enrich the original LBD approach.

- A fully equipped (online) electronic learning environment (ELE) with guidance for each design stage, background materials regarding skills and practices and space to collect (requested) writings, pictures, sketches, simulations, etc.
- The possibility of using tablets, laptops and smartphones for the digital design diary and to access digital resources like the internet and simulation software.
- The obligation to build virtual simulations in addition to real experiments, based on Finkelstein et al. (2005).

Figure 2.1 Design outcome and wiring

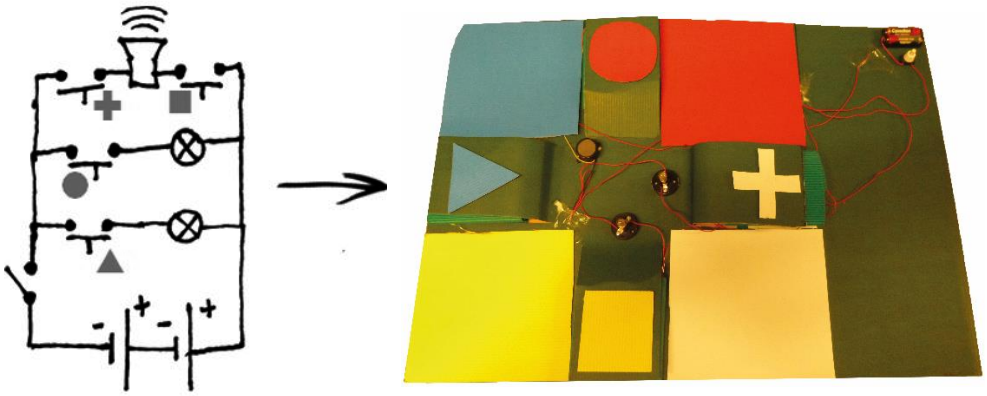


Table 2.2 Scientific objectives and initial appearance

DC electric circuits objectives	Appearance
1. Students can describe properties of direct current: (A) Conservation of current: current will not be consumed in a circuit; (B) Current can be seen, based on an educational model, as a substance for energy transportation.	• The interactive simulation shows current flow and enables current measurement. • Real experimentation enables students to measure current flow.
2. Applying the fact that a battery is an energy source and the driving force behind current flow. Beside a closed circuit, this force is a prerequisite for a functional circuit.	• The effect of a power supply and circuit switching is explored during experimentation. • Dance pad operation is based on circuit switching.
3. Knowing the effect of series and parallel switching on current flow (through a battery): parallel components increase and series components decrease current flow.	• Similar to objective 1
4. Recognising and designing series, parallel and combined circuits and, with respect to this, identifying and describing circuit operation.	• Operation is based on proper wiring. Students have to meet design specifications A to D. • Wiring can be studied by experimentation.
5. Students know that conductors and insulators influence current flow: conductors enable and insulators impede current flow.	• Students have to design floor pads by combining conducting and insulating materials (design specifications B to D).
6. Students know that circuits (in daily life) have a purpose in transforming an input into an output.	• The dance pad is a daily-life example of a system based on an electric circuit.

Objectives adapted from Oorschot et al. (2014).

Table 2.3 Stages and activities

Stages (time)	Activities[a]	Final products[b]
1. Introducing the design challenge (20-30 min)	Introduction of context, design challenge, activities, organisation, learning sources, time schedules, materials, objectives, etc. (C)	
2. Understanding the challenge, messing about, whiteboarding (50-60 min)	• Exploration of the challenge, learning context and objectives (G) • Writing down ideas, (research) questions and hypotheses (G): what to do and learn? • Whiteboarding: sharing results, feedback (C)	Design diary stage 2 • Flip chart for whiteboarding (G)
3. Investigate & explore, poster session (120-180 min)	• Formulate and distribute (scientific) research questions (C) • Discussion "fair test rules of thumb" (C) • Design and conduct experiments, collect data, conclude (G) • Presentation: poster session, feedback session (C) • Discussion about results and fair testing: redoing/adjustments (C/G)	Design diary stage 3 • Final research questions (C) • Fair test rules of thumb (C) • Laboratory notebook (G) • Poster (G)
4. Establishing design rules of thumb (20-30 min)	• Determination of design rules by using experiment results (C) • Focus on science content involved: use of science vocabulary and concepts (C)	Design diary stage 4 • Design rules of thumb (C)
5. Design planning, pin-up session (80-90 min)	• Devise, share and discuss design solutions: divergent thinking (G) • Poster: provisional design solution (G) • Pin-up session (posters): feedback session (C) • Adjusting the provisional design solution (G) • Redoing until satisfied: final design solution (C/G)	Design diary stage 5 • Design posters (G) • Design sketch (G)
6. Construct & test, analyse & explain, gallery walk (120-180 min)	• Prototyping and design realisation (G) • Testing the design based on design specifications (G) • Gallery walk: determine shortcomings; feedback/reflection (C) • Adjustments of design solutions and rules (C/G)	Design diary stage 6 • Prototype (G)
7. Iterative redesign (60-120 min)	• Iteration of steps depending on decisions made (C/G) • Improving the design (G) • Final discussion about design solutions and scientific concepts (C)	Design diary stage 7 • Final solution (G) • Final reflection (individual)

C = class activity or product; G = design group activity or product.

[a] Available resources: ELE, smartphones, laptops, tablets, Microsoft Office ® software, interactive simulation, internet access, materials and tools for design realisation, materials for conducting experiments.

[b] Design diary (ELE-archived): reflections, feedback, descriptions and pictures/movies. Bulleted lists are stage-specific.

2.2.2 Framework for learning

Because the students' focus and the way they use and learn science from that is the main topic of this study, literature was studied to become more informed about elements related to concept learning. This resulted in three important, closely connected, elements that were helpful in collecting and analysing qualitative data. According to Horton (2006), as shown in Table 2.4, a learning activity has three essential types of interaction that should contribute learning. Within these interactions five important intertwined activities can be specified. Maybe not surprisingly, all elements in Table 2.4 are, to a greater or lesser extent, part of the LBD approach.

2.2.3 Data collection

To get informed about the (advancement of) students' mastery of content knowledge pre- and post-exams (multiple choice) were used. The same exam was used for pre- and post-testing and a control group (n = 26), not taught the task-related content, was used to rule out knowledge absorbing from taking the test. Questions were based on validated multiple choice tests that proved to uncover students' (mis)conceptions (Engelhardt & Beichner, 2004; Licht & Snoek, 1986; Niedderer & Goldberg, 1993). The exam consisted of 20, objective-linked, questions. Each objective was served by pairs of similar conceptual and contextual questions to investigate differences in de- and recontextualisation (transfer). Figure 2.2 shows two examples of paired questions.

During the challenge direct non-participant observations took place to investigate students' and teachers' behaviours and actions. The event- and scan-based observations mainly focused on occurrence, frequency and (indirectly) absence of events. The observations were guided by observation forms to respond to the simultaneous occurrence or close temporal proximity of events. These forms included a list of behaviours and events, grouped by the learning-related key elements in Table 2.4, with space for describing the observation in detail.

During the learning task sound recordings were made of teacher instructions, teacher-student interaction, collaboration between students within design groups and class activities. Sound recordings provided authentic data (regarding the content of explication, reflection and feedback) and expressed students' thoughts and use of science vocabulary. Especially, because students were encouraged to think aloud.

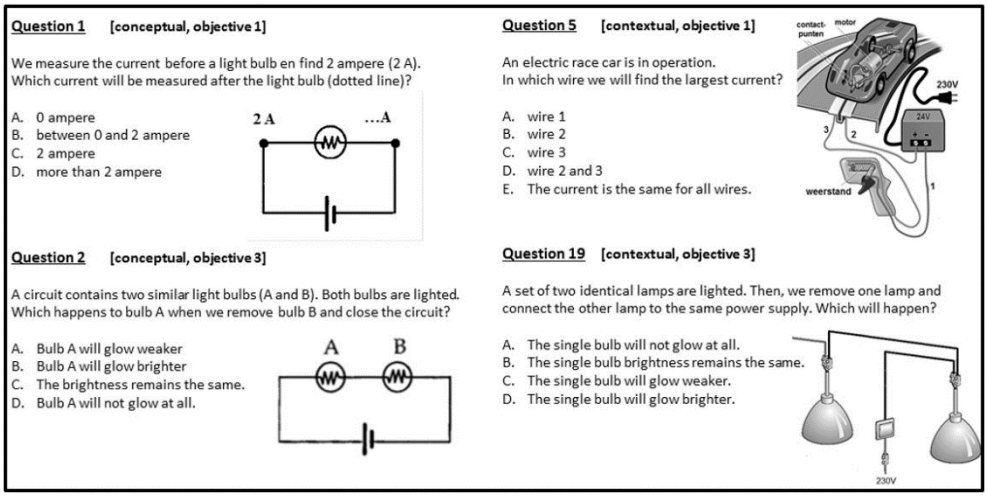
Table 2.4 Learning-related interactions and elements

Type of interaction	Learning-related elements
1. Student (to student) interaction	(A) COLLABORATION. Sharing information enriches the individual learning process and fortifies knowledge building (Parkinson, 2001; Roth, 1995). Sketching and drawing help students to externalise and share ideas and it allows peers to review ideas (Popovic, 2004; Roth, 2001). The presence of the construction materials and tools, which are necessary for design creation, stimulates peer discussion about scientific concepts (Murphy & Hennessy, 2001; Roth, 2001).
	(B) REFLECTION. Reflecting on knowledge, skills, practices, attitudes and received feedback makes students more aware of doing and thinking and stimulates to maintain strengths or to make adjustments. Student collaboration provides input for reflection (Roth, 1995).
2. Student to teacher interaction	(C) TEACHER AND PEER FEEDBACK. Providing feedback and receiving peer and expert feedback is invaluable for teaching and learning. Constructive feedback, also important for self-reflection, provides insight into doing and thinking and reveals students' strengths and weaknesses (Kolodner, 2002a; Kolodner, Gray, et al., 2003). Constructive feedback is relevant, goal directed, well timed, behaviour focused, collaborative, factual and respectful (Wiggins, 2012) and focuses on knowledge, skills and attitudes.
	(D) EXPLICIT TEACHING. Students often solve problems intuitively by using their awareness and prior knowledge (Hennessy & McCormick, 1994; Roth, 1995). Students rarely solve problems in a strategic way by using (scientific) domain-related knowledge (Parkinson, 2001). Also new insights are rarely linked to underlying concepts. All of this, results in trial and error behaviour (Popovic, 2004). To prevent this, teachers should help students making strategic decisions and knowledge domain connections (Kolodner, Gray, et al., 2003; McCormick, 1997). By doing this, processes and content become explicit (Hennessy & McCormick, 1994).
3. Student to content interaction	(E) PROCESS-RELATED ISSUES. First, mistakes are an important learning source and provide information about students' (mis)conceptions. Thus, mistakes must not be corrected prematurely but should be provided by feedback (Kolodner, Gray, et al., 2003). Second, experiencing different contexts in which the same concepts occur fortifies learning because students' knowledge is always context related and not directly related to decontextualised knowledge domains. Through de- and recontextualisation, complemented by explication, understanding is supported (Brandsford et al., 2003; Fortus et al., 2004; Johnson, 1997; Parkinson, 2001). Third, time pressure impedes learning because students do not take ownership of the learning process (Murphy & Hennessy, 2001). Encouraging students, by using positive and constructive feedback, is to be preferred. Fourth, to incentivise the learning process sufficient control of the classroom management and organisation is needed (e.g. through clear instructions and high-quality learning materials) (Bruinsma, 2003). However, it is very important that teachers know when to intervene and when to hold back: sensitive assistance (Murphy & Hennessy, 2001).

Questionnaires (mostly open-ended) were used to ask students to reflect on the learning process. Questions were based on the STARR method that provides a framework for proper reflection (Verhagen, 2011). Especially, students were asked to express their opinion on learning outcomes, disturbing elements and activities that stimulated learning. Questioning took place after the learning intervention and included all students.

For deeper understanding of students' answers, retrospective interviews took place at the end. Stimulated-recall techniques were used to investigate the extent to which students used science consciously; according to literature a rich source of data (Popovic, 2004; Rennie et al., 2012; Roth, 2001). In preparation for this, student products were studied to become informed about science used and the successfulness of design outcomes. Visible scientific elements were noted and served as stimulus during interviews. Sixteen students, the number data occurred to be saturated (Mason, 2010), and all teachers were interviewed.

Figure 2.2 Examples of paired conceptual and contextual questions



Questions are paired horizontally. Question numbers and objectives correspond to Tables 2.2 and 2.6.

2.2.4 Analysis

The results of the pre- and post-exam scores will be represented by the total number of correct answers among all students and corresponding proportions. This was performed per question, for contextual and conceptual questions separately and for

all questions. The proportions were used to calculate the gain index $\langle g \rangle$. The latter is defined as the ratio of the actual average gain (%post-%pre) to the maximum possible average gain (100-%pre) (Hake, 1998). A paired samples *t* test and a Wilcoxon signed-rank test were used to determine differences between pre- and post-scores. Both tests were used because frequency analysis showed the data was only approximately normally distributed. The internal consistency of the exam was tested by calculating Cronbach's alpha for the items within the different objectives, resulting in an average alpha value. Finally, a factor analysis was used to test the (number of) assumed objectives the exam is based on.

For the qualitative data we derived guidelines for analysis from methodological literature (Boeije, 2005; Trochim, 2006). Table 2.5 gives an overview of the qualitative data collection and a brief description of the analysis.

Because observation forms were based on Table 2.4 those elements were also used as labels for (re)grouping observations: (A) collaboration, (B) reflection, (C) feedback, (D) explication, (E) process-related. A sixth label was added, (F) miscellaneous, for observations that were hard to define. In addition, also the type of interaction (Table 2.4) was noted. In the context of methodological triangulation, the same labelling method was used for analysing sound recordings, questionnaires and interviews, where in case of questionnaires and interviews labelling took place per question. Sound recordings were first broken down into fragments after whereupon labelling started. Next, per data collection the data was sorted by type of interaction in order to specify the initial focus. Then, the data was sorted by learning-related element(s) to gain insight into the learning process. This resulted in sub-categories of common content where each sub-category was accompanied by a short description. At this stage, the researchers, to guarantee reliability by peer debriefing, compared their findings until agreement was reached. According to literature, inter-rater agreement can be determined by dividing the number of agreements by the sum of agreements and disagreements (Bijou, Peterson, & Ault, 1968). In our case, (N_A=54, N_D=8) the agreement was 0.87 which is sufficient.

Furthermore, sound recordings and interviews were analysed to study changes in science learned. First, sound recordings of student collaboration were used to study changes in verbal use of scientific terms during the process. For this, the usage of 13 predefined scientific, design-related terms was established for two stages. Second, student products were examined by writing down the science used that was visible in products. Then, student interviews made clear, by studying the quality of scientific underpinning, whether this science was understood and used consciously.

Design outcomes were rated per specification by two experts and using three categories (successful, partially successful and unsuccessful). The percentage of successes indicated how successful students were. By calculating the linear weighted Cohen's Kappa inter-rater agreement was established.

For the qualitative part validity and reliability was ensured in several ways (Hake, 2004; Niedderer & Goldberg, 1993). First, data collection and analysis were based on scientific literature for guaranteeing test-validity resulting in well-founded results. Second, by coding, peer debriefing and member checking a coherent and explicit chain of analysing and reasoning was provided. Third, direct investigation techniques in a real-world educational setting avoided experimental settings that may cause quasi-valid results because important impacts are ruled out. Fourth, methodological and investigator triangulation was used to check results and interpret findings.

Table 2.5 Overview of qualitative data analysis

Data type	Implementation	Analysis
Observations	Non-participant expert observations (event- and scan-based) guided by observation forms based on elements in Table 2.4.	Grouping and categorising observations using labels equal to learning-related issues in Table 2.4.
Sound recordings	Recordings of teacher instructions, student-teacher interaction and student-student interaction.	• Similar to observation analysis. • Counting relative usage of scientific, design-related terms during student collaboration.
Product analysis	(1) Examining successfulness of design outcomes (two experts) by scoring per design specification based on three categories. (2) Examining the underlying science students used for creating their products.	(1) Calculating the weighted Cohen's Kappa and the relative number of successes. (2) Studying, which science, according to Table 2.2, is visible in products.
Questionnaires	Students had to reflect on the learning process: outcomes, disturbing elements and activities that stimulated learning.	Categorising and labelling, similar to observation analysis, students' answers per question.
Interviews	Students: retrospective semi-structured interviews to deepen questionnaire answers. Complemented by stimulated-recall techniques to check the extent to which students used science for design outcomes consciously. Teachers: semi-structured interviews to investigate their opinions regarding learning outcomes, disturbing elements and activities that stimulated learning.	• Similar to questionnaire analysis. • Determining, by studying students' reasoning, whether underlying science is understood and used consciously for design realisation.

2.3 Results

2.3.1 Students' achievements

Table 2.6 shows the pre- and post-exam results (experimental and control group) listed by objective. Cronbach's alpha, for each individual objective, indicates that the questions have sufficient internal consistency. Regarding objectives 1 to 6 we find an overall alpha of 0.76.

A principal component analysis suggests, according to Kaiser's criteria (eigenvalue >1), that seven factors were present. However, scree plot analysis indicated, based on linear coinciding, the data should be analysed for six factors. Studying the (rotated) component matrix 17 test items (questions) across the components matched the distribution of questions across the objectives, which gives an 85 percent match.

The control group, used to determine a possible learning effect from completing the test, showed now gain ($\%$pre = 29; $\%$post = 30). For the experimental group, a paired samples t test indicates the overall gain is significant, $t(76) = -18.18$; $p < 0.001$. This is confirmed by the Wilcoxon signed-rank test that gives the same significance. Even though the experimental group made significant progress, substantially more gain could be possible because the overall gain is just enough to be called medium (Hake, 1998). Compared to the gains achieved in (traditional) physics course studies and LBD studies, this gain is similar (Churukian, 2002; Coletta & Phillips, 2005; Hake, 1998; Kolodner, 2002b).

The exam results regarding objectives 1, 4, 5 and 6 are consistent where objective 5 barely shows any gain and for objectives 2 and 3 an anomaly is shown. Analysing the questions with no or low gain two things are noteworthy. First, question 2 shows a slight decline because students used the concept for parallel current behaviour, which was mainly important, for a series circuit. Second, the other questions also appealed to concepts that were barely exposed during the challenge (potential difference and resistance). For example, objective 5 (resistance and current flow) was addressed by the increasing number of components students had to add to their design. However, a correlation with changing current was not investigated. Objective 1 and 4 (highest gains) were appealed strongly during the challenge. Thus, unravelling the requested design is important to predict learning outcomes, to set objectives and to notice possible shortcomings. Finally, differences between contextual and conceptual questions were not found.

Table 2.6 Overview of pre- and post-exam results

Question information			Pre-exam				Post-exam				Difference				
			Score		Proportion		Score		Proportion		Abs.		GainInd.[b]		Gain[c]
No.	Obj.[a]	Type	LBD	Cont.	LBD	Cont.	LBD	Cont.	LBD	Cont.	LBD	Cont.	LBD	Cont.	LBD
1	1	CC	26	9	0.33	0.35	53	10	0.68	0.38	27	1	0.52	0.06	Medium
6	1	CC	11	3	0.14	0.12	39	3	0.50	0.12	28	0	0.42	0.00	Medium
5	1	CT	12	2	0.15	0.08	55	2	0.71	0.08	43	0	0.65	0.00	Medium
9	1	CT	4	2	0.05	0.08	45	4	0.58	0.15	41	2	0.55	0.08	Medium
12	2	CC	21	7	0.27	0.27	53	8	0.68	0.31	32	1	0.56	0.05	Medium
17	2	CC	22	8	0.28	0.31	26	7	0.33	0.27	4	-1	0.07	-0.13	Low
15	2	CT	22	6	0.28	0.23	32	8	0.41	0.31	10	2	0.18	0.10	Low
20	2	CT	23	6	0.30	0.23	41	6	0.53	0.23	18	0	0.33	0.00	Medium
2	3	CC	46	11	0.59	0.42	39	13	0.50	0.50	-7	2	-0.15	0.13	None
7	3	CC	29	10	0.37	0.38	59	9	0.76	0.35	30	-1	0.61	-0.10	Medium
13	3	CT	31	9	0.40	0.35	35	7	0.45	0.27	4	-2	0.09	-0.22	Low
19	3	CT	27	7	0.35	0.27	52	8	0.67	0.31	25	1	0.49	0.05	Medium
10	4	CC	24	10	0.31	0.38	41	12	0.53	0.46	17	2	0.32	0.13	Medium
11	4	CC	22	9	0.28	0.35	40	7	0.51	0.27	18	-2	0.32	-0.22	Medium
3	4	CT	17	7	0.22	0.27	40	7	0.51	0.27	23	0	0.38	0.00	Medium
18	4	CT	48	12	0.62	0.46	57	11	0.73	0.42	9	1	0.30	-0.08	Medium
16	5	CC	22	5	0.28	0.19	23	7	0.30	0.27	1	2	0.02	0.10	Low
8	5	CT	25	7	0.32	0.27	29	6	0.37	0.23	4	-1	0.08	-0.14	Low
4	6	CC	46	11	0.59	0.42	59	10	0.76	0.38	13	-1	0.41	-0.09	Medium
14	6	CT	28	8	0.36	0.31	48	10	0.62	0.38	20	2	0.40	0.11	Medium
Total		CC	269	83	0.35	0.32	432	86	0.56	0.33	163	3	0.33	0.02	Medium
		CT	237	66	0.31	0.25	434	69	0.56	0.27	197	3	0.37	0.02	Medium
		Tot.	506	149	0.33	0.29	866	155	0.56	0.30	360	6	0.35	0.02	Medium

CC = conceptual question; CT = contextual question; LBD = LBD students; Cont. = control group.

[a] Obj. = objective, objective numbers according to Table 2.2.

[b] Gain-index: $\langle g \rangle$ = (post - pre) / (1 - pre), in the case of regression: (post - pre) / (pre).

[c] High gain: $\langle g \rangle \geq 0.70$, Medium gain: $0.70 > \langle g \rangle \geq 0.30$, Low gain: $\langle g \rangle < 0.30$ (Hake, 1998).

Table 2.7 shows how students' designs were scored by two experts. For these results the linear weighted Kappa κw is 0.70 (lower limit = 0.60; upper limit = 0.79), which gives a substantial agreement. The average number of successes (successful), based on all specifications and both experts, is 73 percent. For the specifications

based on science content (A to D) this percentage is 84 percent, which implies that a medium gain, according to science learned, was sufficient for design realisation.

Despite the fact students performed reasonably well and students' talking, as illustrated in Figure 2.3, showed increasingly more scientific terms, interviews made clear, shown by two examples in Table 2.8, students lacked scientific reasoning. This is supported by the observation students continuously tended to apply trial and error to complete tasks. According to the knowledge dimensions of Bloom's taxonomy, scientific insights were used as isolated facts and explicit interrelationships, which enable them to function together, remained underexposed (Krathwohl, 2002).

Table 2.7 Assessment of 25 design outcomes by two experts

Design specification according to Table 2.1	Successful		Partially successful		Unsuccessful	
	Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2
A	22	23	2	2	1	0
B	20	20	4	4	1	1
C	21	20	3	5	1	0
D	21	21	4	3	0	1
E	24	24	1	1	0	0
F	11	10	12	15	2	0
G	9	11	13	9	3	5

Table 2.8 Two examples of poor scientific reasoning

Example 1 (Interview 3)	Example 2 (Interview 8)
Q. Why you used a parallel circuit to build the dance pad?	Q. How your self-designed floor pad works?
A. Because the laptop told me to do.	A. By stepping on it.
Q. Why did you not choose a series circuit?	Q. Why does it result in, for example, flashing a light?
A. Then, the dance pad will not work.	A. Because we used aluminium foil.
Q. Why?	Q. Why is this foil so special for your design?
A. Everything goes on and off at the same time.	A. Because then current can pass.
Q. Why is it that parallel circuits do not do this?	Q. Does a normal switch functions like your floor pad?
A. Because then the parts do not have the same wire.	A. No, a normal switch contains no aluminium foil.
Q. Is there a difference in the amount of current that flows through series or parallel circuits?	Q. How do you call things that can easily let current through?
A. No, it is the same battery and current always comes back to the battery.	A. Conducting

Table 2.8 Continued

Stimuli used during Interview 3 (left) and Interview 8 (middle and right)

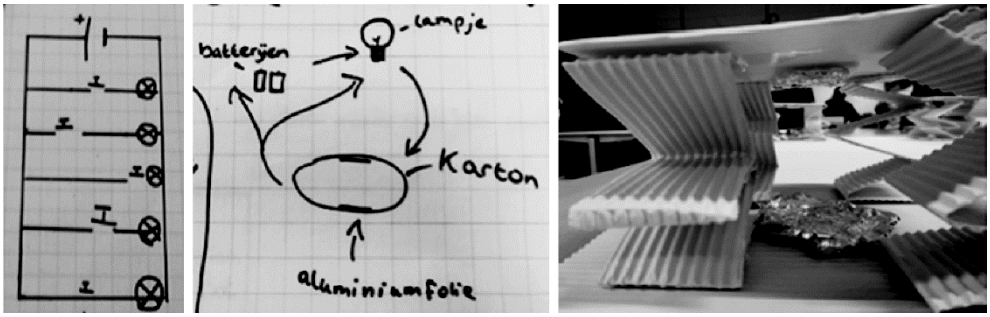
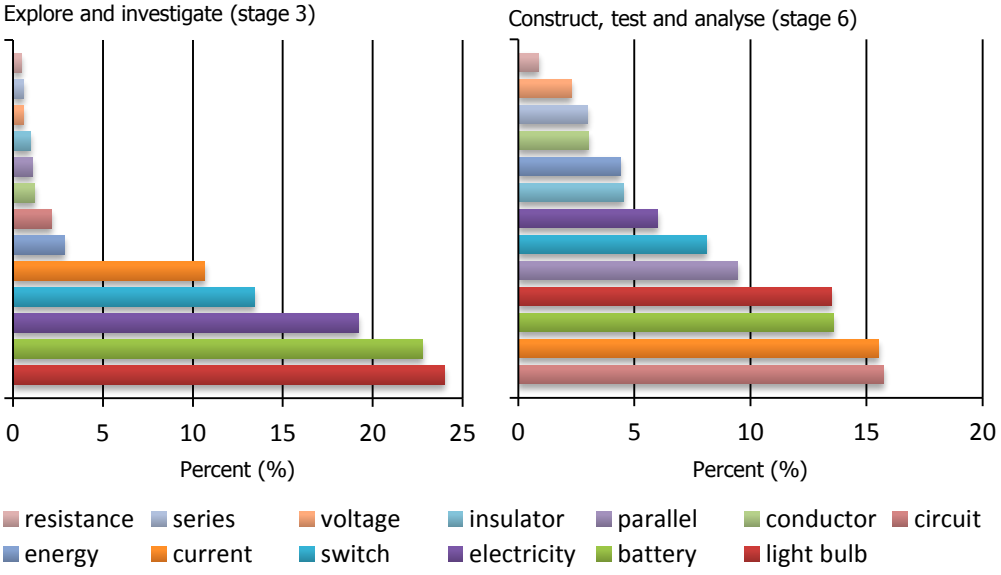


Figure 2.3 Relative usage of scientific and design-related terms



Sound recordings of five design groups were analysed by counting the usage of 13 predefined design- and objective-related terms. This was done for student discussion (40 minutes per group) during the early exploration stage and for one of the final stages (stage 6). In case of stage 3 a total number of 417 terms was found compared with 741 terms for stage 6. For both stages the relative distribution of terms is shown. Beside the fact the total number of terms increased, the initial relatively large difference in usage decreased and certain terms became more favourite (e.g. current, circuit and parallel). The terms resistance, voltage and series stayed less favourite and were never explicitly addressed during the task.

2.3.2 Students' focus

Because the students' focus is one of the main topics of this study, students were questioned about learning outcomes. Table 2.9 shows that experienced learning outcomes were mainly task- and product-related. Only nine percent of all replies were related to a better mastery of electricity concepts. According to questionnaires and interviews, concepts were seen as a tool for designing a dance pad where the latter was, maybe logically, qualified as the ultimate goal of the challenge. This also explains that the virtual simulation was a successful tool for circuit creation, but circuit operation was not sufficiently understood. Overall, as suggested earlier, our novice design students indeed focused on process-related issues needed for success.

Table 2.9 Learning outcomes

Learning outcomes: What have you learned from the challenge? [a]	Proportion[b]
Knowing how to design (a dance pad)	0.33
The practice of creating electric circuits (for a dance pad)	0.18
Creating posters for class discussion	0.13
Proper use of construction materials and tools	0.10
(Better) mastery of electricity concepts	0.09
Knowing how to collaborate with students	0.07
Learning outcomes other than mentioned above (e.g. seeking for information, usage of ICT for educational purposes, presentation techniques, engineering concepts)	0.10

[a] Descriptions are revised to make categorisation possible.

[b] Relative distribution of all replies gathered through questionnaires and interviews.

2.3.3 Learning-related interactions

To investigate science-related learning incitements students were asked to rate activities incorporated in Table 2.4. Rating took place, as shown by the results in Table 2.10, by using a five-point Likert scale (very poor, poor, fair, good, very good).

Table 2.10 Learning incitements

Activities	To what degree did the activities listed below help you learn about electricity?								
	-- [1]	- [2]	o [3]	+ [4]	++ [5]	N	Average	Modus	%(>o)
Student (to student) interaction	**25**	**70**	**83**	**39**	**14**	**231**	**2.8**	**3**	**23**
■ Suggestions/advice from peers	6	22	29	16	4	77	2.9	3	26
■ Reviewing own thinking/doing	17	29	16	12	3	77	2.4	2	19
■ Searching for information	2	19	38	11	7	77	3.0	3	23
Student to teacher interaction	**11**	**23**	**56**	**86**	**55**	**231**	**3.7**	**4**	**61**
■ Suggestions/advices from teacher	3	9	19	26	20	77	3.7	4	60
■ Teacher-guided class sessions	5	5	20	28	19	77	3.7	4	61
■ Teacher-guided science talking	3	9	17	32	16	77	3.6	4	62
Student to content interaction	**10**	**22**	**62**	**66**	**71**	**231**	**3.7**	**5**	**59**
■ Circuit simulation (software)	0	3	21	23	30	77	4.0	5	69
■ Real circuit experimentation	8	14	19	18	18	77	3.3	3	47
■ Creating products/design (parts)	2	5	22	25	23	77	3.8	4	62

Table 2.11 Observed triggers for student discussion

Trigger for student discussion[a]	Proportion[b]
Design-related activities and the presence of materials and tools	0.26
Prescribed by the learning task	0.21
The making of sketches and drawings	0.19
Teacher-stimulated discussions	0.16
Scientific experimentation (real experiments and simulation software)	0.10
Other triggers (e.g. information seeking, spontaneous, non-task-related triggers)	0.08

[a] Descriptions are revised to make categorisation possible.

[b] The proportions are based on the relative distribution of observed events.

Student (to student) interaction

Table 2.10 shows that student (to student) interaction was least helpful to learn about electricity. Especially, self-reflection was not appreciated as a useful learning activity. Collaboration with peers scored a better rating (fair) where non-prescribed collaboration was mainly triggered by the presence of construction materials and tools and the making of sketches and drawings. This was established by the results

of counting different triggers for student discussion, shown in Table 2.11, based on observation forms. Regarding information seeking, interviews made clear that gathered information was not shared spontaneously among peers. The major reason for this was, also demonstrated by interviews, the inability of students to properly estimate the value of the information. Furthermore, enthusiastic, highly involved students tended to dominate collaboration or, in the case of no effect, to act alone. This, in order to finish a task as quickly as possible and to experience a sense of accomplishment.

Student to teacher and content interaction

These interactions are rated equally where circuit simulation gets the highest score regarding learning about electricity. However, interviews made clear, as mentioned before, students need considerable assistance to explicate scientific insights and design decisions adequately. For this, the teacher seems to be important: 12 of 16 interviewed students mentioned the teacher as the most reliable and important source for this kind of reasoning and fellow students were seen as incompetent doing this. Nevertheless, all teachers described the (guidance of the) LBD task as intensive, time consuming, complex and a real challenge for students and teachers. Especially, the process of sensitive assistance, mentioned before, seemed to be difficult. Reasons for this were mainly time constraints and the tendency to be too helpful. Students' reactions were more or less similar and included the complexity of the design diary and challenge as a whole, mainly due to the extent and openness, experienced time constraints and, sometimes, the low intensity of relentless senses of accomplishment. Students often mentioned to find it difficult to stay focused and to make up their mind, but nearly 72 percent also mentioned they became more motivated than usual, which also was noted by the teachers. Finally, nearly one fifth of the students indicated it would be desirable to enrich the challenge by adding non-dance pad-related tasks or content. Table 2.12 provides an overview of the most important criticism expressed by students and teachers.

Table 2.12 Criticism expressed by students (questionnaires) and teachers (interviews)

Students' criticism[a]	Proportion[b]
1. Having lack of time or experiencing time constraints	0.30
2. The complexity of the task due to diversity, content and openness	0.20
3. One-sided focus on the dance pad (over a long period of time)	0.18
4. Difficult to stay focused and concentrated (tumultuous environment and task duration)	0.11
5. The dependency on ICT quality (wireless network connection, hardware and software)	0.09
6. The teacher providing advice and guidance instead of answers and confirmation	0.06

Teachers' criticism: examples of teachers' pronouncements[c]	Corresponding students' criticism
"We also ran into time constraints and this led to some amount of stress to get everything done."	1
"Some students had problems to keep on track. […] The learning task is quite complex and appeals to many skills. […] I had to appeal to the utmost of my abilities."	2,4
"Students often lacked concrete input from me […]. They asked for answers and confirmation […]. It was obvious they often hackled the uncertainty about their progress."	2,6
"Often, I found it difficult to give proper feedback or information. […] I want to help students but I do not want to impede their learning process by giving too less, too much or wrong information.	2,6
"It was very busy and noisy in the classroom. A few children asked me to create some rest."	4
"Students described administrative operations as time consuming, disturbing and confusing. This was strengthened by the fact that internet access was often a problem."	1,2,5
"Two groups could not finish their design […] and they were not amused […]. They had just too little time and lost a lot of time due to completing the design diary."	1
"The network access was frustrating. Also some laptops refused to run the simulation software."	5
"[…] so more teaching or learning activities are necessary to cover the learning content."	3
"[…] and then he asked me whether the dance pad was the only topic or something else was coming on. […] Students often struggle to stay focused when a task is complex or time consuming."	1,2,3,4

[a] Descriptions are revised to make categorisation possible.

[b] Relative distribution of students' criticism based on the total number of criticisms mentioned in questionnaires.

[c] Pronouncements teachers made during interviews (translated from Dutch to English).

2.4 Discussion and implications

By studying the practice of LBD and less emphasis on pre- and post-testing, this study reveals why concept learning has its limitations, despite the fact LBD theoretically provides a rich learning environment. It clarifies why the found average medium gain (0.35 gain-index) stayed relatively low and offers room for improvement. For example, a previous survey of pre-post-test data for 62 introductory physics courses, based on interactive engagement (IE) methods, showed gain-indices up to 0.60 (Hake, 1998). Those IE methods are, similar to LBD, designed to promote conceptual understanding through heads- and hands-on activities, contributed by peer feedback and discussion and intensive teacher guidance (Hake, 1998). A main difference between those IE methods and LBD is the amount and extensiveness of objects of integration where LBD seems to be more diverse: teachers and students defined the LBD challenge as complex, mainly due to the extent and openness. Where time constraints, the malfunctioning of the virtual simulation and network connection, and a disturbing emphasis on the (extensive) design diary were additional negative elements. Thus, this complexity and extensiveness forced students to focus on completing the requested activities and delivering requested products. Therefore, in accordance with the hypothesis stated before, students were indeed strongly product and process focused (What to do and what to deliver?) and qualified scientific content (What to learn?) as tools they needed for success.

The science students learned and used for producing their design mainly became available from activities that strongly determined a successful completion of the challenge. First, the virtual simulation that provided insight in electrical wiring and, second, teacher-driven activities (e.g. student-teacher interaction and teacher-driven class discussions) when concepts were explicitly discussed. Therefore, the more concepts directly determined a successful design outcome, the better the concepts were understood. An important fact also indicated by Jones (1997) for technological concepts. The students' strong focus on acting and delivering successful products, according to students the main goal, suppresses the fact that those processes (can/must) increase their concept-related knowledge. This resulted in the fact that concepts, certainly when they were poorly design-related, were badly or only partially understood. This lack of focus on scientific objectives and associated concepts caused the learning of isolated facts that stayed, more or less, implicit. Students used more scientific terms and symbols and designed proper electric

circuits but did not achieve a deeper conceptual understanding. Thus, students learned (incomplete) concepts, just enough for design implementation, and learned too little explicit interrelationships between concepts, which is essential to master the knowledge domain (Brandsford et al., 2003; Wiggins & McTighe, 2006).

This problem of incidental, implicit, informal or unintentional learning was also found in other non-LBD studies (Baskett, 1993; Kerka, 2000; Marsick & Watkins, 2001; Rogers, 1997). For example, our findings correspond to the important design-related issue stated in the run-up to the presentation of this study: design is seen as an instructional strategy where product realisation has the emphasis and more conceptual awareness is necessary to improve design performances and conceptual understanding. Therefore, the results of this study can be more broadly understood: the practice of design offers a rich learning environment but an overall reinforcement of conceptual awareness is required.

2.4.1 Possibilities for improvement and further research

According to the previous, there are mainly two (interrelated) problems for which solutions will need to be found: (1) Reducing the complexity of the challenge without diluting the potentially rich learning environment. (2) More focus on domain-specific objectives and related (scientific) concepts where important interrelationships become explicit.

In general, a detailed analysis of related concepts, crucial for succeeding, is necessary: when they (have to) emerge and how they are related? This also makes clear which concepts are poorly task related and need to be addressed otherwise (e.g. through demonstrations, lectures, further readings, experiments, etc.). Previous studies provide some clues where to search for improvement. To discuss and explicate concepts students used, for their products and during their collaboration, the technique of guided discussion may be helpful (Brandsford et al., 2003). This teacher-led discussion technique encourages students to share (scientific) insights and develop deeper understanding. To emphasise and explicate the important role of concepts for design purposes (elements of) informed design might be interesting (Burghardt & Hacker, 2004). This strategy aims for thoughtful design decisions, based on scientific and mathematical concepts, without reverting to trial and error; the tendency the students in our study had. Furthermore, applying explicit instruction (Archer & Hughes, 2011) and the use of scaffolding strategies (Bamberger & Cahill, 2013) are interesting. Both strategies help to facilitate students'

understanding and to oversee the learning process. Students are guided through the learning process with clear instructions, proceeding in small steps, checking for understanding and achieving active and successful participation by all students. This topic of successful participation could also respond to a problem that was observed during the study: students (in design groups) were sometimes not equally involved.

To conclude, (the learning outcomes of) LBD activities are very teacher dependent. On the one hand due to teaching decisions made in preparation of the task and, on the other hand, because of teacher guidance during the task (sensitive assistance). Maybe this is not surprising because the teacher plays a significant role in enabling successful learning outcomes (Bamberger & Cahill, 2013; Van der Veen & Van der Wal, 2012). Thus, it will be valuable to study (the interplay of) concept learning and teacher handling in detail to distract important clues for appropriate teacher behaviour. This research interest will be central to Chapter 3.

3

Teaching strategies to promote concept learning by design challenges

This chapter has been accepted for publication in adapted form as:
van Breukelen, D., van Meel, A., & de Vries, M. (in press). Teaching strategies to promote concept learning by design challenges. *Research in Science & Technological Education*.

3.1 Introduction

Chapter 2 revealed, regarding research questions 1 and 2 in section 1.5, how and when scientific content was addressed by students and what they learned from this. Results showed a strong product and process focus (What to do and deliver?) and students qualified content (What to learn?) as incidental design tools. As a result, mainly implicit learning of loose facts and incomplete concepts took place where teacher-driven activities seemed to dominate learning (positively and negatively). This, along with the fact teachers involved described task guidance as intensive and complex, asks for a deeper understanding of pedagogical strategies to manage design-based learning environments. Therefore, the study central to this chapter explored these strategies and more specific the interaction with concept learning. This necessity is supported by educational literature that claims conceptual learning is highly teacher dependent (Bamberger & Cahill, 2013; Van der Veen & Van der Wal, 2012). Using design faces teachers with an open-ended nature where teachers must relinquish directive control (Burghardt & Hacker, 2004). As a result, teachers leave or undermine LBD activities because they are not able to adjust to a new kind of classroom control (Wendell, 2008).

To address this research theme, the second set of research questions in section 1.5 were leading: What teaching strategies dominate and (directly) affect the learning of science content and, by analysing all teaching interventions during LBD, what is the relative number of interventions that directly appeal to these strategies? And finally, which teaching strategies, based on the answer to the previous question, should get more attention to enhance concept learning?

3.2 Method

A design-based mixed methods study was used, as for the first study, to face the research questions. Six first-year student teachers (science) and two teacher trainers (principal investigators included) were involved. Student teachers had prior experiences on characteristic LBD components and sufficient prior knowledge regarding the science domain addressed. The study was supported by the same theoretical, learning- and teaching-related, framework developed for the first study. However, this framework was supplemented by specific guidelines for appropriate teaching behaviour. Based on the final framework, a LBD challenge was developed and performed. Quantitative data was used to examine students' level of concept

learning. Qualitative data, complemented with a quantitative analysis regarding the intensity of applied teaching strategies and students' views on the effectiveness of these strategies, revealed which strategies were directive to learn conceptual knowledge. Combining all data, it was possible to establish which strategies should get more attention, aiming for better pedagogical strategies.

According to Crouch and McKenzie (2006), the qualitative approach and small number of participants (less than 20) requires the investigators to participate in the study. This enables investigators to establish continuing, fruitful relationships with participants and to address the research in depth by theoretical contemplation. Then, the validity increases and drawing conclusions through analysis and induction is possible. Therefore, both investigators participated by guiding the LBD challenge.

3.2.1 Design of the challenge

The LBD task again addressed the "direct current electric circuits" physics domain and two design groups were challenged to design a solar power system for a model house, illustrated in Figure 3.1. The activity took three successive days (two to three hours a day; eight hours in total) and was guided by an instructive presentation and a student's and teacher's guide. To accomplish the task, design specifications were given (Table 3.1) that stimulated the use of science, decision-making and creative thinking. Regarding these specifications and the scientific objectives shown in Table 3.2, the most fundamental design principles concerned proper wiring (combining series and parallel parts) and regulating current, voltage and resistance for maximum efficiency. Common LBD stages and activities (Table 3.3) were applied to guide the process and, furthermore, students were allowed to use digital learning resources.

Figure 3.1 Model house and layout

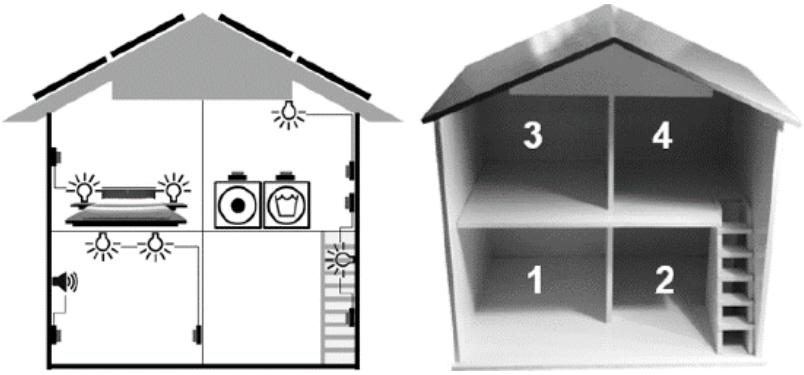


Table 3.1 Design specifications and components

Design specifications (in combination with Figure 3.1)			
A. [ROOM LAYOUT] Room 1: 2 lamps operated by 1 switch and a doorbell (SP) operated by 1 switch. Room 2: 1 lamp operated by a set of 2-way switches (staircase wiring). Room 3: 2 lamps operated by 1 switch. Room 4: 1 lamp operated by 1 switch, 1 washing machine (M2) with adjustable speed operated by 1 switch, 1 dryer (M1) operated by 1 switch.			
B. [SOLAR POWERING] The entire lightning has to be connected to a separate (combination of) solar cell(s). The same applies to the doorbell and washer-dryer combination.			
C. [EFFICIENCY] The energy efficiency of the entire wiring has to be as high as possible and the use of materials as less as possible. In any case, it is not allowed to use more components than available.			
Component	Quantity	Component	Quantity
Motor 1.5 V DC (M1)	1	Solar cell 4 V / 35 mA	4
Motor 3.0 V DC (M2)	1	Solar cell 5 V / 81 mA	4
Mini-speaker 800 mW (SP)	1	Solar cell 0.5 V / 400 mA	4
Set: LEDs, resistors, wires, switches	1	Solar cell 0.5 V / 800 mA	4

Table 3.2 Scientific objectives and interrelatedness with the challenge

DC electric circuits objectives	Appearance
1. PHYSICAL ASPECTS OF ELECTRIC CIRCUITS. Resistance is a property of an object and hinders current flow (Ohm's Law). Equivalent resistance in series increases and in parallel decreases as more elements are added. The necessity of a closed circuit to enable current flow. Interpretation of pictures, diagrams and symbols, according to a variety of circuits.	Resistors are necessary to reduce current flow and a variable resistor is necessary to adjust the washing machine's speed. Furthermore, students have to interpret and design a variety of circuit parts in order to meet the requested wiring.
2. ENERGY AND POWER. Apply the concepts of energy (dissipation, conversion and conservation) and power (work done per unit time) to a variety of circuits.	Students have to establish the amount of energy supply and consumption by the designed circuit in order to reach maximum efficiency.
3. CURRENT. Understand and apply conservation of current (Kirchhoff's point rule) to a variety of circuits. Explaining the behaviour of an ideal current source.	Combining series and parallel parts (solar cells and components), to meet design specifications, forces students to investigate and calculate current flow and potential differences. Furthermore, students have to investigate the behaviour of (combined) solar cells to get informed about differences regarding to (well-known) voltage sources.
4. POTENTIAL DIFFERENCE, VOLTAGE. The amount of current is influenced by potential difference. Application of the concept of Kirchhoff's loop rule ($\sum V = 0$ in a closed loop). Explaining the behaviour of an ideal voltage source.	

Table 3.3 Stages and activities

Stages (time)	Activities[a]	Final products[b]
1. Introducing the design challenge (15-20 min)	Introduction of context, design challenge, activities, organisation, learning sources, time schedules, materials, objectives, etc. (C)	
2. Understanding the challenge, messing about, whiteboarding (50-60 min)	• Exploration of the challenge, learning context and objectives (G) • Writing down ideas, (research) questions and hypotheses (G): what to do and learn? • Whiteboarding: sharing results, feedback (C)	Design diary stage 2 • Flip chart for whiteboarding (G)
3. Investigate & explore, poster session (120-180 min)	• Formulate and distribute (scientific) research questions (C) • Discussion "fair test rules of thumb" (C) • Design and conduct experiments, collect data, conclude (G) • Presentation: poster session, feedback session (C) • Discussion about results and fair testing: redoing/adjustments (C/G)	Design diary stage 3 • Final research questions (C) • Fair test rules of thumb (C) • Laboratory notebook (G) • Poster (G)
4. Establishing design rules of thumb (20-30 min)	• Determination of design rules by using experiment results (C) • Focus on science content involved: use of science vocabulary and concepts (C)	Design diary stage 4 • Design rules of thumb (C)
5. Design planning, pin-up session (80-90 min)	• Devise, share and discuss design solutions: divergent thinking (G) • Poster: provisional design solution (G) • Pin-up session (posters): feedback session (C) • Adjusting the provisional design solution (G) • Redoing until satisfied: final design solution (C/G)	Design diary stage 5 • Design posters (G) • Design sketch (G)
6. Construct & test, analyse & explain, gallery walk (120-180 min)	• Prototyping and design realisation (G) • Testing the design based on design specifications (G) • Gallery walk: determine shortcomings; feedback/reflection (C) • Adjustments of design solutions and rules (C/G)	Design diary stage 6 • Prototype (G)
7. Iterative redesign (50-60 min)	• Iteration of steps depending on decisions made (C/G) • Improving the design (G) • Final discussion about design solutions and scientific concepts (C)	Design diary stage 7 • Final solution (G) • Final reflection (individual)

C = class activity or product; G = design group activity or product.

[a] Available resources: electronic learning environment (ELE), smartphone, laptop, tablet, Microsoft Office ® software, internet access, materials and tools for design realisation, materials for conducting experiments.

[b] Design diary (ELE-archived): reflections, feedback, descriptions and pictures/movies. Bulleted lists are stage-specific.

3.2.2 Framework of teaching strategies

To gain insight into proper teaching strategies, the theoretical framework of learning-related interactions and elements, developed for the first study, was leading. This framework, discussed in section 2.2, was extended for use in the study central to this chapter. By taking literature on pedagogical strategies, teacher competences and STEM education into account, the framework was complemented by a set of cohesive teaching guidelines. These guidelines should help teachers to take enough control of the learning environment by intervening when necessary and holding back when possible: sensitive assistance (Murphy & Hennessy, 2001).

In this context, a distinction was made between skills emerging during the activity (anticipatory skills: A), induced by the intervening teacher, and skills important for construction and preparation of the activity (preparatory skills: P). Concerning the latter the developed LBD task had, inter alia, the following characteristics: think-pair-share structured fixed moments of student collaboration; all materials and tools were available from start to finish; the design diary and LBD rituals forced students to reflect, to provide and receive feedback and to explicate (used) science; students had to make sketches and drawings; learning objectives were discussed explicitly; clear instructions (student's guide and instructive presentation) were used to guide each stage; the teacher's guide contained all teaching guidelines and guidelines for how and when to make science explicit. Table 3.4 shows the final framework of learning-related interactions and teaching guidelines, where the table is partly adopted from Chapter 2 for the sake of completeness and underpinning.

Table 3.4 Learning-related interactions and teaching guidelines

Interaction	Elements and guidelines
1. Student (to student) interaction	(A) COLLABORATION. Sharing information enriches learning and fortifies knowledge building (Parkinson, 2001; Roth, 1995). Sketching and drawing help students to externalise, share and review ideas (Popovic, 2004; Roth, 2001). Construction materials and tools, which are necessary for design creation, stimulate peer discussion (Murphy & Hennessy, 2001; Roth, 2001). ■ | P | Collaboration should be organised in advance by a fixed structure. ■ | A | Stimulate collaboration: students have to be the first point of call. ■ | A - P | Stimulate and (partially) obligate students to draw and sketch. ■ | A - P | Ensure the availability of materials/tools (and stimulate to use them).

Table 3.4 Continued

	(B) REFLECTION. Reflecting on knowledge, skills, practices, attitudes and feedback makes students aware of doing and thinking and stimulates to maintain strengths or to make adjustments. Collaboration provides input for reflection (Roth, 1995). ■ | P | Provide learning tasks with fixed moments of well-structured reflection. ■ | A | Stimulate reflective thinking: ask questions that excite reflection. ■ | A - P | Stimulate students to base future handling on reflection. ■ | A - P | Attend to the fact that reflection should focus on knowledge, skills, attitudes, failures and successes.
2. Student to teacher interaction	(C) TEACHER AND PEER FEEDBACK. Providing and receiving feedback is invaluable for learning. Constructive feedback concerns knowledge, skills and attitudes and reveals strengths and weaknesses (Kolodner, 2002a; Kolodner, Gray, et al., 2003). Constructive feedback is relevant, goal directed, well timed, behaviour focused, collaborative, factual and respectful (Wiggins, 2012). ■ | A | Be sure to give proper, timely feedback. ■ | A - P | Ensure feedback serves as input for reflection and future actions. ■ | A | Do not be a problem solver for students but act like a resource: redirect and provide tips/hints.
	(D) EXPLICIT TEACHING. Students often solve problems intuitively by trial and error (Hennessy & McCormick, 1994; Roth, 1995) and rarely in a strategic way by using content knowledge (Parkinson, 2001). Also new experiences are rarely linked to concepts (Popovic, 2004). Teachers should help students to explicate thinking and doing (Kolodner, Gray, et al., 2003; McCormick, 1997). ■ | P | Discuss all learning objectives explicitly. ■ | A | Stimulate students to think out loud. ■ | A - P | Use moments of feedback and reflection as explication tools. ■ | A - P | Explicate extensive and complex elements in smaller units. ■ | A | Conscientiously use, connect and repeat proper (scientific) terminologies and insights emerging from the task.
3. Student to content interaction	(E) PROCESS-RELATED ISSUES. First, mistakes reveal students' (mis)conceptions and must not be corrected prematurely but provided by feedback (Kolodner, Gray, et al., 2003). Second, application of concepts in different contexts fortifies learning. Through de- and recontextualisation understanding is supported (Brandsford et al., 2003; Fortus et al., 2004; Johnson, 1997; Parkinson, 2001). Third, time pressure impedes learning (Murphy & Hennessy, 2001). Providing positive and constructive feedback is to be preferred. Fourth, to incentivise learning sufficient control and organisation is needed (e.g. clear instructions and high-quality learning materials) (Bruinsma, 2003). ■ | A | Do not correct mistakes prematurely but provide them with feedback. ■ | P | Build in multiple contexts in which the same concepts occur. ■ | A | Prevent time pressure: use constructive feedback for encouragement. ■ | A - P | Take care of clear instructions and (high-quality) learning materials and encourage students to use them.

3.2.3 Data collection

To get informed about changes in conceptual understanding an identical pre- and post-exam was used. A control group was used to determine a possible learning effect from just completing the test. Multiple choice questions were taken from the validated Determining and Interpreting Resistance Electric Circuit Test (DIRECT), specially designed for use with high school and university students (Engelhardt & Beichner, 2004). The test consisted of 46 items where each objective in Table 3.2 was served by multiple questions.

The participating principle investigators guided the challenge by using strategies in Table 3.4. To investigate the intensity of appealed strategies all activities were videotaped. Afterwards, the recordings were used to analyse teacher handling in detail and remarkable events, maybe important to complement questionnaires and interviews, were noted. A questionnaire (open- and closed-ended) was used to study students' views on which teaching strategies were directive for concept learning or which guidance lacked. Questions were based on the STARR method that provides a framework for reflection on learning outcomes (Verhagen, 2011). For deeper understanding of students' answers, all students were included in retrospective semi-structured interviews where questionnaire items were leading. By combining questionnaire and interview data, it was possible to identify which strategies dominated conceptual learning. Complemented by the intensity of applied strategies, it became clear to what extent strategies were sufficiently addressed.

3.2.4 Analysis

The pre- and post-tests were scored for each objective by the percentage and number of correct answers. Percentages were used to calculate the gain index $\langle g \rangle$: ratio of actual average gain (%post - %pre) to the maximum possible average gain (100 - %pre) (Hake, 1998). A Wilcoxon signed-rank test was used, because of a limited normal distribution, to investigate differences between pre- and post-scores. Calculating Cronbach's alpha established the internal consistency.

Video recording analysis was conducted by both principle investigators in order to establish an acceptable level of inter judgemental reliability. The investigators independently categorised and counted teacher interventions applied, by using categories A to E in Table 3.4 including a short description. For this, the challenge was, based on Table 3.3, dived into four cohesive, nearly time-equal, parts: stage 1-2 (introduction - exploration), stage 3 (investigation), stage 4-5 (designing) and

stage 6-7 (construction - testing) and anticipatory skills had the most attention because preparatory issues were taken into account during task construction. Afterwards, investigators compared their findings and, based on interventions categorised by both investigators, the linear weighted Cohen's Kappa was calculated. All inconsistencies were discussed and resolved and interventions not noticed by both investigators were discussed for in- or excluding. Then, agreed interventions were rated by both investigators simultaneously, by using a three-point Likert scale (poor, fair, good), after which member checking verified the ratings. Finally, the results were translated into a teacher anticipatory intervention table.

For analysing questionnaires and interviews and combining it to other data, basically to get informed about the effectiveness of teaching strategies, elements of a grounded theory approach were used based on Charmaz (2006): a method for collecting and analysing qualitative data, regarding actions in practice, based on theoretical perspectives. For this, categories A to E in Table 3.4 served as sensitising concepts that were used for initial coding of questionnaires (open-ended question) and transcripted interviews. Coding took place by the investigators concurrently in order to guaranty reliability but also to record lines of thought and moments of decision-making; according to Charmaz (2006) important for increasing rationality and validity. By deepening the coded data, sub-categories of common content were distracted where skills in Table 3.4 offered guidance. By doing this, theoretical sampling took place and more insight was offered into the coherence and interplay of teaching strategies included in the theoretical framework. Finally, it was possible to draw conclusions from available data and underlying theories.

3.3 Results

3.3.1 Pre- and post-test results

Table 3.5 shows how well students performed on each of the scientific objectives. A Cronbach's alpha of 0.74 indicates the questions have sufficient internal consistency. The control group, used to determine a learning effect from completing the test, shows no average gain. For the experimental group the Wilcoxon signed-rank test indicates the overall gain is significant, $p < 0.001$. Even though a significant progress is found, substantially more gain could be possible because the overall gain is just medium for each objective (Hake, 1998). Compared to gains found in previous physics course studies, including LBD and Study 1, this gain is comparable or slightly higher (Churukian, 2002; Coletta & Phillips, 2005; Kolodner, 2002b). Nevertheless,

again this gain pointed out to be sufficient for design realisation because both design groups delivered a successful design (Figure 3.2). This successfulness was determined by both investigators and concerned all design specifications.

The gains found for the individual objectives are comparable. Analysing the number of questions with no/low gain and high gain, specified in Table 3.6, confirms this conclusion. These questions are spread across the objectives and by determining the related key concepts per objective there is a high degree of similarity. Key concepts concerning the high gain questions were appealed strongly during the challenge and were crucial for succeeding. The no/low gain questions appealed to underlying concepts that were barely exposed during the challenge.

Table 3.5 Results pre- and post-exam (experimental and control group)

		Pre-exam				Post-exam				Difference				
		Score		Perc. (%)		Score		Perc. (%)		Abs.		GainInd.[a]		Gain[b]
Obj.	Numb.	Exp.	Cont.	Exp.	Cont.	Exp.	Cont.	Exp.	Cont.	Exp.	Cont.	Exp.	Cont.	Exp.
1	18	77	68	71	63	90	70	83	65	13	2	0.42	0.05	Medium
2	8	28	31	58	65	37	31	77	65	9	0	0.45	0.00	Medium
3	8	26	33	54	69	37	34	77	71	11	1	0.50	0.07	Medium
4	12	39	44	54	61	56	42	78	58	17	-2	0.52	-0.05	Medium
	Total	170	176	62	64	220	177	80	64	50	1	0.47	0.01	Medium

Obj. = objective (Table 3.2); Numb. = number of questions; Exp. = experimental (n = 6); Cont. = control (n = 6).

[a] Gain-index: $\langle g \rangle$ = (%post-%pre)/(100-%pre), in the case of regression: (%post-%pre)/(%pre).

[b] High gain: $\langle g \rangle \geq 0.70$, Medium gain: $0.70 > \langle g \rangle \geq 0.30$, Low gain: $\langle g \rangle < 0.30$ (Hake, 1998).

Table 3.6 Number of high gain and no/low gain questions

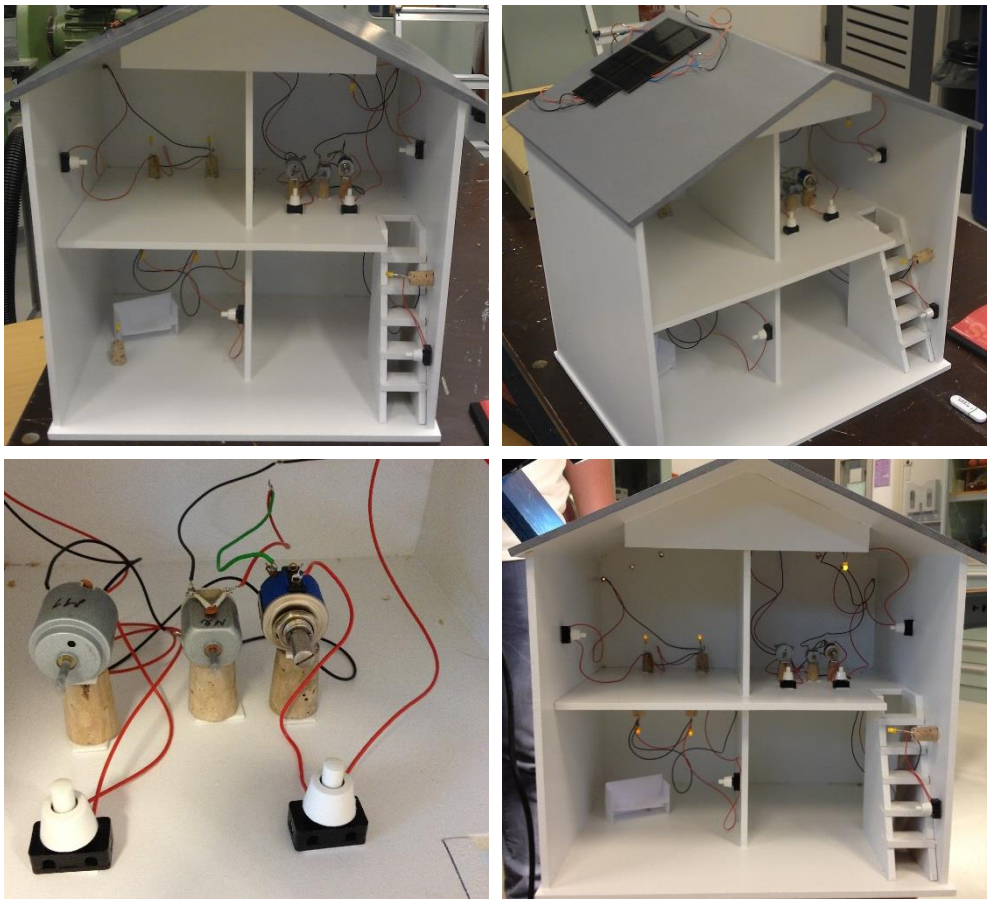
	No/low gain[a]		High gain[b]	
Obj.	Numb.	Key concept	Numb.	Key concept
1	3	Conceptual nature of resistance	4	Circuit operation based on wiring
2	2	Conceptual nature of electrical energy and energy dissipation	2	Energy and power calculations
3	2	Behaviour of current in components	2	Behaviour of (combined) current sources
4	3	Effect of voltage change on circuit operation	3	Applying Kirchhoff's loop rule

Obj. = objective (according to Table 3.2); Numb. = number of questions.

[a] Pre-test: a maximum of two good answers; Post-test: a maximum of three good answers.

[b] Pre-test: a maximum of two good answers; Post-test: five or six good answers.

Figure 3.2 Example of design outcome



3.3.2 Intensity of applied teaching strategies

A total of 152 and 172 interventions were categorised by the investigators respectively where 138 interventions were noticed by both investigators, which is 87 percent of the finally agreed interventions. Based on these 138 interventions, the linear weighted Kappa κ_W is 0.61 (lower limit = 0.50; upper limit = 0.72), so inter-rater agreement can be specified as moderate or on the very margin of substantial. Discussing and resolving afterwards revealed a few important issues responsible for a lot of the inconsistencies. These issues mainly concerned the strong entanglement of skills in Table 3.4 and, to a lesser extent, non-visible interventions where, during

the challenge, just the guiding investigator was aware of. The latter was simply solved by discussing the interventions. The first issue was resolved by agreement how to categorise strongly intertwined interventions. The examples in Table 3.7 show that categorisation has to take place based on the factual message of the intervention and, hence, the direct visible response of the student(s) that follows.

Table 3.7 How to categorise strongly intertwined interventions?

Situation	Teacher action	Category	Underpinning
Student uses the wrong equation to calculate the equivalent resistance of a parallel circuit.	"Why you use that equation?"… …[no reaction]… "Please explain this to your group members"	Collaboration [A]: Externalising ideas within design group.	Despite the fact the question has a reflective nature and aims for explaining content, collaboration is stimulated and takes place.
A design group measures the voltage of a solar cell; combined current and voltage measurement is required.	Perceiving the situation without intervention… [design group asks for approval]…Teacher stimulates to move on.	Process-related [E]: No premature intervention in the case of failure.	Although collaboration is stimulated, the intervention aims for learning from failures.
Student asks how solar cells behave when connected in series.	"That is for you to find out. Please search the internet for an answer and explain us".	Process-related [E]: Stimulate students to use resources.	Although the teacher hopes the student will be able to explain conceptual content, the use of resources is stimulated.

After reaching agreement, 159 interventions were processed in Table 3.8 that shows how interventions are spread across the stages and categories. It shows that 65 percent of all interventions directly appealed to providing feedback and stimulating collaboration. To a much lesser extent students were directly stimulated to explicate doing and knowing. Table 3.8 also shows how the investigators rated the interventions. Rating took place by consultation and the clarity and quality of the intervention were taken into account. For example, in the case of feedback the quality was established by using the rules for constructive feedback: relevant, well timed, goal directed, etc. Furthermore, through member checking the ratings were verified. For this, five interventions per category (25 in total) were discussed in detail with the student teachers afterwards that resulted in a limited number of adjustments, not affecting the overall picture. In general, Table 3.8 demonstrates that the quality of teacher interventions was more than fair where feedback interventions and explicit teaching strategies lag behind a little.

Table 3.8 Teacher Anticipatory Interventions (TAI)

		Number of interventions					Quality of interventions			
		1-2	3	4-5	6-7	Total	[-1]	[0]	[+1]	Mean
A	**Collaboration**	**9**	**16**	**16**	**6**	**47**	**2**	**12**	**33**	**0.66**
1	Stimulating collaboration by referring back to the group	6	8	8	3	25	0	3	22	0.88
2	Encourage students to externalise and review ideas (within groups)	3	5	6	2	16	2	5	9	0.44
3	Encourage students to externalise and review ideas (between groups)	0	2	1	1	4	0	2	2	0.50
4	Other (e.g. Mediation in the case of friction within design groups)	0	1	1	0	2	0	2	0	0.00
B	**Reflection**	**2**	**3**	**6**	**4**	**15**	**1**	**3**	**11**	**0.67**
1	Asking reflective questions to students; stimulate reflective thinking	1	3	4	1	9	0	2	7	0.78
2	Stimulate students to use (previous) reflection outcomes to move on	0	0	2	2	4	1	0	3	0.50
3	Other (e.g. Verifying the quality of self-reflection by students)	1	0	0	1	2	0	1	1	0.50
C	**Feedback**	**8**	**19**	**21**	**9**	**57**	**9**	**14**	**34**	**0.44**
1	Providing corrective feedback; expressing concerns (verbal, teacher-driven)	2	8	10	4	24	3	6	15	0.50
2	Providing positive feedback; expressing appreciation (verbal, teacher-driven)	3	5	5	2	15	0	3	12	0.80
3	Responding to student questions through feedback (verbal, student-driven)	2	3	4	1	10	1	4	5	0.40
4	Other (e.g. Non-verbal communication that alludes to providing feedback)	1	3	2	2	8	5	1	2	-0.38
D	**Explicit Teaching**	**3**	**11**	**6**	**3**	**23**	**5**	**8**	**10**	**0.22**
1	Stimulate students to explicate doing (process-related)	0	2	4	2	8	2	4	2	0.00
2	Explain conceptual content to students (teacher-driven)	1	5	1	0	7	1	1	5	0.57
3	Stimulate students to explicate conceptual content (content-related)	2	3	0	1	6	2	2	2	0.00
4	Other (e.g. Explicate extensive/complex proceedings in smaller units)	0	1	1	0	2	0	1	1	0.50
E	**Process-related Issues**	**3**	**6**	**7**	**1**	**17**	**0**	**5**	**12**	**0.71**
1	Stimulate students to use available resources (e.g. internet, materials, etc.)	3	3	4	0	10	0	2	8	0.80
2	No premature intervention in the case of (impending) failures/mistakes	0	1	2	0	3	0	2	1	0.33
3	Applying a flexible time management (preventing time pressure)	0	0	1	0	1	0	0	1	1.00
4	Other (e.g. Departing from intended procedures)	0	2	0	1	3	0	1	2	0.67
	Total	**25**	**55**	**56**	**23**	**159**	**17**	**42**	**100**	**0.52**

Interventions according to Table 3.4; Number of interventions per stage (1-2, 3, 4-5, 6-7); Quality of interventions: [-1] = poor, [0] = fair, [+1] = good.

3.3.2 Effectiveness of applied teaching strategies

According to questionnaire and interview responds, students experienced the highest learning gains according to two aspects. First, the behaviour of (combined) solar cells and, second, a strengthening and anchoring of prior knowledge learned during secondary education (e.g. electrical calculations and measurements, circuit creation and operation), mainly because they were crucial for facing the complex challenge. These experiences are in accordance with the analysis of high-gain questions in Table 3.6. But why did they learn?

The questionnaire contained a set of events that directly appeal to the teaching guidelines in Table 3.4. Each of the learning-related elements (A to E) was served by five events (25 in total) that were listed in no particular order. Students had to rate each event by using a five-point Likert scale (very poor, poor, fair, good, very good) based on what degree the event was helpful to learn more about electricity. Table 3.9 shows the results sorted by category. Furthermore, analysing open-ended questionnaire items and interview responds, resulted in a list of events that were most helpful, according to students, to learn about electricity. These events, shown in Table 3.10, were listed by the number of references that were made to the events by students.

Table 3.9 Effectiveness of events based on close-ended questionnaire items

	To what degree did the events help you learn more about electricity?					
Teacher-driven events	- -	-	0	+	++	N/A
A. Collaboration	**1**	**6**	**12**	**8**	**3**	**0**
■ You had to work together within design groups	0	1	2	2	1	0
■ You were encouraged to externalise ideas to other students	0	2	3	1	0	0
■ Working in groups was organised by a fixed structure	1	1	4	0	0	0
■ You had to share information with other design groups	0	2	1	2	1	0
■ The possibility to learn from other students	0	0	2	3	1	0
B. Reflection	**1**	**7**	**10**	**5**	**0**	**7**
■ You were obligated to self-reflect at fixed moments	1	3	2	0	0	0
■ Verifying the benefits of your reflection	0	1	2	0	0	2
■ The teacher stimulated reflective thinking during the process	0	2	2	2	0	1
■ You were assisted during reflection by peers and the teacher	0	0	2	2	0	2
■ You were encouraged to base future handling on reflection	0	1	2	1	0	2
C. Feedback	**0**	**3**	**9**	**12**	**5**	**1**
■ You had to write down and use received feedback	0	3	2	1	0	0
■ The teacher provided you with feedback instead of solutions	0	0	3	2	1	0
■ There were moments for providing and receiving feedback	0	0	2	2	2	0
■ You had to process received feedback in order to move forward	0	0	2	3	0	1
■ The teacher provided you with immediate feedback	0	0	0	4	2	0
D. Explicit teaching	**0**	**2**	**9**	**11**	**7**	**1**
■ The teacher discussed all learning objectives explicitly	0	0	5	1	0	0
■ The moments the teacher explained content	0	0	1	1	4	0
■ You were stimulated to use scientific terminology	0	2	1	3	0	0
■ The fact you had to explain your own knowing and doing	0	0	1	4	1	0
■ Electricity-related concepts were constantly addressed	0	0	1	2	2	1
E. Process-related issues	**2**	**4**	**8**	**8**	**8**	**0**
■ Received instructions and guidance during the challenge	0	0	1	2	3	0
■ The fact you could learn from failures	0	1	2	3	0	0
■ Presence of learning materials (e.g. constructions tools, ICT)	0	0	1	1	4	0
■ The fact the challenge was dived into smaller steps (stages)	0	1	3	1	1	0
■ You had to keep up a design diary	2	2	1	1	0	0

Five-point Likert rating scale: [--] = very poor, [-] = poor, [0] = fair, [+] = good, [++] = very good.

Table 3.10 Events helpful to learn more about electricity

Why have you learned about electricity? [a]	Number of references
Moments when underlying science was made explicit (supported by) by the teacher	22
Conducting experiments and applying insights in the design	15
Teacher-guided class discussions for sharing information and insights among design groups	13
Teacher feedback regarding conceptual content and process (no direct explication of science)	11
Clear instructions and transparency of what to do and deliver	9
Learning from peers within design groups	8
Other (e.g. learning from failures, absence of time pressure, reflection)	5

[a] Descriptions are revised to make categorisation possible.

Combining Tables 3.9 and 3.10 demonstrates that explicit teaching strategies, teacher feedback and process-related issues were highly appreciated by students to learn about electricity. Especially when interventions directly appealed to underlying science (e.g. explaining science, conducting experiments, sharing insights during class discussions) or when an ongoing learning process was stimulated (e.g. clear instructions, process feedback, equipment of the learning environment).

Analysing students' criticism, also based on open-ended questionnaire items and interview responds, resulted in a list of non-constructive or lacking elements (Table 3.11) that according to students were not helpful to learn about electricity of even impeded learning. According to this list, students mainly asked for additional learning events, helping them to explicate science and even to de- and recontextualise science addressed. For this, students proposed traditional teaching techniques, like performing demonstrations, addressing theoretical exercises/problems, explaining theoretical backgrounds and concept mapping. Furthermore, students hackled the amount of administration (extensive design diary), mainly because of the limited amount of administration that was necessary to learn or move on. For example, also explaining the moderate appreciation of reflection in Table 3.9, there was a lot of requested reflection, but in too little occasions this reflection affected advancement directly. As a result, reflection becomes disturbing and abortive.

Table 3.11 Non-constructive or lacking learning events

What interventions/events were not helpful or lacked to learn more about electricity? [a]	Number of references
Too few moments for explaining electricity concepts (in general)	16
Absence of exercises to activate prior knowledge or to deepen/anchor new knowledge	11
Too much administration (extensive design diary)	10
One-sided focus on solar cell-related issues / limited variety in contexts	8
A limited active use of obligated moments of reflection (and other design diary content)	6
Other (e.g. task duration and a lack of concentration, friction within the design group)	4

[a] Descriptions are revised to make categorisation possible.

3.4 Discussion and implications

Despite the fact this study concerns a limited number of participants, it enabled the detailed exploration of the interplay of teacher handling and concept learning during LBD. According to Zainal (2007), studies like this are necessary to provide holistic and in-depth information about complex social contexts where large quantitative studies often remain on the surface.

The developed framework of (concept) learning-related teacher strategies, which forms the theoretical basis of this study, appeared to be very useful to study the interplay of concept learning and teacher handling. During analysis, the clustered interventions pointed out to be complete and identifiable where preparatory skills are important to predict learning outcomes and set objectives. For example, by studying the pre-post-exam outcomes it seems plausible, just like the previous study showed, that high gain questions were appealed strongly during the challenge and were crucial for succeeding. Thus, again, it seems that detailed task analysis is useful to predict (conceptual) learning outcomes and to uncover task-driven concepts that are addressed directly: direct concepts. Additional, less directive (indirect) concepts, complementing the scientific knowledge domain, should be addressed otherwise (teacher-driven). The more, because the understanding of loose concepts strengthens when interrelationships between the majority of concepts within the knowledge domain are understood (Stoddart, Abrams, Gasper, & Canaday, 2010).

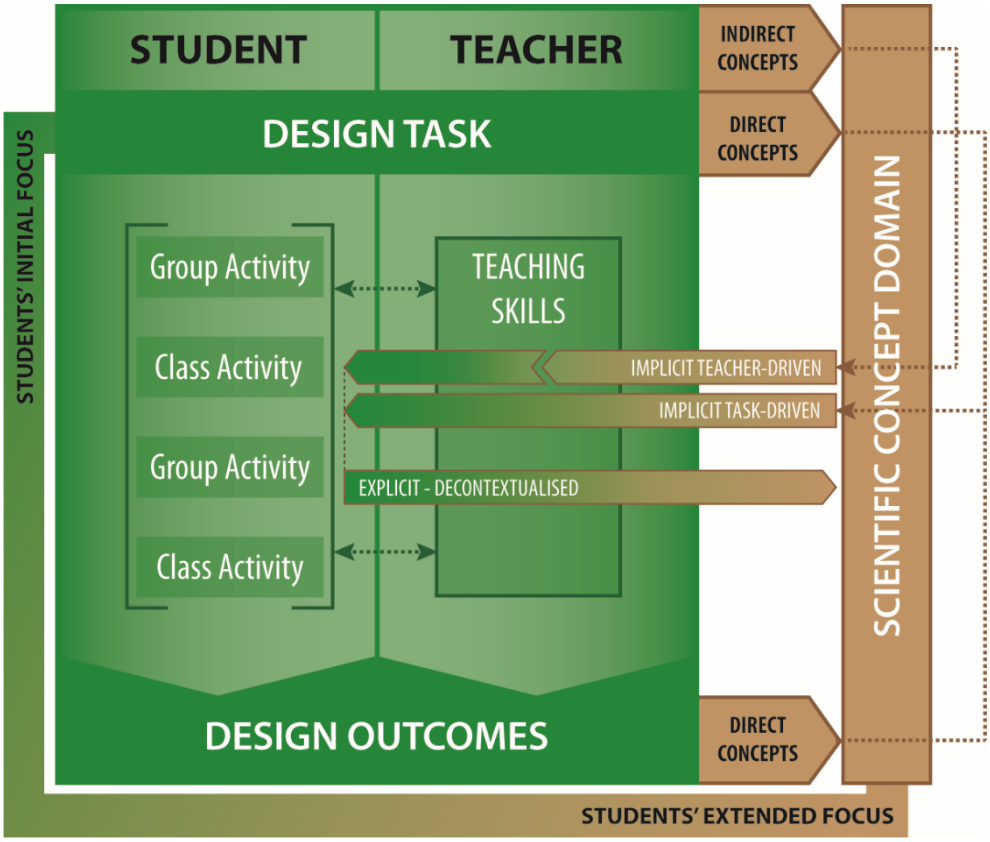
For learning concepts, explicit teaching strategies, teacher feedback and process-related issues were highly appreciated by students. Especially, when those

interventions directly appeal to underlying science (e.g. explaining science, conducting experiments, sharing insights during class discussions) or when an ongoing learning process was stimulated (e.g. clear instructions, process feedback, equipment of the learning environment). Unfortunately, analysis of teacher handling showed that most of the teacher interventions concerned the stimulation of collaboration and moments of feedback that were indirectly related to explaining science, like the third example in Table 3.7. Only 13 percent of all interventions concerned, to a greater or lesser extent, direct explication of underlying science. Furthermore, the challenge lacked sufficient de- and recontextualisation of addressed concepts, which was also an important criticism expressed by students.

In general, the results of this study (and the previous study) fit together with insights about knowledge transfer (Brandsford et al., 2003; Kolodner, Gray, et al., 2003; McCormick, 1997). To express this, the Design-based Science Interference Model in Figure 3.3 was developed. Conceptual knowledge, students need to learn, is always context-related (implicit) where direct concepts are strongly task driven and indirect concepts have to be teacher driven and complementary. To recognise and understand these concepts within the task context, they have to become explicit. For this, the teacher is crucial, as discussed before. To deepen conceptual understanding, important interrelationships between concepts have to become clear: at first inside the task context and subsequently context-free. By addressing the concepts in new contexts (recontextualisation) further comprehension should take place. Doing this, the initial task-related student focus, which appeared to be very strong in the previous study (general secondary education) compared with this study (student teachers), is extended to a better understanding of the entire (context-free) conceptual knowledge domain. Then, students should be able to master the conceptual framework independently from the context (knowledge transfer).

To strive for better knowledge transfer the LBD challenge concerning this study has several areas for improvement, from which every design-based learning challenge can learn. First, more explicit teaching strategies should be used to explicate direct concepts. Second, indirect concepts have to be addressed (stronger) during the task, including proper explication. Third, de- and recontextualisation of concepts is necessary for deeper understanding (e.g. by using traditional teaching techniques). Fourth, interrelationships between concepts should become explicit. Chapter 4 will take all suggestions for improvement, based on Studies 1 and 2, into account by translating them into task modifications and trying them out.

Figure 3.3 Design-based Science Interference model



4

Explicit teaching and scaffolding to enhance concept learning by design challenges

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4.1 Introduction

The studies central to Chapters 2 and 3 studied LBD's conceptual learning process in detail from a student's and teacher's perspective. By unravelling the learning process it became clear why and how students used and learned scientific concepts during design activities and how much room for improvement was left. The preliminary studies showed that students were able to manage a conceptual learning gain comparable to those achieved in many (traditional) physics-related courses (Hake, 1998). In that way, the findings of the LBD studies conducted by Kolodner, Gray, et al. (2003) are confirmed. Although students learned science at an apparently acceptable level, more progress should be possible because LBD, compared with traditional educational settings, provides a sound theoretical basis for a higher level of concept learning. A topic discussed in Chapter 1. The preliminary studies revealed two (interrelated) causes that prevented concept learning from reaching a (much) higher level. First, the complexity and extendedness of design challenges obscured scientific content (What to learn?) and forced students to become product and process focused (What to do and deliver?). This resulted in the use and learning of loose facts with too little coherence. Second, explication of underlying science had too little attention during task construction and teacher intervention, resulting in addressing an incomplete and disguised framework of conceptual knowledge. The study central to this chapter aims to address these problems by suggesting improvements, based on literature on learning sciences, concerning explicit teaching and scaffolding strategies, which will be discussed in detail later on. The central research questions are: Will application of explicit teaching and scaffolding strategies positively affect concept learning by offering a more comprehensive, coherent and explicit framework of scientific knowledge, and by how many this affects students' conceptual learning gains? Does skill performance, despite the interventions, still increase and how it is (cor)related with concept learning? Finally, a comparison takes place with previous studies to discover why and how the improvements affect (concept) learning.

4.2 Design of the challenge and modifications

For this study, an existing LBD challenge was modified for better concept learning. The challenge originated from the second study, discussed in Chapter 3, that concerned first-year student teachers (science), which will also be the case in this

study. Design groups (three students per group, randomly chosen) were challenged again to design a solar power system for a model house. All design specifications for room layout, solar powering and efficiency were adopted from the second study, just like the intended scientific objectives and general LBD stages and activities. For an overview of this content we refer to Figure 3.1 and Tables 3.1 to 3.3. In brief, students were encouraged to use underlying science and to go through processes of decision-making and creative thinking. Based on the interrelatedness of design specifications and scientific objectives, the most fundamental design principles concerned proper wiring (combining series and parallel parts), and regulating current, voltage and resistance for maximum efficiency. The entire process, which took six periods of 90 minutes, was guided through an instructive presentation and a student's and teacher's guide.

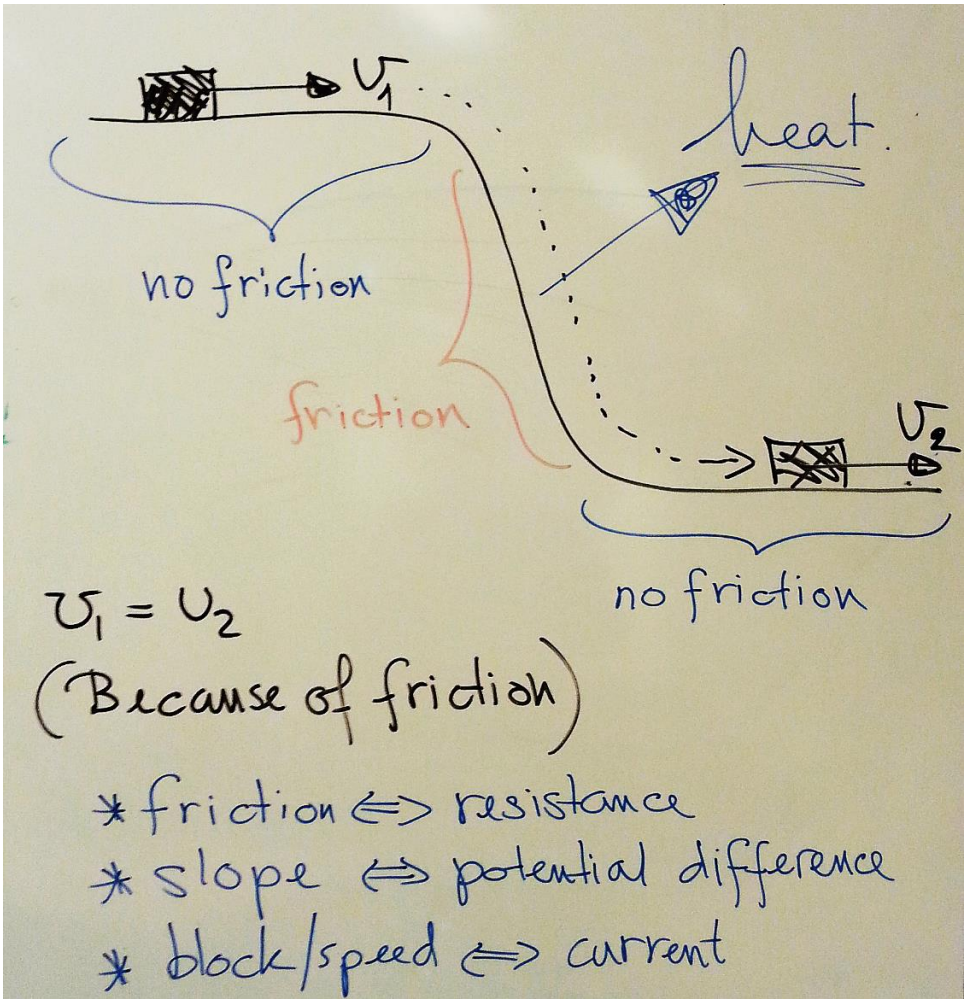
Although many components/elements of the challenge were adopted literally from the second study some important modifications were implemented to reduce the complexity and extendedness of the task and to enhance explicit teaching of underlying science. As mentioned, all modifications, discussed in the following subsections, mainly concerned explicit teaching and scaffolding strategies.

4.2.1 Backward design

The pre- and post-exam outcomes of the preliminary studies revealed that high gain question were strongly task related and crucial for succeeding. Thus, detailed task analysis is important to unravel task-exposed and -underexposed concepts and to predict learning outcomes. Additional less directive concepts, complementing the knowledge domain, should be addressed otherwise (teacher-driven) through additional teaching interventions. This approach corresponds to the idea of backward design (Wiggins & McTighe, 2006), which states that education designers must begin to think about assessment and objectives before deciding what to do and how to teach. Regarding the solar challenge, initially designed for Study 2, there were four topics of underexposed science: (1) conceptual nature of resistance, (2) nature of electrical energy and energy dissipation, (3) behaviour of current in components, (4) effect of voltage changes on circuit operation. To explore 1 to 3, students used simulation software and the fourth topic was addressed by additional experimentation. All topics, addressed as interludes, were complemented by class discussions and didactic analogies for clarification. Topic 1 and 3 were addressed after experimentation (stage 3) because experimentation contained resistance-

current measurements. Topic 2 was addressed after design testing (stage 6) because then efficiency calculations took place. Topic 4 was addressed after the final stage by replacing the solar cells in the final design with a traditional voltage source. Figure 4.1 shows a whiteboard picture, taken after class discussion, which illustrates an analogy between current and resistance, and gravitational motion on an incline. Where the latter was a familiar context for the participating student teachers.

Figure 4.1 Analogy between electrical resistance and gravitational motion



Although the spoken language during the challenge was Dutch, the analogy was written in English for use in this thesis and because the students teachers were used to English terminologies and physics literature.

4.2.2 Guided discussion

For teacher guidance during class discussion the technique of guided discussion (Carpenter et al., 1996) was used to highlight and explicate underlying science. When students worked in groups, they were challenged to think and make sense of what they were doing. Then, by observing students' thinking and doing it became clear what individual students understood about science. Based on this, the teacher made notes about which students should present their insights during class discussion. This might concern insights that are incorrect but useful to initiate a discussion of common misconceptions. Eventually, more sophisticated insights were used as input to head for proper reasoning and understanding. Both inputs and class discussion provide the teacher with information about students' knowledge and (existing) cognitive gaps, whereupon better understanding can be obtained.

4.2.3 Informed design

Informed design aims to enhance students' prior knowledge through preparatory activities, called knowledge and skill builders (KSBs) (Burghardt & Hacker, 2004). Then, students are better prepared to approach design challenges from a more knowledgeable base and to tackle design problems by conceptual closure. Based on Study 2, a preparatory activity was created for this study surrounding the behaviour of solar cells. Students involved in Study 2 incorrectly assumed, without testing, that collar cells behave like (ideal) voltage sources. This assumption resulted in insignificant and time-consuming experimentation and finally trial and error behaviour during design planning. To prevent this from happening, students had to do, during stage 2, some information seeking, accompanied by a class discussion regarding characteristics of (combined) solar cells.

4.2.4 Explicit instruction and scaffolding

According to Archer and Hughes (2011), explicit instruction is characterised by a series of supports or scaffolds where students are guided through the learning process with clear statements about the purpose of and rationale for learning activities. It embraces 16 instructional elements that aim for a systematic method of teaching with emphasis on proceeding in small steps, checking for student understanding, and achieving active and successful participation by all students. LBD

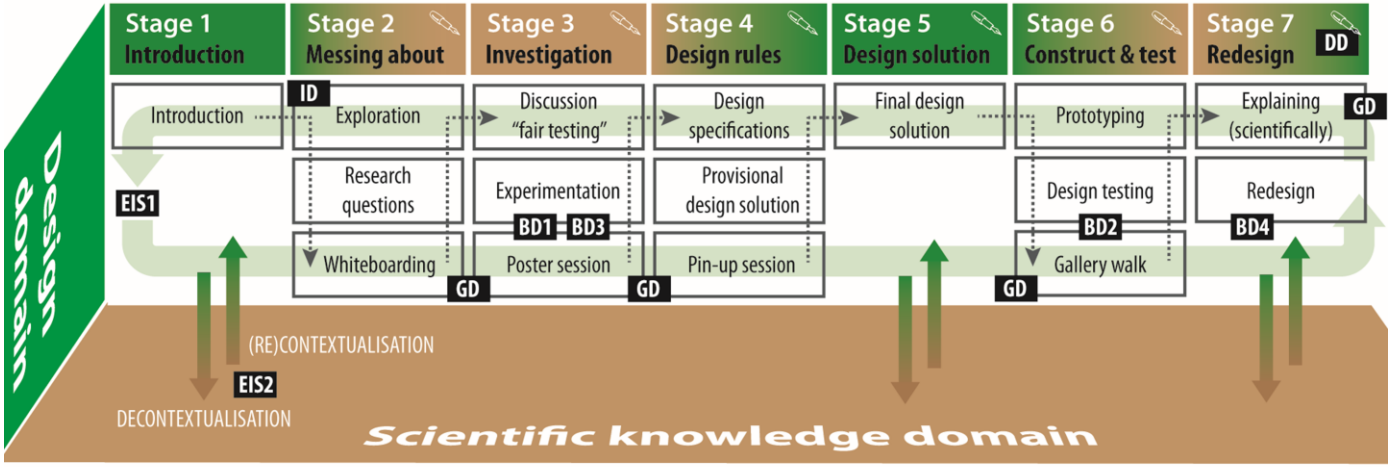
takes account of most of the elements and the adjustments mentioned before also fit into explicit instruction. However, teacher guidance should also fit the educational setting. Design challenges face teachers with a new kind of classroom control (Wendell, 2008) where teachers must relinquish directive control (Burghardt & Hacker, 2004). Thus, teachers need to develop pedagogical strategies for guiding complex design-based science tasks (Bamberger & Cahill, 2013). Study 2 that investigated these strategies resulted in a framework of important teaching guidelines (Table 3.4) that were directive for teacher handling during this study.

4.2.1 Adjustment of the design diary

Students involved in Studies 1 and 2 hackled the amount of administration (design diary) mainly because a limited amount of administration was necessary to learn or move on. For example, there was a lot of requested reflection but in too few occasions this affected advancement directly. As a result, reflection became disturbing and abortive. Therefore, administration was reduced and many written proceedings were replaced by process pictures accompanied by short subscriptions.

Figure 4.2 visualises all LBD stages and corresponding elements, which have already been discussed extensively in Chapters 1 to 3. Furthermore, the figure shows how the original LBD approach and discussed modifications interact.

Figure 4.2 Implementation of modifications in the LBD process



All stages and rectangular boxed activities in the white part of the figure are traditional LBD components. Colours: green colour = design-related focus; brownish colour = science-related focus. ✎ = moments of administration and reflection. Additions based on backward design: BD1 and BD3 = simulation, didactic analogy and class discussion to explicate the nature of resistance and the behaviour of current; BD2 = didactic analogy and class discussion to explicate the nature of electrical energy and energy dissipation; BD4 = experimentation of the effect of voltage changes on circuit operation. GD = guided discussion as approach for moments of teacher-guided class discussion. ID = preparatory activity based on informed design: studying the behaviour of (combined) solar cells. Modifications based on explicit instruction and scaffolding: EIS1 = teacher guidance based on the framework of teaching guidelines; EIS2 = continuous explication of addressed science. DD = adjustment of the design diary: reduced administration and reflection.

4.3 Method

Twenty-one first-year student teachers (science) took part in this design-based mixed methods study where they faced the improved solar challenge. All participants had prior experiences on characteristic LBD elements and sufficient prior knowledge regarding the science domain. The challenge was guided by the principal investigator (teacher trainer) because of the relatively small number of participants. According to Crouch and McKenzie (2006), as pointed out in Chapter 3, this offers the possibility to establish a sustainable relationship with participants and to provide added depth to the study, all resulting in an increased validity.

Quantitative data was collected to study students' progress in concept learning and video recordings were used to generate quantitative data about skill performances. Qualitative data was used to discover how task improvements affected concept learning by comparing students' comments to previous studies.

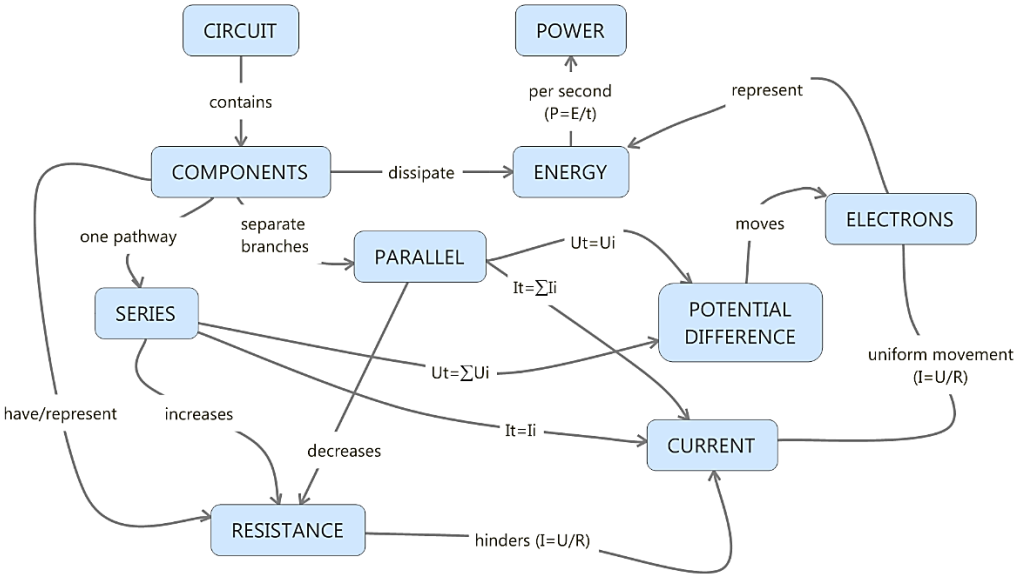
4.3.1 Data collection

To study a change in conceptual understanding, again the pre-post-exam developed for Study 2 was used. In brief, the characteristics of this test were: 46 multiple choice questions based on the validated Determining and Interpreting Resistance Electric Circuit Test (DIRECT) especially designed for use with high school and university students (Engelhardt & Beichner, 2004) where each scientific objective was served by multiple questions. Study 2 already showed, by using a control group, that there was no task learning effect from just completing the test.

Study 1 showed that students mainly learned incomplete concepts and had difficulties in making proper knowledge connections and therefore did not achieve deeper conceptual understanding. This conclusion was partially based on multiple choice tests. According to Stoddart et al. (2010), close-ended tests like this often fail to measure conceptual understanding because students easily can make guesses and therefore knowledge structures remain invisible. Using concept maps is suggested as a more meaningful way of assessing conceptual understanding. Therefore, beside multiple choice testing, students were asked to create a concept map before and after the challenge. For this, a proposition-based concept map test was developed, based on Yin, Vanides, Ruiz-Primo, Ayala, and Shavelson (2005), where students had to create 16 fundamental propositions (a connection between two concepts by using linking words or phrases) within a set of 10 predefined task-related concepts. The selection of concepts and the number of propositions were

based on a peer reviewed expert map, shown in Figure 4.3, designed by two experts. According to literature, proposition-based concept map tests, based on an expert map, appear to be superior to other mapping strategies in assessing conceptual understanding (Cañas et al., 2003; Rye & Rubba, 2002). It is important to note that Yin et al. (2005) established small task learning effects in some cases due to the development of mapping skills. Those effects will be minimal for this study because the student teachers were familiar with mapping techniques.

Figure 4.3 Expert concept map



To study an increase in students' skill performances we chose and slightly adapted the approach used in previous LBD research, by Holbrook, Gray, Fasse, Camp, and Kolodner (2001), in order to make comparison possible. Students were videotaped when working, partially in groups, on similar performance tasks before and after the challenge. Tasks were taken from the Performance Assessments Links in Science Website database (SRI International Center for Technology in Learning, 1999) and were suitable for use with senior high school students (aged 16 - 18); comparable to first-year student teachers in this study. During the pre-task students had to determine the power dissipated in a combination of two resistors connected in series to a battery. The post-task concerned the determination of how well different wires radiate heat when voltage is applied across each wire. Both tasks

included three parts: (a) students designed an experiment or procedure for fair testing, (b) students ran a specified experiment and collected data, and (c) students analysed the data to draw conclusions and make recommendations. The videotapes were analysed, also according to Holbrook et al. (2001), on seven science-related dimensions: negotiations during collaboration, distribution of efforts and tasks, attempted use of prior knowledge, adequacy of prior knowledge, scientific reasoning, experimentation skills and self-checks. Because the dimensions contain a mix of individual and collaboration skills, each activity (a to c) started with an individual preparation, followed by a sharing session and ended with task completion by teamwork.

Afterwards an open-ended questionnaire was used to investigate students' views on which activities stimulated or impeded concept learning. Questions were based on the STARR method that enables reflection on learning outcomes (Verhagen, 2011). By interpreting students' answers, also in the light of preliminary studies, it is possible to establish whether the improvements are appreciated or room for improvement is left. Open-ended questions were used to prevent students' views from being swayed by possible answers. To verify the questionnaires' data reduction and interpretations, nine students, the number that made themselves available, were interviewed simultaneously (respondent validation through focus group discussion). During this session also some remarkable differences and correlations regarding learning outcomes were discussed for deeper understanding.

4.3.2 Analysis

The multiple choice tests were scored per student by the proportion of correct answers among 46 items. Proportions were used to calculate the gain $\langle g \rangle$: ratio of actual average gain (post – pre) to the maximum possible average gain (1 – pre) (Hake, 1998). A paired samples t test and a Wilcoxon signed-rank test were performed to investigate differences between pre- and post-scores. This combination was used because literature indicates that for relative small sample sizes using both tests increases the possibility to detect type I and II errors (Meek, Ozgur, & Dunning, 2007). Establishing Cronbach's alpha revealed the internal consistency of the exam.

The concept maps were scored per student. For this, all propositions (16 per concept map) were rated by two experts individually. Based on Yin et al. (2005) and Rye and Rubba (2002), the following scores were awarded: three points for a

scientifically correct expert proposition (analogous to the expert map), two points for other correct propositions, one point for a weak or partially correct proposition and no points for incorrect propositions. Based on the experts' allocated scores, the linear weighted Cohen's Kappa was calculated, which was sufficient. Then, the experts' average scores were assigned as final scores. Finally, the proportion scores (based on a 48 maximum score) were used, similar to multiple choice test analysis, to calculate gains and to investigate pre-post-score differences.

Analysis of the videotaped performance assessments took place by using a scoring rubric (Table 4.1) where each performance dimension was served by a five-point rating scale (1 to 5), with five being the highest level/score. Although the rubric's scale and dimensions are similar to that used by Holbrook et al. (2001), the level descriptors were adjusted for more validity. The original rubrics assessed skill performances by capturing the extent to which students in a group participated in practicing a skill: if more students were actively involved the group got a higher rating. According to Jonsson and Svingby (2007), this (possibly) causes validity problems because this method fails to reveal the quality of students' individual performances. Because a well-validated rubric, matching all the skill dimensions, was not available, a rubric was created by combining existing rubrics. For this, we used an available qualitative framework of criteria to guaranty an acceptable level of validity because a more sophisticated approach, achievable within this study, is still in its infancy (Baartman, Bastiaens, Kirschner, & Van der Vleuten, 2006; Moskal & Leydens, 2000). In short, rubrics compromising the following properties were selected: applicability to a five point scale, level descriptors based on observable behaviour of individuals, univocal descriptors that actually reflect the skill dimension, some degree of validation, (some) development based on experiences, expert involvement and applicable for the target group. Based on the final rubric, two experts rated students' skill competences individually, whereupon, after establishing an acceptable Cohen's Kappa, the experts' mean ratings were assigned as final scores. Differences between pre- and post-ratings were also tackled by paired samples *t* tests and Wilcoxon signed-rank tests.

To investigate the strength of the relationships between pre- and post-assessment variables, the Pearson product-moment correlation coefficient was computed for all possible combinations of variables. It is particularly interesting to find out how the multiple choice test and concept map test are correlated because they both concern conceptual knowledge. Furthermore, it reveals which skills strongly interacted with conceptual learning.

Table 4.1 Scoring rubric for assessing skill dimensions

[1] Negotiations[a]				
1	2	3	4	5
Not at all	Rarely makes compromises to accomplish a common goal and has difficulty getting along with other group members.	Occasionally makes compromises to accomplish a common goal, and sometimes helps keep the group working well together.	Usually makes necessary compromises to accomplish a common goal.	Consistently makes necessary compromises to accomplish a common goal.
[2] Distributed efforts and tasks[a]				
1	2	3	4	5
Not at all	Performed little duties of assigned team role and contributed a little amount of knowledge, opinions, and skills to share with the team. Relied on others to do the work.	Performed a few duties of assigned team role and contributed a small amount of knowledge, opinions and skills to share with the team. Completed some of the assigned work.	Performed nearly all duties of assigned team role and contributed knowledge, opinions, and skills to share with the team. Completed most of the assigned work.	Performed all duties of assigned team role and contributed knowledge, opinions, and skills to share with the team. Always did the assigned work.
[3] Using prior knowledge[b]				
1	2	3	4	5
Not at all	Identifies connections between prior events and experiences or prior concepts that relate to the context.	Identifies multiple prior experiences and events or prior concepts that relate to the context.	Prior events, experiences and concepts are identified and applied to the problem.	Prior events, experiences and concepts are routinely recalled that assist in problem solving.
[4] Adequacy of prior knowledge[b]				
1	2	3	4	5
Not at all	At least one of the mentions of prior knowledge is followed up on and is useful.	A few of the mentions of prior knowledge were appropriate to the problem and used during the process.	Multiple mentions of prior knowledge were effectively selected and followed up on and were important for succeeding.	Nearly all mentions of prior knowledge are routinely followed up on and were important for succeeding and understanding.

Table 4.1 Continued

[5] Use of science terms, scientific reasoning[c]				
1	2	3	4	5
Not at all	States ambiguous, illogical, or unsupported conclusions without proper use of science concepts. Demonstrates no ability to distinguish between causal and correlational relationships.	States general conclusions by using science terms, but beyond the scope of the inquiry findings limitations and implications. Demonstrates limited ability to distinguish between causal and correlational relationships.	States scientifically formulated conclusions focused solely on the inquiry findings. The conclusion arises specifically from and responds to findings. Demonstrates appropriate ability to distinguish between causal and correlational relationships.	States a scientifically formulated conclusion that is a logical extrapolation from the inquiry findings limitations and implications. Demonstrates advanced ability to distinguish between causal and correlational relationships.
[6] Experimentation and fair testing[d]				
1	2	3	4	5
Not at all	Experimentation was done chaotically, without (proper) knowledge of how to control variables. At least one variable was tested.	Only some of the experimental tasks were done satisfactorily; some understanding of fair testing was present by controlling at least two (dependent) variables.	Most of the experimental tasks were done neatly and satisfactorily; an acceptable amount of understanding of fair testing and controlling for variables was present.	Experimental tasks were done in an organised and effective way by understanding for fair testing and controlling all variables.
[7] Self-checks[d]				
1	2	3	4	5
Not at all	A few improper self-checks took place without serious consideration for improvements.	A few self-checks took place by questioning several aspects of the procedure but were not properly addressed (without serious consideration)	(Some) self-checks took place by questioning several aspects of the procedure but were not optimally addressed.	Self-checks took place by questioning several aspects of the procedure and affected in improvements while performing the task

[a] Adapted from Franker (2015). [b] Adapted from Rhodes and Finley (2013). [c] Adapted from Rhodes (2010). [d] Adapted from Chan (2009).

For questionnaire analysis, at first to categorise responds, we distinguished between positive and negative opinions on the process of conceptual learning. After this, within these categories, common themes were grouped and tagged by a description, resulting in sub-categories of impeding or stimulating properties. Finally, all questionnaires were re-read to make sure all responses were categorised properly. During the group interview, all properties were discussed and, based on students' input, slightly customised or filled up. Finally, remarkable differences and correlations regarding assessment outcomes were accompanied by a uniform group opinion on how to interpret results. For theoretical underpinning of students' opinions, scientific literature was searched through.

4.4 Results

Table 4.2 gives a complete overview of all pre- and post-assessment results per student including mean scores and standard deviations. For the multiple choice test the average Cronbach's alpha, based on individual objectives, is 0.72 for the pre-test and 0.69 for the post-test. The linear weighted Kappa values for the concept map and performance assessment analysis are shown in Table 4.3. Thus, in the case of all assessments the reliability is sufficient.

The conceptual learning gains for the multiple choice test are significant, $t\,(20) = -30.87$; $p < 0.001$, just as for the concept map test, $t\,(20) = -24.58$; $p < 0.001$. This is confirmed by the Wilcoxon signed-rank test that gives the same p - value for both tests. The mean gain for the multiple choice test (0.68) significantly increased compared with Study 2 (0.49) and Study 1 (0.35) and exceeds conceptual gains (LBD) found by Holbrook et al. (2001) that revealed mean gains up to 0.40. Compared to a large previous survey of pre-post-test multiple choice data for physics courses (Hake, 1998), that showed maximum gains between 0.60 and 0.70, our students were equally successful. Remarkably, the highest gains found by Hake (1998) resulted from interactive engagement (IE) methods that were designed, similar to LBD, to promote conceptual understanding through heads- and hands-on activities contributed by (peer) feedback, collaboration and intensive teacher guidance. Incidentally, a critical comment should be made because mapping test data showed significantly lower ($p < 0.001$), but still substantial, gains (mean gain = 0.49; lowest gain = 0.37; highest gain = 0.64). This will be discussed in detail later on.

Table 4.2 Results pre- and post-assessments: multiple choice test, concept map test, skill performances

	Multiple choice			Concept map			Performance assessment[b]													
	Proportion			Proportion			Negotiations		Distr.eff.tasks		Pr.know.use		Pr.know.adeq.		Scient.reas.		Experiment.		Self-checks	
Stud.	Pre	Post	Gain[a]	Pre	Post	Gain[a]	Pre	Post	Pre	Post	Pre	Pre	Post	Pre	Post	Pre	Post	Post	Pre	Post
1	0.37	0.80	0.69	0.40	0.72	0.57	2.00	3.00	2.50	3.00	2.00	3.00	1.50	4.00	2.00	3.00	3.00	4.00	1.50	4.00
2	0.37	0.78	0.66	0.40	0.64	0.43	3.00	4.00	3.00	5.00	1.00	2.50	1.00	3.00	1.00	2.50	2.50	3.50	2.00	3.00
3	0.39	0.78	0.64	0.41	0.70	0.53	2.50	3.00	3.00	3.00	1.50	2.50	2.00	3.00	1.50	3.00	3.00	4.50	2.00	4.00
4	0.57	0.91	0.80	0.58	0.79	0.56	1.00	2.00	2.00	3.00	4.50	5.00	4.00	5.00	3.00	4.00	3.50	4.00	2.00	4.00
5	0.46	0.83	0.68	0.49	0.67	0.38	1.00	2.00	1.50	3.00	3.00	4.00	3.00	4.50	3.00	4.00	2.50	4.00	1.00	4.00
6	0.35	0.78	0.67	0.36	0.63	0.44	3.00	3.00	2.00	2.50	2.00	3.00	2.00	3.00	2.00	4.00	3.00	3.50	2.00	5.00
7	0.28	0.70	0.58	0.33	0.56	0.37	2.50	3.50	3.00	3.00	2.00	3.00	1.50	3.50	1.00	2.50	3.00	5.00	2.00	3.50
8	0.41	0.78	0.63	0.43	0.70	0.51	2.00	4.00	2.50	3.00	3.00	4.00	3.00	4.00	2.50	4.00	3.50	4.50	2.00	4.00
9	0.41	0.78	0.63	0.41	0.69	0.51	2.00	2.50	2.00	3.00	2.50	4.00	2.50	4.00	2.50	4.00	1.50	4.00	1.00	4.00
10	0.28	0.85	0.79	0.29	0.66	0.55	1.00	2.00	1.50	3.00	1.00	3.00	1.50	4.00	1.00	3.00	2.00	3.50	2.00	3.50
11	0.33	0.72	0.58	0.33	0.60	0.43	2.00	4.00	2.00	4.50	2.00	4.00	2.00	3.50	2.00	3.00	2.00	3.00	2.00	3.00
12	0.46	0.78	0.60	0.43	0.67	0.45	2.50	3.00	2.00	3.50	2.00	3.00	2.50	3.50	3.00	3.50	2.00	3.00	1.50	4.00
13	0.33	0.76	0.65	0.38	0.61	0.41	2.00	3.50	3.00	4.00	2.00	3.00	1.50	3.00	1.00	3.00	1.50	3.00	2.00	3.00
14	0.35	0.74	0.60	0.44	0.64	0.38	3.00	4.00	2.00	4.00	2.00	4.00	2.00	4.00	2.00	3.50	2.50	3.50	2.00	4.00
15	0.39	0.83	0.71	0.39	0.68	0.51	2.00	4.00	2.50	5.00	2.00	4.00	2.00	4.00	1.50	3.00	3.00	4.00	1.00	4.00
16	0.39	0.83	0.71	0.42	0.71	0.54	2.00	2.50	2.00	3.00	2.00	4.00	2.00	4.00	2.00	3.00	3.00	4.00	2.00	5.00
17	0.46	0.87	0.76	0.39	0.75	0.64	3.50	4.00	3.00	4.00	3.50	4.50	3.00	4.00	3.00	3.50	3.00	3.00	2.50	5.00
18	0.24	0.72	0.63	0.28	0.59	0.46	2.00	3.50	3.00	4.00	1.00	3.00	1.00	4.00	1.50	2.50	3.00	4.00	2.00	4.50
19	0.22	0.80	0.75	0.30	0.61	0.48	2.50	3.00	2.00	4.00	1.50	3.50	1.00	4.00	1.00	2.00	3.50	4.50	3.00	3.00
20	0.39	0.83	0.71	0.36	0.69	0.54	2.50	3.00	3.00	3.50	2.00	4.00	2.00	4.00	1.00	2.50	3.00	5.00	2.50	4.00
21	0.37	0.83	0.72	0.42	0.73	0.58	2.00	4.00	3.00	4.00	2.00	3.50	2.00	4.50	1.50	3.00	2.50	4.00	3.00	5.00
Mean (SD)	0.37 (0.08)	0.80 (0.05)	0.68 (0.07)	0.39 (0.07)	0.67 (0.06)	0.49 (0.07)	2.19 (0.66)	3.21 (0.72)	2.40 (0.54)	3.57 (0.71)	2.12 (0.84)	3.55 (0.67)	2.05 (0.76)	3.83 (0.53)	1.86 (0.74)	3.17 (0.60)	2.69 (0.60)	3.88 (0.61)	1.95 (0.55)	3.98 (0.66)

Stud. = student; SD = standard deviation.

[a] Gain-index: $\langle g \rangle$ = (post - pre) / (1 - pre); high gain; $\langle g \rangle \geq 0.70$, medium gain: $0.70 > \langle g \rangle \geq 0.30$, low gain: $\langle g \rangle < 0.30$ (Hake, 1998).

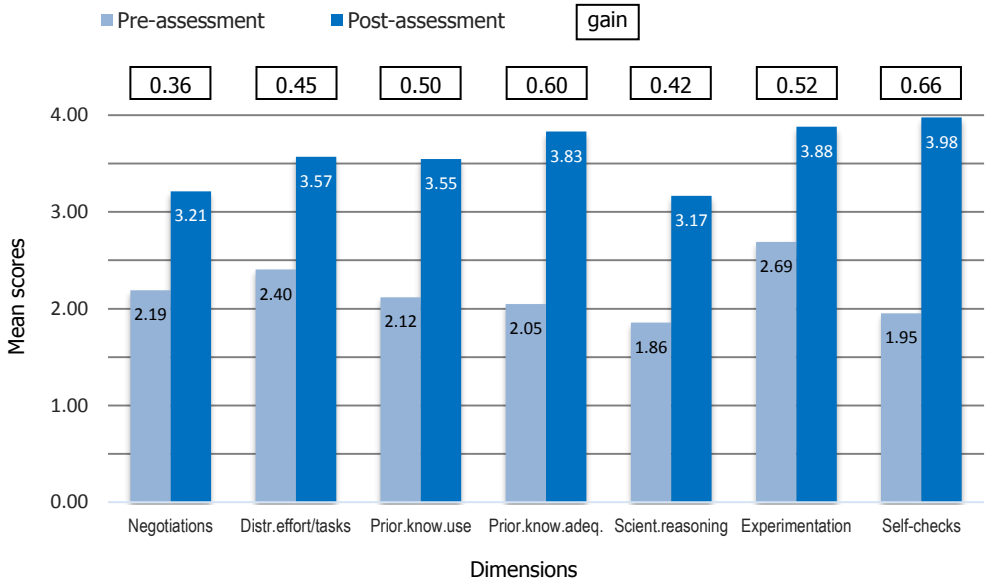
[b] Mean scores awarded by two experts per skill dimension, based on a 5-point scoring rubric with 5 being the highest rating. Dist.eff.tasks = distribution of efforts and tasks; Pr.know.use = use of prior knowledge; Pr.know.adeq. = adequacy of prior knowledge; Scient.reas. = scientific reasoning; Experiment. = experimentation.

Table 4.3 κw for concept map and performance assessment ratings

Test	κw pre-ratings (limits)	κw post-ratings (limits)
Concept map test	0.68 (lower = 0.62; upper = 0.74)	0.65 (lower = 0.58; upper = 0.72)
Performance assessment	0.62 (lower = 0.52; upper = 0.72)	0.66 (lower = 0.58; upper = 0.74)

Studying the performance assessment results in Table 4.2, shown graphically in Figure 4.4, it indicates that all skill dimensions show an increase in achievement level, where the highest progressions concern the adequacy of prior knowledge, experimentation skills and self-checks. However, all improvements are significant ($p < 0.001$) and fairly comparable to the performance assessment results found by Kolodner, Camp, Crismond, Fasse, Gray, et al. (2003). Those results showed scores between 2.00 and 3.00 for honours non-LBD students (the category befitting the students in our study at pre-testing) and scores up to 4.00 for typical LBD students (students exposed to LBD). Overall, students in this study reached, compared with previous LBD studies, much higher conceptual learning gains, while advancement in skill performances was not hindered.

Figure 4.4 Mean skill performances based on assessment results



Dimensions and results are based on Table 4.2. Gain = (post – pre) / (5 – pre).

According to Table 4.4 there were strong (significant) positive correlations between the pre-scores of the multiple choice and concept map test, as well as for the post-scores. The gains of both tests showed a lower, but fair, correlation (r = 0.683, n = 21, $p < 0.01$) that can be explained by the fact that the mean gain for the concept map test was significant lower compared with the multiple choice test. According to Constantinou (2004), multiple choice test and concept map test results vary to a greater or lesser extent, depending on which kind of learning is assessed through the multiple choice test (e.g. rote learning or meaningful learning). In general, Ruiz-Primo, Schulz, and Shavelson (1997) state that the correlation between both tests should be positive because they measure the same knowledge domain, but the magnitude may differ. The interviewed students all agreed that the concept map test was more difficult because it stronger appealed to mastering well organised, relevant knowledge structures.

Table 4.4 Positive Pearson product-moment correlations of assessment results

Variables		1	2	3	4	5
1. Multiple choice test	Pre	-				
	Post	-				
2. Concept map test	Pre	0.900**	-			
	Post	0.831**	-			
3. PA - Prior knowledge use	Pre	0.790**	0.766**	-		
	Post	0.496*	0.500*	-		
4. PA - Prior knowledge adequacy	Pre	0.883**	0.817**	0.920**	-	
	Post	0.568**	0.550**	0.725**	-	
5. PA - Scientific reasoning	Pre	0.758**	0.689**	0.753**	0.834**	-
	Post	0.692**	0.426	0.447*	0.428*	-

Based on pre-post-results in Table 4.2. PA = performance assessment. *$p < 0.05$; **$p < 0.01$.

Furthermore, Table 4.4 shows moderate or strong positive correlations between the conceptual tests and three dimensions of the performance assessment (use and adequacy of prior knowledge and scientific reasoning) that also positively correlated with each other. Other positive or negative correlations between variables were not found or appeared to be weak or occasional. These findings correspond to previous findings: Schreiber, Theyßen, and Schecker (2016) found high correlations between conceptual tests and the preparation and evaluation of experiments, where prior knowledge and scientific reasoning are important, and low correlations with respect

to conducting the experiment by following the rules for fair experimentation. Stone (2014) states that general skills, like collaboration and reflection, have a limited interconnectedness with science-specific skills (practices) and the knowledge domain, where Zimmerman (2000) explicitly mentions the weak relation between conducting reception experiments and mastering conceptual knowledge, and strong relations between conceptual knowledge, prior knowledge and scientific reasoning. All these insights perfectly reflect our findings where the interviewed students also emphasised the concept-free character (according to science knowledge) of collaboration, reflection and conducting a prescribed experiment. On the other hand, students compared the use and adequacy of (prior) knowledge in relation to scientific reasoning, to the mental activity important for creating a concept map, which reflects the mastering of knowledge structures.

Table 4.5 Positive and negative opinions about concept learning

Influences on concept learning			
Stimulating factors (N = 106)	Perc.	Impeding factors (N = 44)	Perc.
Explication of underlying science by the teacher	28	Fragmentation of addressed science	36
(Results of) conducted experiments and simulations	20	Fragmentation of the task	29
Learning from peers: collaboration, sharing information, peer feedback	16	Uncertainty and uncomfortability (because of the new educational setting)	13
Teacher feedback during the task (not including direct explication of science)	13	Too little attention to deeper assimilation of addressed science	11
Clear instructions and transparency of tasks and objectives	12	Other (e.g. false information sharing, task duration)	11
Other (e.g. reflection, information seeking, the design context)	11		

Perc. = relative distribution (%) of all questionnaire replies within each category on which the corresponding sub-categories were distracted. Descriptions were redefined based on the group interview.

Table 4.5 shows the results of the questionnaire analysis where the number of positive replies largely exceeds the negative ones. According to students, activities that directly appeal to underlying science (explicit teaching and experimentation) are invaluable for concept learning, complemented by sufficient teacher and task guidance (feedback, clear instructions and transparency). These results are perfectly consistent with the results of Studies 1 and 2. It is, however, surprising that in this

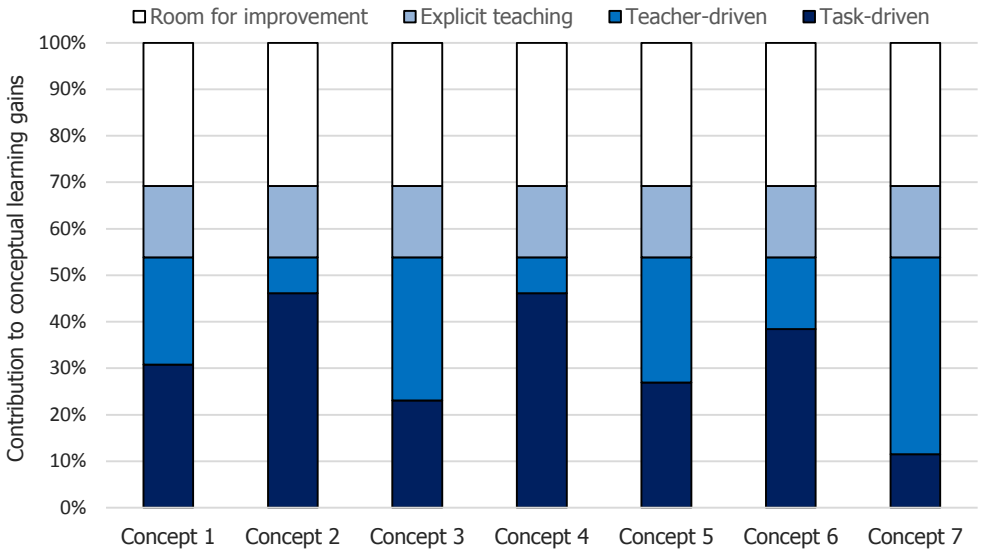
study learning from peers is clearly more appreciated. Maybe because this study revealed less trial and error behaviour and therefore students acted more like a role model or because the guided discussion approach, where the use of students' insights is directive, clarifies that peers are an important learning source. Although interviewed students seemed to confirm both statements a sloid validation failed to appear because students could not reach a uniform statement.

Taking the impeding factors into account, fragmentation is still an issue. First, students experienced too little coherence in addressed science and, second, students described the number of stages and accompanying administration as disruptive to the ongoing learning process. Also some students missed assimilation of addressed science for anchoring. Compared with the preliminary studies, the initial problems of addressing an incomplete science domain and a lack of science explication seem to be tackled. However, despite the improvements, coherence still is an issue and the amount of administration is still disruptive.

4.5 Discussion and implications

The adjustments, deduced from the two preliminary studies, to enhance concept learning by design challenges seem to be successful because this study reveals a solid improvement of conceptual learning gains without reducing a positive effect on skill performances. Especially, when the multiple choice test results (the assessment form used in all studies) are taken into account: gain-indices increased from the lower limit of medium (> 0.30) up to the very margin of high (0.70) where the latter is more or less reserved for the most successful physics-related courses (Hake, 1998). Students' responses show, which can be considered as an important reason for improved concept learning, that in contrast to the preliminary studies little comments were made about a lack of (explicit) science teaching. It seems that a combination of backward design, guided discussion and informed design is an appropriate remedy to enhance concept learning by extending strongly task-driven concepts and further deepening of all concepts. This happens, first, by introducing additional teacher-driven concepts (weakly task-driven) to complement the knowledge domain; important for understanding individual concepts. Second, by explicating and deepening all science addressed (explicit teaching). Figure 4.5 illustrates how contributions to conceptual learning gains may possibly collude where, of course, nearly always room for further improvement is left.

Figure 4.5 Quantitative model for contributions to conceptual learning gains



The (distribution of) percentages and number of concepts are fictional and just used for illustration purposes where there is some resemblance to percentages found in the series of LBD studies. Concepts 1 to 7 represent the knowledge domain.

This study provides some interesting clues where to search for further improvements. First, this study reveals significant positive correlations between students' conceptual performances, the use and adequacy of (prior) knowledge and scientific reasoning. Second, although students reached substantial conceptual learning gains, the concept map test gains were significantly lower compared with multiple choice test gains. Third, students compared the use and adequacy of (prior) knowledge combined with scientific reasoning to the mental activity important for creating concept maps. Fourth, students mentioned the fragmentation of addressed science and a lack of deeper assimilation of addressed science as important shortcomings. Thus, combining all four, more coherence of addressed science may be valuable because mastering explicit interrelationships between domain concepts enhances learning (Brandsford et al., 2003; Wiggins & McTighe, 2006). This may also improve the adequate use of knowledge and scientific reasoning and, with this, meaningful learning (important for concept mapping).

Beside fragmentation of science addressed, according to students, the same comment applies to the task itself. Although students experienced sufficient guidance and task transparency, they described the number of stages and accompanying administration as disruptive to the ongoing learning process. Maybe a reduction of the number of (separate) stages and activities, through amalgamation, offers more coherence and less administration where guidance and scaffolding is shifted towards the ongoing process itself rather than breaking it down into parts.

To conclude, both aspects of fragmentation, as discussed before, will be the main topic for the final study, central to Chapter 5, that tries to provide a sophisticated educational strategy for design-based learning activities. However, in general, this study revealed some more interesting research themes. First, it is interesting to study the interaction between skill and concept learning in detail because both types of learning are (partly) correlated and may strengthen each other. All the more, because learning (STEM) skills is regarded as an important goal for modern education, driven by a complex world economy that demands for those skills (ICF & Cedefop for the European Commission, 2015). Second, more insight is needed into the creation, use and validation of rubrics to assess skills. Third, correlations between multiple choice tests and concept map tests are often significant but widely spaced (Constantinou, 2004). Therefore it is necessary investigate this correlation in detail and to find out how conceptual knowledge can be assessed properly depending upon the learning objectives.

5

The FITS model: an improved Learning by Design approach

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5.1 Introduction

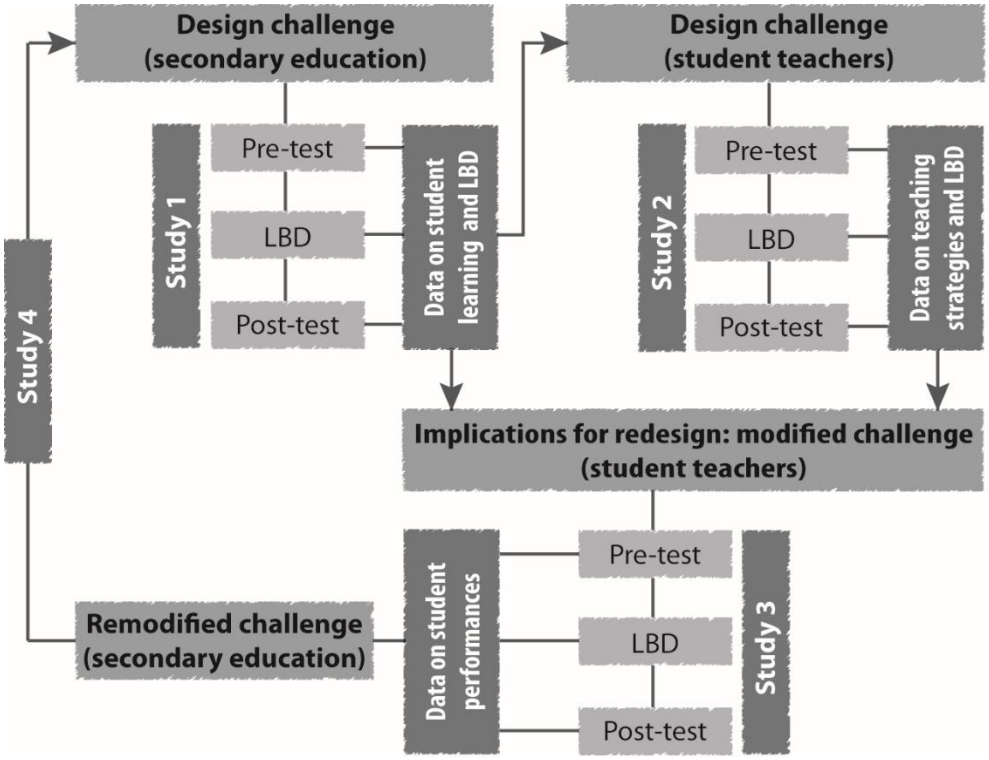
Previous to the study discussed in this chapter three studies (Chapters 2 to 4) investigated the practice of LBD aiming for enhanced concept learning. The series of studies is visualised in Figure 5.1, adopted from Chapter 1, which is necessary to enhance the readability of this chapter because this chapter addresses all previous studies. The first and second study (Chapters 2 and 3) confirmed the findings of Kolodner, Gray, et al. (2003) and showed that students reached conceptual learning gains comparable to those achieved in traditional physics courses (Hake, 1998). More importantly, the studies revealed two interrelated causes that prevented concept learning from reaching a potentially higher level. First, the complexity and extendedness of design challenges made students process and product focused (What to do and deliver?) and obscured scientific content (What to learn?). Second, explication of underlying science had too little attention during task construction and teacher intervention. Both issues caused the learning of loose, incoherent facts and produced an incomplete, disguised framework of conceptual knowledge. A third study among 21 students (Chapter 4) examined the effect of improvements based on explicit teaching and scaffolding strategies. Those improvements resulted in learning gains that significantly exceeded previous gains without reducing positive effects on skill performances. However, beside a small number of students involved, the study revealed two limitations: fragmentation of the task (large number of stages and administration) interfered with the learning process and fragmentation of science addressed (lack of coherence and assimilation) hindered concept learning.

Based on these findings the traditional task developed for Study 1 was adapted for use in this study. First, by implementing modifications based on explicit teaching and scaffolding, comparable to the task developed for the third study. Second, the development of a remodified approach (FITS model: Focus - Investigation - Technological design - Synergy) by implementing additional improvements reflecting the outcomes of the third study: reduction of administration and stages, through amalgamation, and the addition of two traditional science lectures to merge and assimilate science. In summary, the FITS model includes all traditional LBD activities, but several activities are enriched by pre-planned elements for implementing a complete framework of conceptual knowledge and to guarantee design completion from a more knowledgeable base. All (science) content is explicated during the task through explicit teaching strategies and de- and recontextualisation (to facilitate knowledge transfer). For deeper understanding and conceptual coherence, two

science lectures addressed all science involved where especially during the final (synergy) phase it becomes explicit how science and (design) technology enrich each other: concepts and investigation outcomes become more meaningful because their purpose is visible in the design and the design is developed by a more conceptual and systematic approach. The reduction of stages and administration stimulates the ongoing learning process where guidance and scaffolding is shifted towards the ongoing process itself rather than breaking down the process into parts.

The research questions are therefore: Are the improved conceptual learning gains of the previous exploratory studies confirmed quantitatively by the modified LBD group results (by comparison with the traditional approach developed for the first study)? By how many the students' conceptual learning gains will further increase due to application of remodifications resulting in the FITS model?

Figure 5.1 Overview of the studies

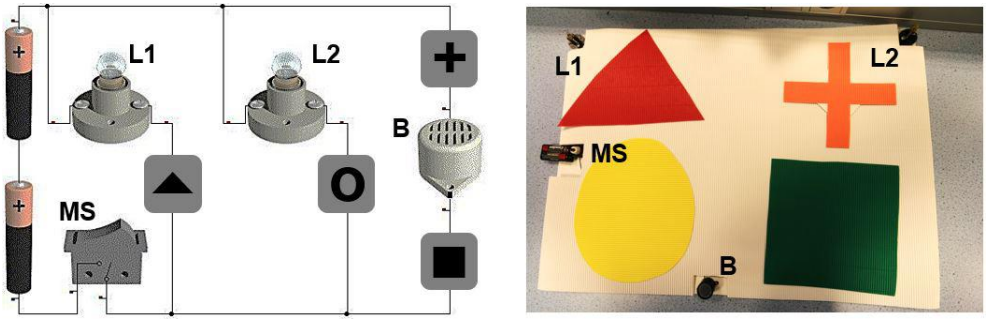


Adopted from Chapter 1, section 1.6.

5.2 LBD task and (re)modifications

For this study the traditional LBD task designed for the first study, discussed in Chapter 2, was used where design groups (four students per group) were challenged during five to six class periods of 100 minutes, to design a battery-operated dance pad that let them use their feet to sound a buzzer or flash lights. Briefly, the design, as shown in Figure 5.2, had to consist of four self-designed floor pads and one readily available main power switch. Four design specifications described circuit operation and three specifications stimulated the process of decision-making and creative thinking by allowing a restricted availability of materials and demanding a durable, attractive design. Thus, the most fundamental scientific design principles, driven by the scientific learning objectives, were proper wiring and fundamental conditions for circuit operation (knowledge about series and parallel circuits and current flow) and a proper use of conducting and insulating materials for floor pad creation (resistance and current flow). To investigate and design circuits students used a simulation (PhET™ DC-circuit construction kit) and real experimentation. A detailed task description can be found in Chapter 2, section 2.2.1.

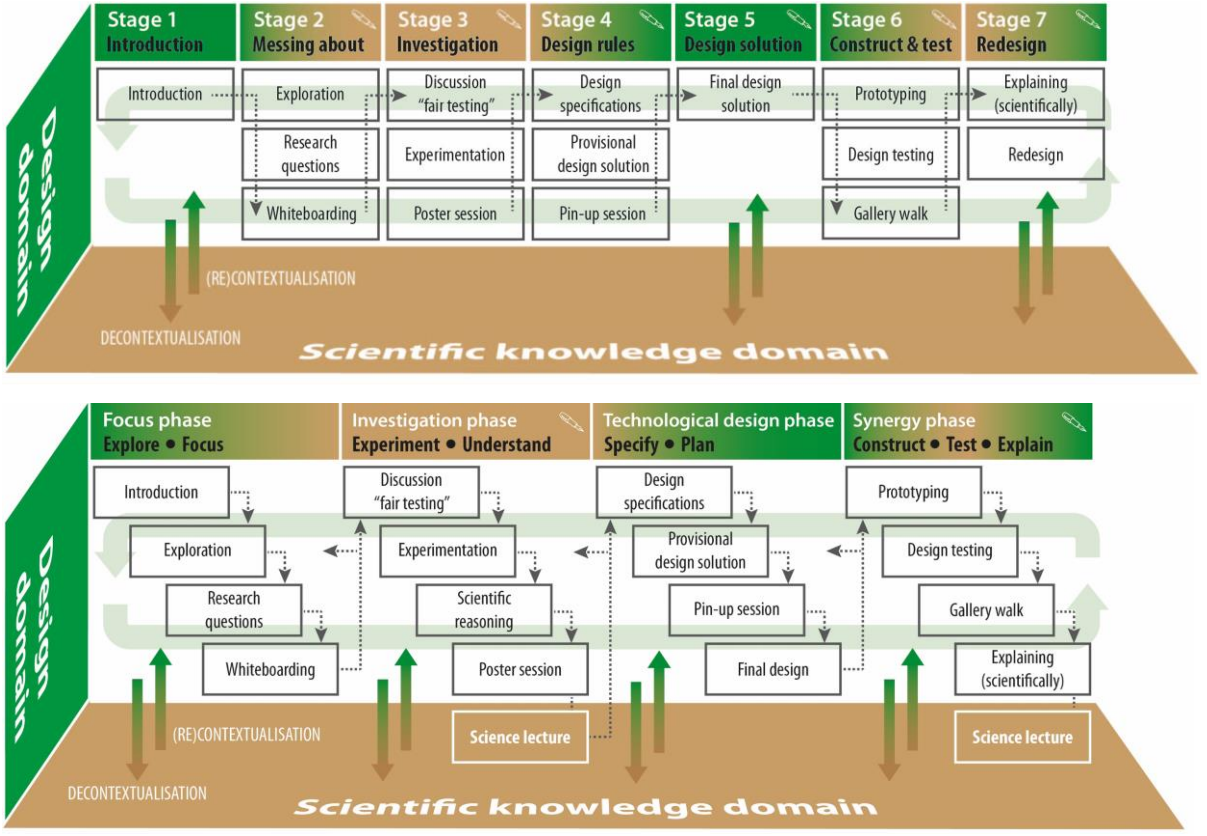
Figure 5.2 Wiring and example of a final design



MS = main power switch; L1 and L2 = lights; B = buzzer; O □ ✚ ▲ = self-designed floor pads (switches).

The challenge was adapted for better concept learning based on previous study outcomes. All (re)modifications, in general facilitating proper knowledge transfer and process guidance, are listed in Table 5.1, and the improved strategies (modified approach and remodified FITS model) are shown graphically in Figure 5.3 where both strategies include all original LBD elements.

Figure 5.3 Modified LBD approach (top) and remodified FITS model (bottom)



✎ = administrative moment. Green colour = design-related focus. Brownish colour = science-related focus. Science is explicated by de- and recontextualisation. All rectangular boxed activities in the white part of the figure are traditional LBD activities. However, in the case of the (re)modified approaches the "Exploration" and "Experimentation" activities are enriched by pre-planned elements as discussed in Table 5.1.

Table 5.1 LBD (re)modifications

Modified approach: modifications based on explicit teaching and scaffolding	
Modification	Underpinning (■) and implementation regarding Figure 5.3 (●)
Backward design (Wiggins & McTighe, 2006)	■ Task analysis to predict learning outcomes by unravelling task-exposed and -underexposed concepts. As a result, underexposed, less directive, concepts complementing the knowledge domain were addressed by additional teacher-driven interventions. ● The effect of resistance and potential differences on circuit operation were underexposed (based on Study 1). By using the simulation software students had to study changes in circuit operation (parallel and series) due to, first, an increasing number of lights and, second, a changing the number of connected batteries. In the case of the modified approach this was done after stage 3 and in the case of the FITS model before the first science lecture. This activity was complemented by information seeking and a class discussion.
Guided discussion (Carpenter et al., 1996)	■ Guided discussion guides class discussions in order to highlight and explicate underlying science. By observing students' thinking and doing during collaboration it becomes clear what students understand about science. Then, correct and incorrect insights are used to discuss (mis)conceptions and to head for proper reasoning and understanding. ● All class discussions were orchestrated by guided discussion. For Figure 5.3 this mainly concerned the following activities: whiteboarding, poster session, pin-up session and gallery walk.
Informed design (Burghardt & Hacker, 2004)	■ Informed design activates and enhances prior knowledge through preparatory activities. Then, students are better prepared to approach design challenges from a more knowledgeable base and to tackle design problems by conceptual closure. ● Students additionally had to explore, during the exploration phase, prior knowledge based on a set of scientific task-related terms (e.g. resistance, current, insulator etc.). By information seeking and group discussion they were forced to share and discuss cognitive gaps.
Explicit instruction and scaffolding (Archer & Hughes, 2011)	■ Explicit instruction is characterised by a series of scaffolds where students are guided through the learning process by proceeding in small steps, checking for understanding, active and successful participation, and clear statements about the purpose of and rationale for learning activities. LBD takes account of most of these elements and other adjustments in this table also fit into explicit instruction. However, teacher handling should also facilitate explicit instruction and scaffolding. The second study resulted in a framework of important teaching guidelines to facilitate this (Table 3.4 in section 3.2.2). ● Teachers were informed about the teaching guidelines and stimulated to use the guidelines during the task. It helped them to relinquish directive control and to guide concept learning by explication of addressed science through de- and recontextualisation of science content emerging (whether planned or not) from the task.

Table 5.1 Continued

Remodified FITS model: remodifications based on reduced fragmentation	
Remodification	Underpinning (■) and implementation regarding Figure 5.3 (●)
Science lectures	■ Domain- and task-related science, addressed during investigation, is discussed explicitly and decontextualised with particular attention to interrelatedness of concepts. Examples of recontextualisation (to other contexts) will foster knowledge transfer. During the synergy phase it becomes visible how science and technology enrich each other: investigation outcomes and scientific concepts become more meaningful because they facilitated design solutions. This will be anchored by explaining the functionality of designs scientifically, complemented by a final complete and coherent picture of science involved. ● The first lecture was planned after the investigation phase to facilitate a conceptual design approach. The second lecture was planned at the end as justified above.
Amalgamation	■ Reduction of the number of (separate) stages and activities offers more coherence and less administration where guidance and scaffolding is shifted towards the ongoing process itself rather than breaking it down into parts. ● The number of administrative moments reduced from six to two and the number of stages from seven to four, resulting in two investigation-dominated phases and two design-dominated phases, both complemented by an administration and reflection session.

5.3 Method

For this study, 237 general secondary education students (aged 12 - 14) took part in a pre-test-post-test design where 110 students faced the modified LBD task and 127 students the remodified task (FITS model). Both groups were spread over five adjacent classrooms guided by five teachers. Students had no specific prior knowledge regarding the science addressed but were familiar with characteristic LBD components. By comparing conceptual learning outcomes for the traditional LBD approach in Study 1 (77 students) and the modified and remodified approach, it was possible to verify learning gains found in the third study and to establish any further enhancement due to remodifications.

5.3.1 Data collection

To investigate students' change in conceptual understanding, the pre-post-exam developed for the first study was used (Chapter 2). This exam contains 20 multiple choice questions based on validated tests that proved to uncover students'

(mis)conceptions (Engelhardt & Beichner, 2004; Licht & Snoek, 1986; Niedderer & Goldberg, 1993). The questions address all science content that is, to a greater or lesser extent, related to the design context, where all questions are formulated outside the design context to investigate knowledge transfer.

To study students' design performances, all final designs were scored on a three-point rating scale (successful, partially successful and unsuccessful) by two experts; a strategy adopted from the first study. By doing this it becomes clear whether more conceptual understanding results in better design outcomes.

All data and results concerning the traditional LBD challenge are taken from the first study where a part of the analysis is also adopted for use in this study.

5.3.2 Analysis

The pre-post-exams, processed for each approach, were scored per question and for all questions by the mean relative number of correct answers. These scores were used to calculate the gain-index $\langle g \rangle$: ratio of actual average gain (post – pre) to the maximum possible average gain (1 – pre) (Hake, 1998). A paired samples t test was used to investigate pre- and post-score differences within each group. The internal consistency was tested by calculating Cronbach's alpha.

To compare scores between all groups on the gain-index, first, one-way ANOVA and Tukey post-hoc tests were performed to compare pre-test results. This test was found to be statistically non-significant, which indicates all groups initially had a comparable level of conceptual understanding. Afterwards, based on the calculated gains, a chart of the relative distribution of achieved gains per group visualised the increase in conceptual understanding. For this, mainly based on Hake (1998), the 0 to 1 gain-index range was divided into four separate ranges (low, medium-low, medium-high, high). An independent samples t test was used to compare the learning gains of the traditional, modified and remodified approach. For this, it was necessary to run three tests to cover all combinations of groups, which increased the possibility of making a type I error. Performing a one-way ANOVA for all groups controlled for this phenomenon and verified the t test results. Based on all results, the effect size was calculated to estimate the size of possible differences: in the case of one-way ANOVA eta-squared η^2 was calculated and Cohen's d for the t tests. Additionally, a post-hoc power analysis was used to identify whether the research design had enough statistical power.

The assessment of design outcomes in the case of the modified and remodified approach, based on the three-point rating scale, was done by two experts concurrently in order to enhance reliability. For the traditional approach this was done by two experts separately, whereupon the mean scores were awarded as final scores (linear weighted Kappa κw was 0.70). The assessment results for each approach are presented in a table by the relative distribution of awarded scores per design specification and for all specifications.

5.4 Results

Analysis of variance showed no significant variation between pre-test scores, $F(2, 311) = 1.41$, $p = 0.246$, and the Tukey post-hoc test revealed no significant differences: $p = 0.147$ (traditional-modified), $p = 0.834$ (traditional-remodified), $p = 0.155$ (modified-remodified). These results indicate that all groups initially had a level of conceptual understanding not significantly different from each other. Table 5.2 shows the exam results and corresponding gains complemented by the Cronbach's alpha values that assume sufficient internal consistency.

Analysing the pre- and post-scores (paired samples t test) within each group, there is a significant increase in all cases: $t(76) = -18.18$; $p < 0.001$, $t(109) = -35.60$; $p < 0.001$, $t(126) = -37.29$; $p < 0.001$. Studying the gains it is obvious that the modified approach resulted in much better learning gains compared with the traditional approach. The mean gain increased from 0.35 ($SD = 0.22$) to 0.56 ($SD = 0.13$); a relative increase of 60 percent. The additional remodifications enabled further growth of the gain to 0.62 ($SD = 0.13$). Although this latter increase seems to be low, it is significant and accounts for a medium effect. This is based on the independent samples t test and corresponding value of Cohen's d: $t(235) = -3.02$, $p = 0.003$, $d = 0.49$. The independent samples t test also indicated that gains were significantly higher for the modified approach ($M = 0.56$; $SD = 0.13$) than for the traditional approach ($M = 0.35$; $SD = 0.22$) with a large effect size: $t(185) = -10.43$, $p < 0.001$, $d = 1.23$. Thus, the traditional and remodified approach also differ significantly: $t(202) = -12.87$, $p < 0.001$, $d = 1.68$. Finally, the t test results were verified by using a one-way ANOVA for all approaches, which also established a significant difference between the groups and a large effect size: $F(2, 311) = 93.02$, $p < 0.001$, $\eta^2 = 0.374$). The Tukey post-hoc test revealed that the gain in the case of the modified and remodified approaches was statistically higher compared with the traditional approach ($p < 0.001$). The test also confirmed a statistical difference

between the modified and remodified approach (p = 0.004). Finally, post-hoc power analysis revealed a power of 87 percent in the case of the modified and remodified intervention. For the other combinations of interventions the power is heading towards 100 percent. Thus, it seems the study design was good enough to detect any statistically significant differences.

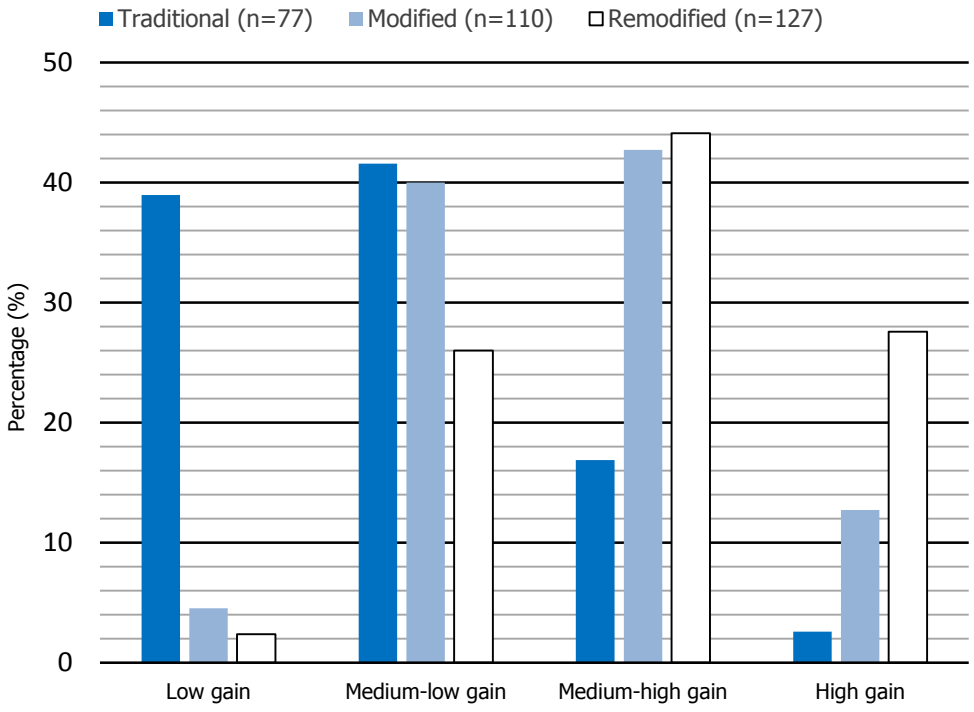
Table 5.2 Pre- and post-exam mean results

	Traditional (n=77)[a]			Modified (n=110)			Remodified (n=127)		
	Relative score			Relative score			Relative score		
Quest.	Pre	Post	Gain	Post	Post	Gain	Pre	Post	Gain
1	0.33	0.68	0.52	0.21	0.81	0.76	0.19	0.83	0.79
2	0.59	0.50	-0.15	0.58	0.86	0.67	0.54	0.87	0.73
3	0.22	0.51	0.38	0.24	0.69	0.60	0.26	0.75	0.66
4	0.59	0.76	0.41	0.68	0.85	0.51	0.63	0.83	0.53
5	0.15	0.71	0.65	0.23	0.81	0.75	0.20	0.83	0.79
6	0.14	0.50	0.42	0.38	0.68	0.49	0.39	0.70	0.51
7	0.37	0.76	0.61	0.35	0.77	0.65	0.34	0.80	0.69
8	0.32	0.37	0.08	0.30	0.58	0.40	0.27	0.62	0.48
9	0.05	0.58	0.55	0.15	0.67	0.61	0.17	0.70	0.64
10	0.31	0.53	0.31	0.35	0.66	0.49	0.31	0.69	0.54
11	0.28	0.51	0.32	0.20	0.65	0.56	0.21	0.71	0.63
12	0.27	0.68	0.56	0.46	0.75	0.54	0.42	0.80	0.66
13	0.40	0.45	0.09	0.45	0.72	0.48	0.43	0.70	0.48
14	0.36	0.62	0.40	0.21	0.61	0.51	0.20	0.65	0.56
15	0.28	0.41	0.18	0.21	0.61	0.51	0.20	0.69	0.61
16	0.28	0.29	0.02	0.27	0.62	0.48	0.25	0.68	0.57
17	0.28	0.33	0.07	0.21	0.59	0.48	0.20	0.62	0.52
18	0.62	0.73	0.30	0.75	0.98	0.93	0.66	0.98	0.95
19	0.35	0.67	0.49	0.37	0.66	0.46	0.37	0.66	0.46
20	0.29	0.53	0.33	0.44	0.77	0.60	0.41	0.82	0.69
Total (SD)	0.33 (0.14)	0.56 (0.14)	0.35 (0.22)	0.35 (0.17)	0.72 (0.11)	0.56 (0.13)	0.33 (0.15)	0.75 (0.10)	0.62 (0.13)
Alpha	0.65	0.76	n/a	0.70	0.67	n/a	0.76	0.70	n/a

SD = standard deviation; Quest. = question; Gain: ⟨g⟩ = (post - pre) / (1 - pre); (Hake, 1998).
[a] Results adopted from Study 1 (Chapter 2, section 2.3).

To study differences in detail a figure of the relative distribution of gains per group was created. For this, mainly based on Hake (1998), the 0 to 1 gain-index range was divided into four separate ranges (low, medium-low, medium-high, high). According to this figure there were many students (39 percent) that only managed a low learning gain in the case of the traditional approach. Due to initial modifications nearly all students were able to reach at least a medium low gain, comparable to mean gains found in traditional physics courses (Hake, 1998), and more students scored in the higher gain ranges. Finally, the figure reveals that the additional remodifications further increase the gain in a similar way but on a higher level. Taking all results into account it is obvious that the (re)modifications significantly improve concept learning on the level of knowledge transfer. See Figure 5.4.

Figure 5.4 Relative distribution of gains



Gain ranges: low gain: $\langle g \rangle < 0.30$; medium-low gain: $0.30 \leq \langle g \rangle < 0.50$; medium-high gain: $0.50 \leq \langle g \rangle < 0.70$; high gain: $\langle g \rangle \geq 0.70$.

Unlike the conceptual learning gains, the assessment of design outcomes reveals no differences between the approaches. Based on all specifications the success rate (+) is just above 70 percent for all interventions. For the science-based specifications (1 to 4) this percentage is even around 80 percent. This suggests that a solid improvement of conceptual learning not automatically leads to better design outcomes and that a limited amount of conceptual understanding is sufficient for proper design realisation. Table 5.3 shows the awarded design scores.

Table 5.3 Assessment of design outcomes

	Relative distribution of awarded scores								
	Traditional (N = 25)			Modified (N = 28)			Remodified (N = 32)		
Design specification[a]	+	o	-	+	o	-	+	o	-
(1) Main power switch operation	90%	8%	2%	86%	7%	7%	84%	10%	6%
(2) Floor pad design and operation light bulb 1	80%	16%	4%	79%	14%	7%	78%	16%	6%
(3) Floor pad design and operation light bulb 2	82%	16%	2%	82%	11%	7%	75%	16%	9%
(4) Floor pad design and operation buzzer	84%	14%	2%	71%	18%	11%	78%	19%	3%
(5) Restricted amount of materials	96%	4%	0%	93%	7%	0%	94%	3%	3%
(6) Durability and solidity	42%	54%	4%	46%	43%	11%	50%	38%	12%
(7) Attractiveness	40%	44%	16%	43%	46%	11%	56%	28%	16%
Total	74%	22%	4%	71%	21%	8%	74%	18%	8%

+ = successful; o = partially successful; - = unsuccessful; N = number of final designs.
[a] Design specifications adopted from Study 1 (Table 2.1, section 2.2).

5.5 Discussion and implications

The first research question asks whether the improved conceptual learning gains of previous studies are confirmed quantitatively by the modified LBD group results in this study. In Study 2 (traditional LBD) and Study 3 (modified LBD) a small group of student teachers had to design a solar power system for a model house where the mean conceptual learning gain increased significantly from 0.37 to 0.68: a relative increase of 81 percent. The modifications tested quantitatively in this study showed a comparable, but somewhat lower, increase from 0.35 to 0.56: a relative increase

of 60 percent. Nevertheless, the increase represents a large effect size (d = 1.23) and high power (close to 100 percent) and probably contributes to most of the total gain achieved by FITS students (0.62 mean gain; d = 1.68). Thus, it is plausible that the initial modifications, based on scaffolding and explicit teaching strategies, are indeed crucial for concept learning and affect concept learning in a positive way.

The further remodifications (a reduction of stages and administration described previously) that resulted in the FITS model, which were implemented based on the outcomes of the third study, enabled students to manage even slightly higher gains. This conclusion touches upon the second research question of this study: By how many the students' conceptual learning gains will further increase due to application of remodifications? Compared with students who faced the modified approach, FITS students reached a slightly higher conceptual learning gain (0.56 gain vs. 0.62 gain). This further increase represents a medium effect size (d = 0.49) and high power (86 percent) and suggests that the additional remodifications are worthwhile and enable an additional learning gain on top of the large effect of initial modifications. This result supports Chaudhury (2011) who states, based on empirical research on human learning, that lectures in combination with activities enhance learning.

In all, FITS students reached much higher conceptual gains than traditional LBD students; gains that are more or less reserved for the most successful physics-related courses (Hake, 1998). The FITS model enriches LBD by providing a design-based learning environment that embeds a complete, coherent and explicit picture of underlying science with special attention to de- and recontextualisation of knowledge. Furthermore, the ongoing learning process is stimulated by shifting guidance and scaffolding towards the ongoing process itself rather than breaking it down into parts. Based on the results of this study, the FITS model can be a catalyst for interdisciplinary teaching where the design domain provides the direction towards scientific and technological learning outcomes by a scientifically paved road.

To conclude, a critical comment should be made. Although FITS students reached high conceptual learning gains, they were not able to use this to produce more sophisticated designs. A possible reason for this, based on all the studies, is the limited number of scientific concepts that are crucial for successful design realisation; this was also a main reason for limited concept learning in the case of the traditional approach. Thus, all (re)modifications might be more or less weakly or indirectly design-related and only focused on improving concept learning. To tackle this, iterative redesign could be used to deepen and/or broaden the design task by implementing more (science) content, which may foster better design performances.

6

General conclusion and discussion

6.1 Introduction

Before we get onto the main findings and conclusions we will briefly repeat the relevance and aim of the research, which is driven by educational and social developments. Science and (design) technology have grown progressively denser in our personal lives, which creates a dynamic and complex world to live in where both disciplines have become strongly entangled (Lelas, 1993). We might expect that school systems respond accordingly by delivering juveniles ready to face this issue. Unfortunately, many curricula are traditionally dominated by separate disciplines (Scott, 2008) where a decreasing interest in and understanding of science and technology is established (Sjöberg & Schreiner, 2010). Several studies indicate that a holistic understanding of science and technology, through interdisciplinary teaching, may improve students' motivation and understanding (Lustig et al., 2009; Osborne & Dillon, 2008; Rennie et al., 2012). Therefore, many national governments aim for interdisciplinary science, technology, engineering, and mathematics (STEM) education (National Science and Technology Council, 2013; Office of the Chief Scientist, 2013; Parliamentary Office of Science & Technology, 2013).

As discussed in Chapter 1 from the 1970s interdisciplinary teaching gained interest among educational developers and gradually, mainly around the year 2000, several design-based learning approaches were developed to bring science and technology together in project-based approaches where design activities are used to learn knowledge, skills and practices. Almost all of these approaches created a meaningful and stimulating learning environment (Wendell, 2008) and resulted in a (significant) improvement of students' skills and practices. Unfortunately, supported by a review of literature on design-based science teaching (Sidawi, 2009), nearly all approaches to a greater or lesser extent experienced difficulties regarding conceptual learning, which became the main topic of this dissertation.

To study limitations in concept learning by design challenges the Learning by Design (LBD) approach was chosen, for reasons pointed out in Chapter 1, as the bedrock of the research. Also LBD appeared to be a quite successful approach because validated performance tasks revealed high student involvement and, compared with non-LBD classes, significantly better collaboration, metacognitive and science skills (Kolodner, Camp, Crismond, Fasse, Gray, et al., 2003; Kolodner, Gray, et al., 2003). However, as indicated before, (scientific) concept learning did not benefit despite the fact this is theoretically facilitated by the didactic and pedagogical foundations of LBD. Therefore, the central research question for the research was:

Why the current practice of design-based learning not yet leads to an expected high level of concept learning, and how learning can be enhanced resulting in an educational strategy where the learning of concepts and skills both are strongly represented?

Six sub-questions were formulated in section 1.5 to support the research and four studies were conducted to provide answers to all the research question. The first study (Chapter 2) unravelled the LBD process to find out how students used and learned science during LBD. A second study (Chapter 3) strongly focused on teacher handling and resulted in a framework of teaching guidelines indispensable for concept learning and proper guidance in general. The third study (Chapter 4) investigated improvements based on the first and second study. A fourth and final quantitative study (Chapter 5) tested the modified LBD approach of the third study on a larger scale and studied additional remodifications providing the FITS model.

6.2 Main findings and conclusions

The main findings and conclusions per study are described in the following sections with the aim of providing answers to the (sets of) research questions. Overall findings that aim to incorporate findings and to answer the central research question are presented at the end.

6.2.1 Concept learning through LBD

To provide the first study, discussed in Chapter 2, with an important research focus, literature was searched through to state a hypothesis why students do not take the theoretically facilitated opportunity to learn content knowledge. According to Gardner (1994), nowadays technology and science engage in a two-way interaction where both professions learn from each other in mutually beneficial ways. Historically, based on a materialist view, design technology frequently preceded science because design realisations, like tools, instruments and artefacts, often were created without the explicit use of scientific content knowledge (Davies, 1997). Many technological creations more and more were used or even created by scientists to investigate scientific phenomena and to increase and improve scientific insights. In turn, those insights were used to produce more sophisticated artefacts. This complex interaction, which has undergone a long development, resulted in the contemporary modern world where science and design technology are strongly interwoven.

This entanglement also lays the foundations for nearly all design-based learning approaches where students have to explore and learn skills and (scientific) concepts that are needed for success by identifying a need to learn them, trying them out, questioning their handling and thinking, and iteration. As discussed, LBD and other comparable approaches facilitate concept learning by creating a constructivist learning environment (Kolodner et al., 1996) where a lot of informative activities and elements should enable concept learning. Despite the fact concept learning is theoretically facilitated, literature indicates that the complicated nature of intertwined disciplines is detrimental to the process of concept learning. Nearly all design-based learning approaches are complex, just like in real-life, due to many objects of integration (e.g. skills, practices, attitudes and content) that often remain under-exposed in the case of unexperienced practitioners (Berlin & White, 1994). For example, expert designers focus on content because skills, practices and activities are familiar. Novices mainly focus on process-related issues, needed for success, in which content knowledge is largely overlooked (Popovic, 2004). Mainly because novices cannot cope with all integrative elements simultaneously. Also Wendell (2008) states that scientific content may not emerge because students focus on doing; the quickest and easiest way to design realisation. In general, students create designs like in early days, without the explicit use of content knowledge. Therefore, the topic of student focus was chosen as an important starting point.

On that basis, the first study investigated student focus during LBD and, more specific, how and when scientific content was addressed and learned by 77 general secondary education students exposed to a traditional LBD challenge as prescribed by Kolodner, Camp, Crismond, Fasse, Hyser, et al. (2003). The challenge addressed the direct current electric circuits domain and design groups were challenged to build a battery-operated dance pad that let them use their feet to sound a buzzer or flash lights. The study confirmed the findings of Kolodner, Camp, Crismond, Fasse, Hyser, et al. (2003) that students were able to manage a medium-low mean conceptual learning gain (0.35 gain-index), which is comparable to those achieved in many traditional physics courses (Hake, 1998). This somewhat disappointing gain is still far from gains managed through, for example, interactive engagement (IE) methods that showed mean gains up to 0.60 (Hake, 1998). Remarkably, IE methods, which merely combine physics-related heads- and hands-on activities, are very similar to design-based learning approaches but contain less integrative elements and seem less complex.

That brings us to the first sub-question of this thesis: When and how, during LBD, students use science for design purposes and how students demonstrate an understanding of scientific concepts? By studying the LBD practice in detail and less emphasis on pre- and post-testing, the study revealed that students mainly learned science that came available from activities that strongly determined a successful design outcome; according to students the main goal of the challenge. For example, the virtual simulation provided insight in electrical wiring and teacher-driven activities (e.g. student-teacher interaction and class discussions), when underlying science was explicated, helped students to learn scientific terminologies and symbols. For the most part, knowledge that was more or less important for completing requested assignments and indispensable for design realisation; something nearly all design groups were able to do on an acceptable level. In general, the more concepts directly determined a successful design outcome the better concepts were understood. An important fact that was also indicated by Jones (1997) for technological concepts. Consequently, the ad hoc exploration and use of science content caused an incoherent and incomplete picture of underlying science.

This conclusion touches upon the thesis' second sub-question: What learning strategies, which can enhance deeper learning of science, are yet missing and how this absence affects learning? The students' strong process focus (What to do and what to deliver?) suppressed the fact that those processes (can/must) increase their concept-related knowledge. A lack of sufficient content focus (What to learn?) mainly was provoked, in line with the hypothesis stated before, by the complexity and extensiveness of the challenge. As a result, students learned isolated facts, just enough for design implementation and realisation, that stayed more or less implicit: students used more scientific terms and symbols and designed proper electric circuits but did not achieve deeper conceptual understanding necessary for knowledge transfer. For example, students had difficulty in scientific reasoning (thinking and reasoning in terms of combinations of science-related abstractions or symbols), which hindered them to explain science-related design decisions and working principles. This problem of incidental, implicit, informal or unintentional learning is also a widespread problem across other non-LBD settings (Baskett, 1993; Kerka, 2000; Marsick & Watkins, 2001; Rogers, 1997).

According to the previous, there were mainly two (interrelated) problems for which solutions had to be found. First, reducing the complexity of the challenge without diluting the potentially rich learning environment. Second, more focus on design-related science concepts where also important interrelationships have to

become explicit. Based on literature, four interesting strategies were distracted for improvement. First, backward design (Wiggins & McTighe, 2006), a detailed analysis of the learning task to expose, inter alia, how underlying concepts are related to the task. This makes clear when to explicate strongly task-related concepts and when and how to address poorly task-related concepts (e.g. through additional demonstrations, lectures, readings, experiments, etc.). Second, the teacher-led technique of guided discussion for sharing (scientific) insights during class discussion and developing deeper conceptual understanding (Brandsford et al., 2003; Carpenter et al., 1996). Third, (elements of) informed design (Burghardt & Hacker, 2004). This strategy aims for thoughtful design decisions based on scientific and mathematical concepts without reverting to trial and error, the tendency the students in our study had. Fourth, application of explicit instruction (Archer & Hughes, 2011) and scaffolding strategies (Bamberger & Cahill, 2013). Both strategies help to facilitate students' understanding and overseeing of the learning process. Students are guided through the learning process with clear instructions, proceeding in small steps, and checking for understanding.

6.2.2 Teaching strategies to promote concept learning

Where the first study focused on student learning the second study mainly addressed teacher handling. For this, there were two main reasons. First, literature claims that (concept) learning is highly teacher dependent (Bamberger & Cahill, 2013; Van der Veen & Van der Wal, 2012). Using design faces teachers with an open-ended nature where teachers must relinquish directive control (Burghardt & Hacker, 2004). As a result, teachers leave or undermine LBD activities because they are not able to adjust to a new kind of classroom control (Wendell, 2008), and therefore they need help to develop adequate pedagogical strategies (Bamberger & Cahill, 2013). Second, the first study revealed that teacher-driven activities seemed to dominate concept learning (in a positive and negative way). Also, teachers described task guidance as intensive and complex, which corresponds to the first reason.

Based on these insights, the second study, which was central to Chapter 3, addressed the third and fourth sub-question of this thesis: What teaching strategies dominate and (directly) affect the learning of science content and, by analysing all teaching interventions during LBD, what is the relative number of interventions that directly appeal to these strategies? Which teaching strategies, based on the answer to the third question, should get more attention to enhance concept learning?

Based on literature upon pedagogical strategies, teacher competences and STEM education a theoretical framework of cohesive teaching strategies was developed (Chapter 3, Table 3.4); strategies important for enhancing (concept) learning and taking enough control of the learning environment. Those strategies were dived into five categories (collaboration, reflection, feedback, explicit teaching and process-related issues) within three types of interaction (student to student, student to teacher and student to content) where a distinction was made between skills emerging during the activity induced by the intervening teacher (anticipatory skills), and skills important for construction and preparation of the task (preparatory skills). During data analysis the interventions pointed out to be complete and identifiable.

Data analysis showed, in compliance with the first study, that detailed task analysis is necessary to predict (conceptual) learning outcomes and to unravel task-driven concepts that are addressed directly by the task: direct concepts. Additional less directive concepts (indirect concepts), complementing the scientific knowledge domain, should be addressed otherwise (teacher-driven). The more, because the understanding of individual concepts strengthens when important interrelationships, between a majority of all concepts within the knowledge domain, are understood (Stoddart et al., 2010). For learning concepts, explicit teaching strategies, teacher feedback and process-related issues were highly appreciated by students. Especially, when those interventions directly appealed to underlying science (e.g. explaining science, conducting experiments, sharing insights during class discussions) or when an ongoing learning process was stimulated (e.g. clear instructions, process feedback, equipment of the learning environment). Unfortunately, most of the teacher interventions (87 percent) concerned the stimulation of collaboration and moments of feedback that were indirectly related to underlying science. Only 13 percent of all interventions concerned, to a greater or lesser extent, direct explication of science where also a lack of de- and recontextualisation was established; something that is indispensable to enhance knowledge transfer.

In general, expressed by the Design-based Science Interference Model in Chapter 3 (Figure 3.3), conceptual knowledge students need to learn is always context-related (implicit) where direct concepts are strongly task-driven. Indirect, weakly task-related, concepts have to be addressed teacher-driven through additional interventions. To recognise and understand task-related concepts they have to become explicit. For this, the teacher is crucial as discussed before. To deepen conceptual understanding important interrelationships between concepts have to become clear: at first inside the task context and subsequently context-free. Through

addressing concepts in other contexts (recontextualisation) further comprehension should take place. By doing this, the initial task-related student focus is extended to a better understanding of the entire (context-free) conceptual knowledge domain. Then, students should be able to master the conceptual framework independently from the context (knowledge transfer).

In general, based on the first and second study, coping two (interrelated) areas of concern may help students to reach a higher level of conceptual learning: explicit teaching strategies, mainly to explicate and deepen content knowledge, and scaffolding strategies to stimulate the ongoing learning process and reduce task complexity, which enables students to draw more attention to conceptual knowledge. To realise this, the suggested strategies for improvement, coming from the first study, were of main importance for the third and fourth study.

6.2.3 Enhanced concept learning

The third study, discussed in Chapter 4, was the first step in answering the final two sub-questions that ultimately will provide an answer the central research question. As mentioned, the study aimed to address the two main concept learning-related problems that resulted from the first two studies: the complexity and extendedness of the task and a lack of science focus and explicit teaching. By implementing improvements the LBD task developed for the second study was adapted for better concept learning. In general, all modifications concerned scaffolding and explicit teaching strategies mainly to improve guidance and to explicate and complement science content. Table 6.1 will briefly repeat the modifications for the sake of completeness. The study's research question were: Will application of explicit teaching and scaffolding strategies positively affect concept learning by offering a more comprehensive, coherent and explicit framework of scientific knowledge, and by how many this affects students' conceptual learning gains? Does skill performance, despite the interventions, still increase and how it is (cor)related with concept learning?

Table 6.1 Brief summary of initial LBD modifications

Modification	Underpinning
Backward design (Wiggins & McTighe, 2006)	Task analysis to predict learning outcomes through unravelling task-exposed and -underexposed concepts. As a result, underexposed, less directive, concepts (complementing the knowledge domain) were addressed through additional teacher-driven interventions built in as interludes (e.g. additional experimentation, information seeking, class discussion).
Guided discussion (Carpenter et al., 1996)	Guided discussion orchestrates class discussions in order to highlight and explicate underlying science. By observing students' thinking and doing during collaboration it becomes clear what students understand about science. Then, correct and incorrect insights are used to discuss (mis)conceptions and to head for proper reasoning and understanding.
Informed design (Burghardt & Hacker, 2004)	Informed design provides a solid basis for coping the challenge by providing focus and by activating and enhancing prior knowledge through built-in preparatory activities. As a result, students are better prepared to approach design challenges from a more knowledgeable base and to tackle design problems by conceptual closure.
Explicit instruction and scaffolding (Archer & Hughes, 2011)	Explicit instruction is characterised by a series of scaffolds where students are guided through the learning process by proceeding in small steps, checking for understanding, active and successful participation, and clear statements about the purpose of and rationale for learning activities. LBD takes account of most of these elements and other adjustments in this table also fit into explicit instruction. However, teacher handling should also facilitate explicit instruction and scaffolding. The second study resulted in a framework of important guidelines to facilitate this: it helps teachers to relinquish directive control and to guide concept learning by explication of addressed science through de- and recontextualisation of science content emerging (whether planned or not) from the task.
Adjustment of the design diary	Students involved in Studies 1 and 2 hackled the amount of administration (design diary) mainly because little administration was necessary to learn or move on. As a result, reflection became disturbing and abortive. Therefore, the amount of administration was reduced and many written proceedings were replaced by process pictures accompanied by short subscriptions.

Based on the pre- and post-assessment results of 21 student teachers it was fair to state that the modifications in Table 6.1 are promising and enhance concept learning without reducing a positive effect on skill performances. The multiple choice test results, coming from a test adopted from the second study, revealed a mean conceptual learning gain (0.68 gain-index) that significantly exceeded the gains found in the first two studies (respectively 0.35 and 0.47 gain-index). Students were able to reach a level of concept learning comparable to achievements found in some of the most successful physics-related courses (Hake, 1998). Students' responses showed, which can be considered as an important reason for improved concept learning, that in contrast with the preliminary only a few comments were made about

a lack of (explicit) science teaching. It seems that a combination of backward design, guided discussion and informed design is an appropriate remedy to enhance concept learning by emphasising weakly task-driven concepts (to complete the knowledge domain), explicating strongly task-driven concepts and further deepening of all concepts by de- and recontextualisation.

Because literature states that close-ended tests often fail to measure conceptual understanding (Stoddart et al., 2010), a second assessment strategy was developed where students were asked to create a proposition-based concept map before and after the challenge. Students were challenged, based on Yin et al. (2005), to create 16 fundamental propositions (a connection between two concepts by using linking words or phrases) within a set of 10 predefined task-related concepts. Analysis revealed strong (significant) positive correlations between the pre-scores of both assessment types, as well as for the post-scores. The gains of both tests showed a lower, but fair, correlation ($r = 0.683$, $n = 21$, $p < 0.01$) that can be explained by the fact that the mean gain for the concept map test was significant lower compared with the multiple choice test. As a reason for this, students expressed that the concept map test was more difficult because it stronger appealed to mastering well-organised, relevant knowledge structures. This ties in with literature, which states that correlations between multiple choice tests and concept map tests are often significant but widely spaced (Constantinou, 2004; Ruiz-Primo et al., 1997). Therefore it is necessary to further investigate this correlation in detail.

As mentioned before, the LBD modifications did not impede students' skill performances. Analysis of performance assessment results showed a significant increase ($p < 0.001$) in achievement level among all skill dimensions (negotiations during collaboration, distribution of efforts and tasks, attempted use of prior knowledge, adequacy of prior knowledge, scientific reasoning, experimentation skills and self-checks), where the highest progressions concerned the adequacy of prior knowledge, experimentation skills and self-checks. Overall, these findings are fairly comparable to the performance assessment results found by Kolodner, Camp, Crismond, Fasse, Gray, et al. (2003). Finally, the study revealed strong positive correlations between concept test results and three dimensions of the performance assessment: use and adequacy of prior knowledge and scientific reasoning. Maybe not surprisingly because these dimensions are fundamental to some of the modifications in Table 6.1. In any case, it seems that concept learning, the use and adequacy of (prior) knowledge and scientific reasoning strongly interact. These findings correspond to Schreiber et al. (2016) who found high correlations between

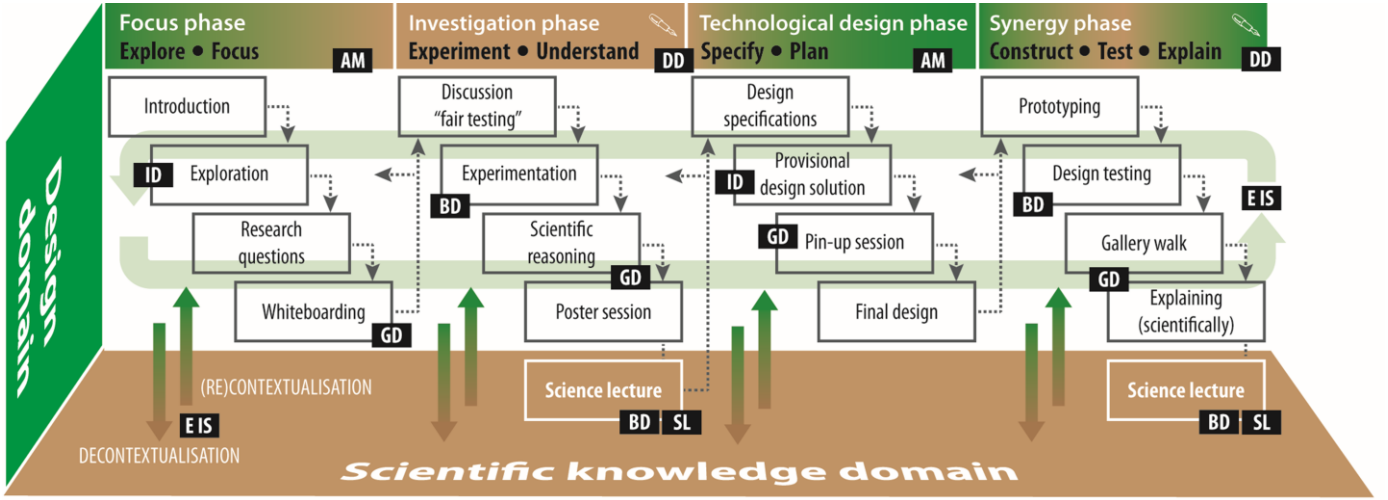
concept learning and the preparation and evaluation of experiments where prior knowledge and scientific reasoning are important.

Although the findings of the study were promising, the study revealed two more points of improvement. First, students experienced too little coherence and assimilation of addressed science content and, second, despite the fact students experienced sufficient guidance and task transparency, they (still) described the large number of separate stages and accompanying administration as disruptive to the ongoing learning process.

6.2.4 The FITS model

The final step in answering the question how to improve the pedagogical structure of design-based learning activities for better concept learning was provided by the fourth and final study (Chapter 5). A study among 237 general secondary education students (aged 12-14) that investigated quantitatively the modifications developed for the third study and additional remodifications coming from that same study. For this, the traditional LBD task developed for the first study was adapted for enhanced concept learning. The modified approach included modifications summarised before in Table 6.1, and the further remodified approach additionally tackled fragmentation of the task (large number of stages and related administration) and fragmentation of addressed science (lack of coherence and assimilation). The latter was done by a reduction of administration and stages, through amalgamation, and the addition of two traditional science lectures to merge and assimilate science. Figure 6.1, partly adopted from Chapter 5, visualises all (re)modifications implemented in and represented by the FITS (Focus - Investigation - Technological design - Synergy) model; more or less a visual representation of the answer to the central research question of this thesis. The final set of research questions, central to the fourth study, were: Are the improved conceptual learning gains of the previous, more or less exploratory, studies confirmed quantitatively by the modified LBD group results (by comparison with the traditional approach developed for the first study)? By how many will the FITS model further enhance concept learning and provide a promising strategy for design-based learning?

Figure 6.1 Implementation of (re)modifications in the FITS model



All stages and rectangular boxed activities in the white part of the figure are traditional LBD components. Colours: green colour = design-related focus; brownish colour = science-related focus. ✎ = moments of administration and reflection. AM/DD = amalgamation and adjustment of the design diary: reduction of separate stages and requested moments of administration and reflection to stimulate the ongoing learning process. SL = science lecture to assimilate and deepen science content. EIS = explicit instruction and scaffolding strategies to facilitate teacher guidance and continuous explication of addressed science, based on the framework of teaching guidelines. GD = guided discussion as strategy for moments of teacher-guided class discussion. ID = preparatory activities to guarantee informed and useful experimentation and decision-making for design creation. BD = additional activities emerged through backward design; mainly to explicate and complement strongly task-related concepts and to address a complete and coherent framework of underlying science; BD activities especially seemed to fit in with experimentation, design testing and science lectures.

In general, the study proved that the (re)modifications coming from Studies 1 to 3 enhanced concept learning significantly. Compared with the traditional LBD approach in Study 1, where 77 students reached a 0.35 (*SD* = 0.22) mean gain, FITS students (n = 127) were able to manage a mean gain of 0.62 (*SD* = 0.13); a gain that is more or less reserved for some of the most successful physics-related courses (Hake, 1998). For this improvement the effect size was large (*d* = 1.68). The initial modifications in Table 6.1 seemed to be responsible for a significant part of this improvement because students who faced the modified approach (n = 110) already achieved a 0.56 (*SD* = 0.13) mean gain accompanied by a large effect size (*d* = 1.23) and power. Therefore it is fair to state that the previous, more or less exploratory, studies revealed and tackled most of the important issues (lack of explicit teaching and scaffolding) that hindered students from reaching a higher level of concept learning. The initial improvements in Table 6.1 enabled students, driven by backward design and informed design, to explore and learn task-underexposed concepts beside the strongly task-related concepts that mainly were responsible for the learning gains achieved in the case of the traditional approach. This was facilitated by additional teacher-driven activities that completed the knowledge domain and activated or extended prior knowledge. Furthermore, explicit teaching strategies and the technique of informed design were useful to explicate addressed science accompanied by sufficient de- and recontextualisation; a process that stimulates knowledge transfer because students are immersed in the context-free scientific knowledge domain and the application of concepts within other contexts.

It will be evident that the initial modifications are fundamental to the success of the FITS model in Figure 6.1. However, additional remodifications that brought the FITS model into completion enabled even slightly, but significantly, higher gains. This was done by providing a complete and coherent picture of involved science through traditional science lectures and by stimulating the ongoing learning process by a reduction of the number of (separate) stages, which offers more coherence and less administration where guidance and scaffolding is shifted towards the ongoing process itself rather than breaking the process down into parts. The medium effect size (*d* = 0.49) and high power (86 percent) implies that the remodifications are worthwhile and enable an additional learning gain on top of the large effect of initial modifications.

6.2.5 Overall findings

Overall, the FITS model that reflects the results of all studies provides a final answer to the central research question: Why the current practice of design-based learning not yet leads to an expected high level of concept learning, and how learning can be enhanced resulting in an educational strategy where the learning of concepts and skills both are strongly represented? Theoretically LBD, just like other design-based learning approaches, offers a rich learning environment for (concept) learning. However, this richness increases the complexity and extensiveness of the task. This forces students, who often are novice designers, to become process focussed (What to do and what to deliver?) where (scientific) content knowledge is largely overlooked and just used as a tool for design realisation. As a result, students address and learn an incomplete and fragmentised knowledge framework dominated by, more or less, isolated facts and terms that are strongly task-related. And in addition, this task-relatedness hinders students to make a knowledge transfer to other contexts because the acquired knowledge is contextualised, which dominates how content is understood. From a teaching perspective, a sophisticated analysis of weakly and strongly task-related science content, to become informed how and when to complement strongly task-related science and to explicate all content, had too little attention during task construction. Furthermore, too few teacher interventions concerned, to a greater or lesser extent, direct explication of underlying science where also a lack of de- and recontextualisation was noticed.

The FITS model seems to be a successful strategy to enhance concept learning and knowledge transfer without reducing the positive effect on skill performances. FITS students learn science content on a level comparable to some of the most successful physics-related courses. For this, a set of modifications was developed and implemented as discussed before in detail. Those modifications enrich and improve the traditional LBD approach and solve the problems of implicit learning, lack of scaffolding and explicit teaching, and fragmentation of the process and science content. The FITS model includes all traditional LBD activities, however, depending on the task and based on the strategy of backward design and informed design, several activities are enriched by pre-planned elements as discussed before (e.g. additional experimentation, class discussions, information seeking, etc.). Mainly to complement strongly task-related knowledge by weakly task-related content and to guarantee that students are better prepared to approach design challenges from a more knowledgeable base. Furthermore, all science content is explicated (teacher-

driven) during the task by using explicit teaching strategies. This explication is enriched by examples of de- and recontextualisation to facilitate knowledge transfer. Science explication is done by anticipating the process and through pre-planned moments of class discussion (e.g. whiteboarding, poster session and pin-up session). For class discussions, the strategy of guided discussion helps to observe students' thinking and doing and to become clear about what students understand about science. Then, correct and incorrect insights are used to discuss (mis)conceptions and to head for proper reasoning and understanding. For deeper understanding, two traditional science lectures provide a complete and coherent picture of science involved where especially during the final synergy phase it becomes explicit how science and (design) technology complement and enrich each other. Scientific concepts and investigation outcomes become more meaningful because their purpose is visible in the design solution, and the design solution is developed by a more conceptual and systematic approach. Beside a lot more science focus, the FITS model contains only four separate stages and two moments of administration (instead of LBD's seven stages and moments of administration). By doing this, more coherence is offered and administration is limited to the amount necessary to move on and face the design challenge. All in all, the ongoing learning process is stimulated where guidance and scaffolding is shifted towards the ongoing process itself rather than breaking it down into parts. For this, the framework of teaching guidelines, developed for the second study, is necessary to relinquish directive control and to teach with attention to sensitive assistance (Murphy & Hennessy, 2001).

Overall, the FITS model provides a learning environment that enables, beside learning skills, a sophisticated level of concept learning and knowledge transfer. Therefore, the FITS model can be a catalyst for interdisciplinary teaching where, visualised in Figure 6.1, the design domain provides the right focus and direction towards high quality learning outcomes along a scientifically paved road.

6.3 Limitations of the study

As discussed in section 1.6 credibility and generalisability are often important limitations of DBR. With respect to credibility, it was possible, based on theoretical insights and recommendations, to organise the studies with attention for ensuring a credible way of creating and performing interventions, collecting and analysing data, and drawing conclusions. Nevertheless, it surely would have been possible to arrange the conducted studies (slightly) different (e.g. other participants, larger data

sets, different additional types of data, other analytical methods, etc.). In this respect, there are many ways to ensure credible results and to study the complex and dynamic educational practice. However, time constraints and feasibility demand informed demarcation and decision-making, which we did. This automatically brings us to the topic of generalisability. The studies central to this dissertation only addressed, due to the iterative process of DBR and a limited amount of time, the direct current electric circuits domain where mainly higher level education students were involved: first-year student teachers and the first grades of higher general secondary education. Thus, many science-related and technology-related knowledge domains stayed untouched, as is the case for the broad range of educational levels and grades. Furthermore, the number of students involved was, mainly because of the in-depth and qualitative character of the preliminary studies, relatively low: 27 student teachers and 314 secondary education students. Combining these limitations, it is obvious that insights gained not necessarily are transferable to other contexts or settings. Nevertheless, the studies facilitated a significant increase in conceptual learning and exposed important elements that were responsible for the increase. This refers back to section 1.6 that generalisability of DBR not directly comes from results that are generally true. The research invested in analytical forms of generalisability to enable researchers and practitioners to investigate their own educational context and to distract credible conclusions (Van den Akker et al., 2013). Then, through combining the local understanding of multiple different studies and iterations it is possible to make generalisations (Anderson & Shattuck, 2012; The Design-Based Research Collective, 2003).

A next limitation concerns the fact that DBR is arranged around interventions, especially when interventions are complex like design-based learning, that try to adapt and improve educational practice. Design-based learning contains many cohesive elements that demand a certain level of basic knowledge and skills. For example, students have to collaborate, negotiate, experiment, design, present, etc. Activities that, in their turn, include specific skills and (procedural) knowledge. When none of these activities are, more or less, familiar to students, they may not be able to cope the challenge and decent learning outcomes cannot be expected. Thus, to give design-based learning a fair shot, it is necessary to involve participants who are able to face the challenge. Therefore, this research focussed on higher level education students who already experienced interdisciplinary learning environments and skills and practices central to design-based learning. The same accounts for teachers and researchers involved. Nevertheless, it is impossible to fully control the

selection of all participants because any selected educational setting includes a wide range of individuals. Therefore the research to some extent may suffer from complexity bias, which might explain why students involved in the preliminary studies failed to learn concepts because they were not sufficiently prepared to face the learning challenge, and vice versa, maybe students involved in the final studies had a more appropriate range of basic skills and knowledge to become successful. Again the same accounts for the teaching skills of teachers involved. A final comment on the intervention-based research approach concerns the fact that new educational settings may induce a certain amount of enthusiasm among students (and perhaps teachers) involved; also an event difficult to monitor. This may cause, by varying degrees, response bias whereby students are temporarily strongly involved in the learning task, which may automatically lead to better performances. We tried to diminish this effect through the pre-selection of participants mentioned before.

The previous topic partly touches upon another aspect that was not taken into account: knowledge retention. The first and second study confirmed the findings of Kolodner, Camp, Crismond, Fasse, Hyser, et al. (2003) that students were able to manage a medium-low mean conceptual learning gain (0.35 gain-index), which is comparable to those achieved in many traditional physics courses (Hake, 1998). However, a review of the effectiveness of active learning strategies suggests that active involvement, collaboration and problem-based learning not necessarily have to lead to better performances, but in many cases they positively influence the retention of knowledge (Prince, 2004). Perhaps, concept learning is better represented, compared with traditional learning techniques, in design-based learning approaches anyway where this hidden advantage only reveals itself after iteration. A longitudinal research approach, where the same students were followed in a series of studies, could have exposed this phenomenon. It might have put concept learning through design challenges into perspective. Furthermore, this alternative research approach could have provided the research with data on the presence or absence of response bias, provoked by a welcome change from everyday educational settings.

For the third study, videotaped performance assessments were used to analyse students' progressions in skill performances. A scoring rubric was constructed by combining existing rubrics because a well-validated rubric, matching all the skill dimensions, was not available. Therefore, we used an available qualitative framework of criteria to guaranty an acceptable level of validity because a more sophisticated approach, achievable within this study, is still in its infancy (Baartman et al., 2006; Moskal & Leydens, 2000). In general, literature indicates that few

rubrics are directly applicable in a valid way because rubric validity contains six aspects that, in most cases, are only partially ensured (Jonsson & Svingby, 2007). Thus, the strategy developed during the third study to measure performance skills, as for rubrics in general, should be reviewed in the future. All the more, because skills are becoming increasingly important within educational settings (Pacific Policy Research Center, 2010).

In the same way as for rubrics, the use of concept maps to assess conceptual learning gains is still in its infancy. Nevertheless, this assessment strategy was addressed in the third study to complement multiple choice test data. Mainly because literature indicates, e.g. Stoddart et al. (2010), that close-ended tests often fail to measure conceptual understanding because students easily can make guesses and therefore knowledge structures remain invisible. Students were asked to create a concept map before and after the challenge. A proposition-based concept map test was developed, based on Yin et al. (2005), where students had to create fundamental propositions within a set of predefined task-related concepts; according to literature a method superior to other mapping strategies in assessing conceptual understanding (Cañas et al., 2003; Rye & Rubba, 2002). However, the third study (student teachers) revealed, beside promising significant positive correlations between both test methods, significant lower gains in the case of the concept map test. Then, concept map testing was also used in the fourth study (first grades of general secondary education) but ruled out afterwards because students were unable to deliver proper concept maps at all. This partly corresponds to Constantinou (2004) who states that correlations between multiple choice tests and concept map tests are sometimes significant but widely spaced. This may indicate that a certain level of concept mapping skills is necessary to use the activity as assessment tool or, perhaps, multiple choice tests are too superficial to unravel knowledge structures. In any case, more should be done to investigate how conceptual knowledge can be assessed properly depending upon the learning objectives.

Lastly, the fourth study revealed that FITS students achieved slightly, but significantly, higher learning gains compared with students who faced the initial modifications. This was established through calculating the level of significance, the effect size and the power of the study. Also insight was given in how learning gains differed by the relative distribution of gains among four gain ranges (low, medium-low, medium-high and high). It would have been useful to investigate, through additional data collection and analysis, how remodifications interfered with concept learning and to expose the areas where additional benefit was obtained.

6.4 Suggestions for further research

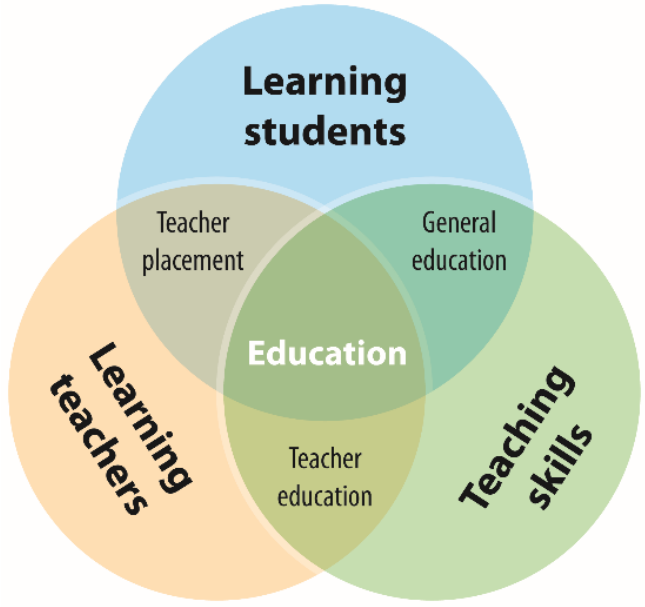
There is no doubt that all limitations discussed in the previous section are eligible for further research. Especially, it is interesting to extend the research to other knowledge domains and educational levels and grades, or to investigate the effect of design group composition, which we organised randomly. Then, it becomes clear how the adjustments, based on explicit teaching and scaffolding, have to interact when the educational setting changes. Furthermore, the development of well-validated rubrics to develop and assess skills (formative and summative) is essential to contemporary modern education. The more, because STEM skills are critical to innovation and in creating a competitive edge in modern-day complex economies, which becomes visible through a worldwide demand for STEM-educated graduates (ICF & Cedefop for the European Commission, 2015). According to the Program for International Student Assessment (PISA) survey in 2012 (OECD, 2014) among secondary education students (aged 15 - 16), nearly one-third of Dutch students involved scored a relatively low level of proficiency in science: level 2 or lower, based on six levels, where the level descriptors include application of scientific knowledge, scientific reasoning, problem solving, decision making and inquiry strategies. This score is slightly below the worldwide average and has remained unchanged since the first survey at the beginning of the year 2000. There is therefore a lot to be gained regarding the teaching and learning of STEM-related skills.

Another topic for further research comes from the fact that FITS students, despite the fact they reached high conceptual learning gains compared with traditional LBD students, were not able to use this advantage to achieve better design outcomes. A possible reason for this, based on all the studies, is the limited number of scientific concepts that are crucial for successful design realisation. Thus, all (re)modifications, which lie at the heart of the FITS model, might be more or less weakly design-related causing improved concept learning but little added value to design realisation. To tackle this, iterative redesign could be used to deepen and/or broaden the design task by implementing more (science) content into the requested design. In summary, there is a need for more research into the interplay of progressions in conceptual learning and enhanced design realisation through iteration and modification.

A final recommendation for further research directly appeals to, as discussed in section 1.5, the higher purpose of this thesis. Improving the pedagogy of design-based learning only makes sense when (future) teachers are able to adjust to the

new kind of classroom control. Therefore, based on Kolodner (2002a), student teachers were involved in the series of studies as a first important step towards the professionalisation of (student) teachers: gaining experience with design-based learning environments as (research) participants in the intervention. However, the research has not yet led to a training program for (student) teachers. According to Feiman-Nemser (2012) and illustrated by Figure 6.2, such a program is necessary to disseminate and further investigate the FITS model in the educational practice. The studies central to the dissertation mainly addressed design-based learning from a learning students and teaching skills perspective. To complete the educational Venn diagram in Figure 6.2, research is needed into the topic of learning teachers and, not to forget, possible disturbances (e.g. organisational constraints) that may prevent teachers from embracing design-based learning. For this, also based on Feiman-Nemser (2012), a training program with the following characteristics could succeed: learning from experiences, learning with and from colleagues and experts, learning from student feedback and learning through teacher induction in general.

Figure 6.2 Educational Venn diagram

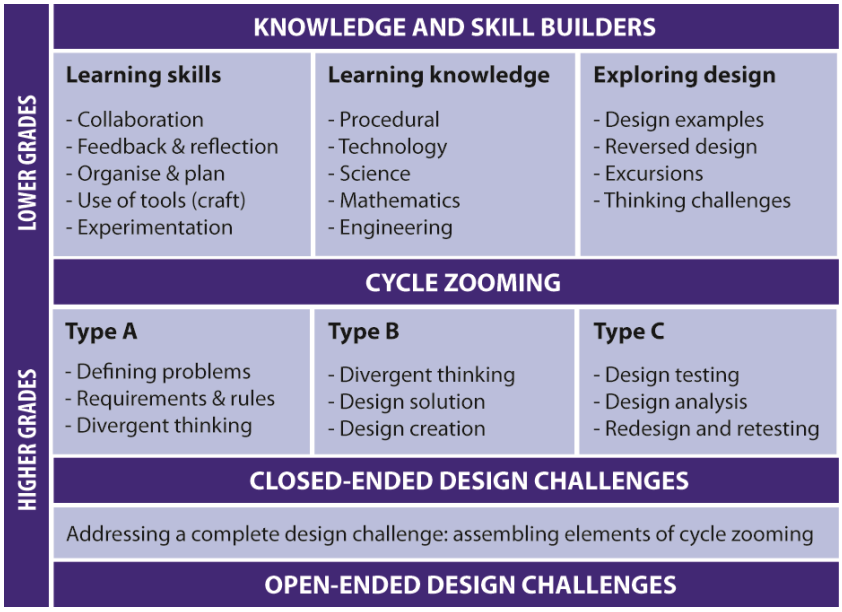


6.5 Implications for educational practice

It is quite obvious that a first implication directly appeals to the implementation of the FITS model in the educational practice. Through exposing students to well-organised and well-guided design-based learning challenges, they are enabled to learn knowledge, skills and practices in authentic, motivational and interdisciplinary learning environments. This may enrich and/or broaden learning experiences coming from traditional learning environments and makes students better prepared to face a highly STEM-dominated world. Furthermore, it enables practitioners and researchers to further investigate and improve design-based learning strategies.

A next implication comes from the complexity of design-based learning. Most of these approaches, like many design challenges in general, are complex due to many objects of integration that demand a certain level of basic knowledge and skills. It is worthwhile to take this complexity into account and to create a curriculum that enables students to learn important knowledge and skills before addressing complex design-based learning interventions. Figure 6.3 gives a suggestion for a curriculum approach that prepares students for dealing with complex design challenges.

Figure 6.3 Curriculum approach for design challenges



Adapted from van Breukelen (2017).

As discussed in Chapter 3, and partly central to the research's limitations and suggestions for further research, the teacher's role is of great importance for the success of design-based learning units. Using design faces teachers with an open-ended nature where teachers must relinquish directive control (Burghardt & Hacker, 2004). As a result, teachers leave or undermine design activities because they are not able to adjust to the new kind of classroom control (Wendell, 2008), which makes potential learning outcomes highly teacher dependent (Bamberger & Cahill, 2013; Van der Veen & Van der Wal, 2012). Teachers should be aware of this phenomenon and realise that uncomfortable experiences and difficulties are to be expected. Then, perseverance should be displayed, through iteration and collaboration, to overcome problems and to improve educational contexts. Educational boards should also play a part in this; they have to notice that teachers need sufficient time and space to improve their skills and education. Therefore, some degree of facilitation (e.g. time, money and training) is necessary that allows teachers, working together in development teams, to move forward.

A final implication concerns the fact that many insights arisen from the research might be, more or less, transferable to other educational settings and contexts. For example, the framework of teaching guidelines, developed during the first and second study, might give more insight in proper teaching behaviour in general. It offers the possibility to reflect on own and others practice and to take responsibility for skill development. Another example concerns the strategy of backward design (Wiggins & McTighe, 2006), which states that education designers must begin to think about assessment and objectives before deciding what to do and how to teach. Detailed learning task analysis is important to unravel task-exposed and task-underexposed content and to predict learning outcomes. Then, underexposed content should be addressed otherwise through additional interventions. Lastly, moments of reflection (by students) should always enrich the learning process, instead of frustrate the process, by incorporating reflective moments carefully. Reflect when necessary and use reflection outcomes explicitly to move on. In general, requested learning outcomes should reflect the trajectory offered to learn.

To conclude, the hope is expressed that teachers stay or become actively involved in the development towards high-quality learning environments. For this, many skills also important to technological design realisation (e.g. critical thinking, problem solving, reflection, etc.) are indispensable for succeeding.

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Curriculum Vitae

Dave van Breukelen was born on the 21st of May 1980 in Sittard, The Netherlands. In 1997 he graduated with honours from the school for higher general secondary education (havo). During this educational stage he became strongly interested in science, especially physics. Combined with an early present interest in teaching his choice for a follow-up study was an easy one: physics education. From 1997 until 2001 he attended the teacher training college of the Fontys University of Applied Sciencies in Eindhoven (PTH) where he obtained his bachelor's degree in physics education. Immediately after graduation he started working as a physics teacher at the Graaf Huyn College, a school for secondary education, in Geleen, The Netherlands. For a period of six years he taught physics at various educational levels (vmbo, havo and vwo) where he eventually also operated as a form teacher and head of the physics department. During his first job as a physics teacher he completed his master's degree in physics education in 2005 at the University of Applied Sciences Utrecht. His master thesis investigated the effect of learning contexts on students' motivation. Since August 2007 he has worked at the Fontys University of Applied Sciences for Teacher Education Sittard as a teacher educator in physics and technology. In this position he has been involved in teaching science, technology and didactics; curriculum development; member and head of the participation council; educational projects and internships; and educational research. Gradually his interests and focus, also driven by governmental and worldwide developments, shifted towards interdisciplinary teaching. This initiated the official start of his PhD project at the Delft University of Technology in August 2012, funded by the Netherlands Organization for Scientific Research (NWO), where interdisciplinary teaching of science and technology was the central topic.

List of Publications

International peer-reviewed scientific journals

van Breukelen, D. H. J., de Vries, M. J., & Schure, F. A. (2016). Concept learning by direct current design challenges in secondary education. *International Journal of Technology and Design Education*. Advance online publication. doi:10.1007/s10798-016-9357-0

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