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The FITS model: An improved Learning by Design approach

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Abstract

Learning by Design (LBD) is a project-based inquiry approach for interdisciplinary teaching that uses design contexts to learn skills and conceptual knowledge. Research around the year 2000 showed that LBD students achieved high skill performances but disappointing conceptual learning gains. A series of exploratory studies, previous to the study in this paper, indicated how to enhance concept learning. Small-scale tested modifications, based on explicit teaching and scaffolding, were promising and revealed improved conceptual learning gains. The pre-test-post-test design study discussed in this paper confirms this improvement quantitatively by comparing the conceptual learning gains for students exposed to the modified approach (n = 110) and traditional approach (n = 77). Further modifications, which resulted in a remodified approach tested with 127 students, show a further improvement through reduced fragmentation of the task and addressed science. Overall, the remodified approach (FITS model: Focus - Investigation - Technological design - Synergy) enriches technology education by stimulating an empirical and conceptual way of creating design solutions.

Keywords Learning by Design, technology, science, concept learning, Focus - Investigation - Technological design - Synergy (FITS) model

Introduction

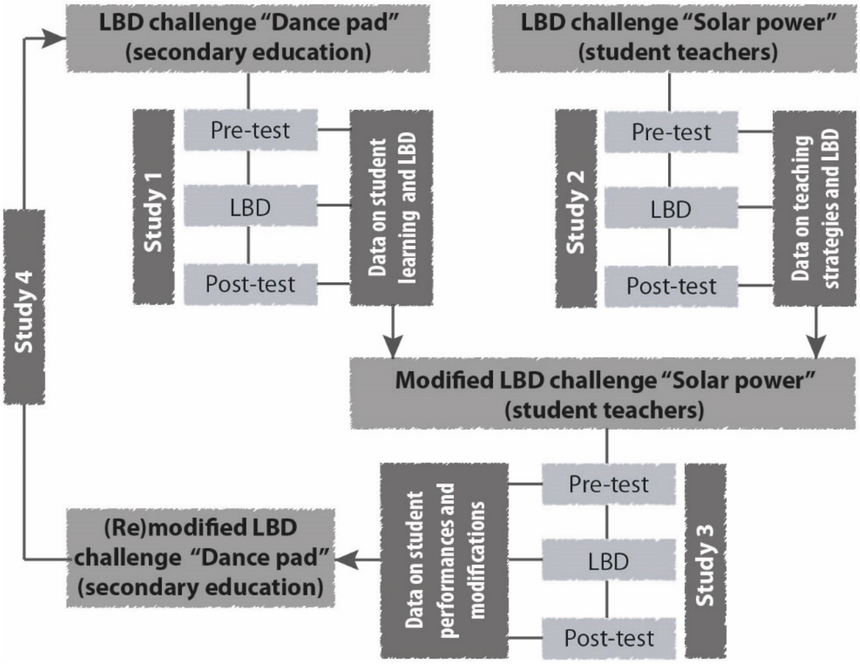
Design activities are a core process of technology education (International Technology Education Association, 2007) but, unfortunately, are often used as an instructional strategy where trial-and-error dominates the process (Burghardt & Hacker, 2004). Therefore, the standards for technological literacy demand a conceptual design approach where, for example, science knowledge enriches design tasks and design technology becomes a catalyst for interdisciplinary teaching. According to research, such developments are necessary to increase students' understanding of and motivation towards STEM subjects (science, technology, engineering and mathematics) because learning becomes more relevant, recognisable and coherent (Lustig et al., 2009; Osborne & Dillon, 2008; Rennie, Venville, & Wallace, 2012). This responds to the worldwide demand for citizens ready to face a complex STEM-dominated world (ICF & Cedefop for the European Commission, 2015).

Learning by Design (LBD) is a reasoned attempt to deal with these issues. LBD is a project-based inquiry approach for interdisciplinary teaching where the learning of science and technology are both represented. It combines the pedagogies of problem-based learning and case-based reasoning (Kolodner, Hmelo, & Narayanan, 1996): students solve design problems by adapting old solutions or interpreting new situations in the light of similar situations. For this, prior knowledge is addressed and new knowledge is developed (e.g., through investigation) within a collaborative and reflective learning environment. LBD studies from 1999 until 2003 (Holbrook, Gray, Fasse, Camp, & Kolodner, 2001; Kolodner et al., 2003) showed, compared to non-LBD settings, high student-involvement and skill performances. Unfortunately, conceptual learning gains were less promising, despite LBD providing a sound theoretical basis for this kind of learning.

Previous to the study discussed in this paper, three exploratory studies investigated the practice of LBD aiming for enhanced concept learning. The series of studies is visualised in Figure 1. The first and second study (Van Breukelen, De Vries, & Schure, 2016; Van Breukelen, Van Meel, & De Vries, 2016) confirmed the findings of Kolodner, Gray, and Fasse (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 (Van Breukelen, De Vries, & Smeets, 2016) 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 LBD task developed for the first study was adapted for use in this study. First, this was done by implementing modifications based on explicit teaching and scaffolding, comparable to the LBD task developed for the third study. Second was 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 re-contextualisation (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)? To what extent will the FITS model further enhance concept learning and provide a successful approach for interdisciplinary teaching?



LBD task and (re)modifications

Figure 1. Overview of the LBD studies

LBD provides a constructivist learning environment where students experience the necessity to learn through a variety of reflective, iterative hands- and heads-on activities concerning design technology, science practices, public presentations, collaboration and teacher-guided class discussions (Kolodner, Camp, et al., 2003). Students (operating in design groups) first have to explore things they need to learn for design realisation. By information seeking and experimentation they find answers to the research questions in order to apply them in the design. Design realisation and investigation of this application may lead to additional questions and reinvestigation. To share and deepen design-related principles and concepts, teacher-guided class sessions take place (poster and pin-up session, white boarding and gallery walks).

For this study, the traditional LBD task designed for the first study 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. The design, as shown in Figure 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 and attractive design. Thus, the most fundamental scientific design principles, determining 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 an interactive simulation (PhET^{TM} DC-circuit construction kit) and real experimentation. A more detailed task description can be found in Appendix: Table A1 and Van Breukelen, De Vries, and Schure (2016).

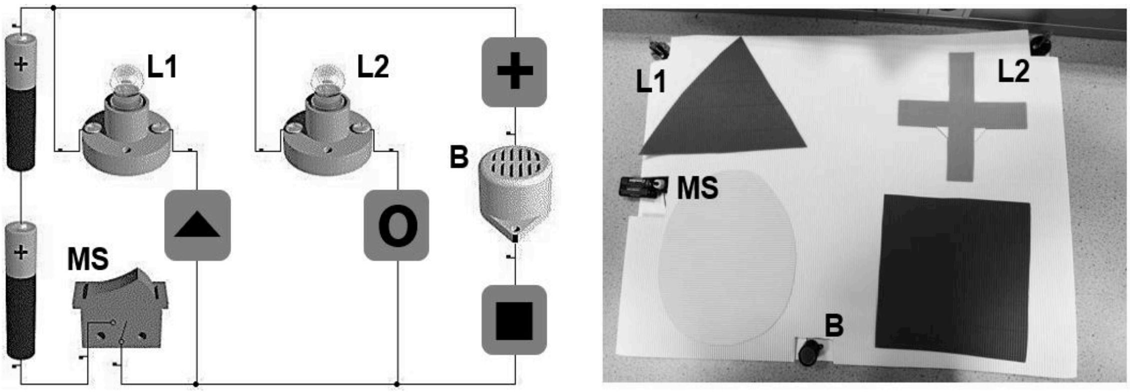


Figure 2. Wiring and example of a final design

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

The challenge was adapted for better concept learning based on previous study outcomes. All (re)modifications are listed in Table 1 and the improved models are shown graphically in Figure 3 (modified approach) and Figure 4 (remodified FITS model) where both models include all original LBD elements.

Because concept learning is central to this study it is important to explain how LBD facilitates this. LBD tasks address problems where students' pre-task conceptions are not sufficient for succeeding: LBD deliberately addresses 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 conceptual conflicts (challenging phase); and fourth, students adopt new conceptual models (application phase). Based on literature, for example, 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 learn conceptual knowledge within and because of the design context, this context strongly determines the level of conceptual performance (Murphy & McCormick, 1997). In that way, the newly adopted conceptual framework is strongly contextualised, which hinders students from de- and re-contextualising knowledge with respect to other contexts (knowledge transfer). (Lin, Hu, & Tsai, 2010; Murphy & McCormick, 1997; Sidawi, 2009). This process of mastering task-related knowledge, de-contextualising knowledge, recognising transfer opportunities and making an effective knowledge transfer (re-contextualising) corresponds with the higher levels of Bloom's taxonomy (Krathwohl, 2002) and represents deep conceptual understanding. All modifications in Table 1 facilitate knowledge transfer and therefore enhance concept learning.

Table 1. LBD (re)modifications

Modified approach: Modifications based on explicit teaching and scaffolding			
Modification	Fig.	Underpinning	Implementation
Backward design (Wiggins & McTighe, 2006)	3 & 4	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 amount of lights and, second, a changing number of connected batteries. This was

			done after stage 3 in Figure 3 and before the first science lecture in Figure 4. This activity was complemented by information seeking and a class discussion.
Guided discussion (Carpenter, Fennema, & Franke, 1996)	3 & 4	This 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 Figures 3 and 4 this mainly concerned the following activities: white boarding, poster session, pin-up session, gallery walk.
Informed design (Burghardt & Hacker, 2004)	3 & 4	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.	During the exploration phase, students additionally had to explore, 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 & scaffolding (Archer & Hughes, 2011)	3 & 4	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 (Van Breukelen, Van Meel, et al., 2016) resulted in a framework of important teaching guidelines to facilitate this.	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 science addressed through de- and re-contextualisation of science content emerged (whether planned or not) from the task.

Remodified FITS model: Re-modifications based on reduced fragmentation

Remodification	Fig.	Underpinning	Implementation
Science lectures	4	Domain- and task-related science, addressed during investigation, is discussed explicitly and de-contextualised with particular attention to interrelatedness of concepts. Examples of re-contextualisation (to other contexts) will foster knowledge transfer. In the synergy phase, it becomes visible how science and technology enrich each other: investigation outcomes and scientific concepts become more meaningful because they have 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	4	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 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.

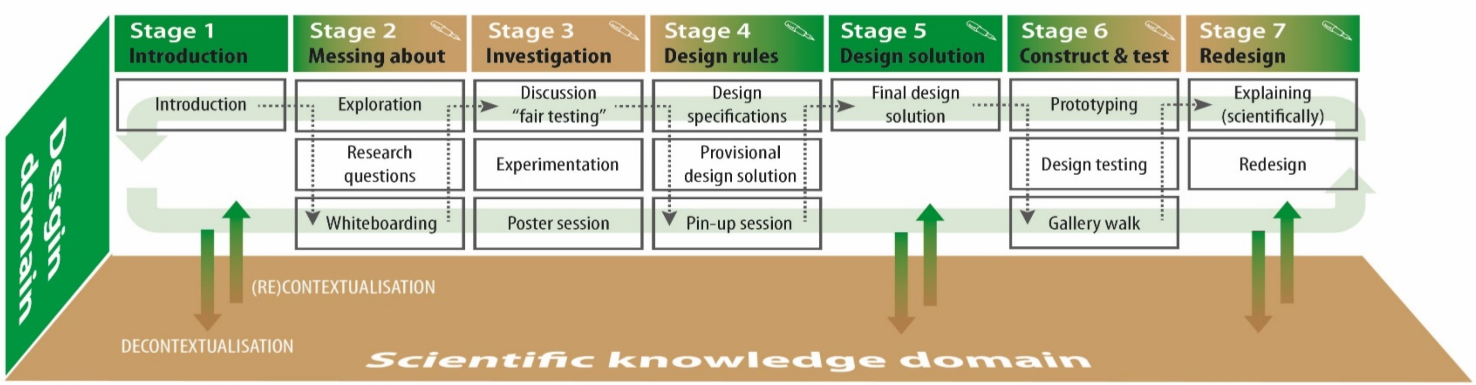


Figure 3. Modified LBD approach

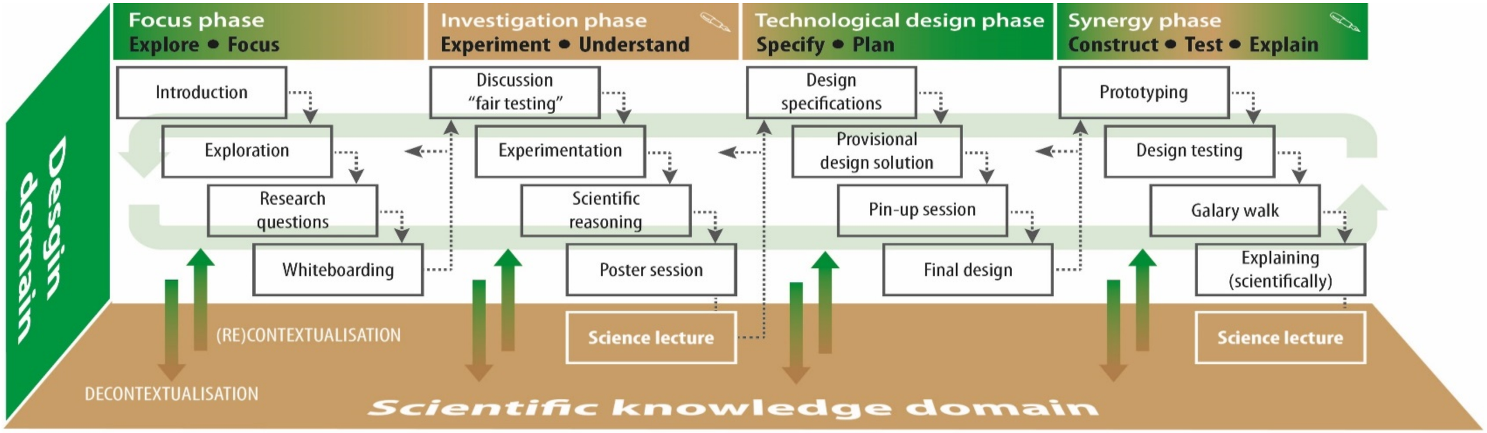


Figure 4. Remodified LBD approach: FITS model

Note: Figures 3 and 4. ✎ = administrative moment. Green colour = design-related focus. Brownish colour = science-related focus. Science is explicated by de- and re-contextualisation. All rectangular boxed activities in the white part of the figure are traditional LBD activities. However, in case of the (re)modified approaches the "Exploration" and "Experimentation" activity are enriched by pre-planned elements as discussed in Table 1.

Method

For this study, 237 general secondary education students (aged 12-14) took part in a pre-test-post-test design where 110 students did 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 (77 students) (Van Breukelen, De Vries, & Schure, 2016) and the modified and remodified approach, it was possible to verify learning gains found in the third study (Van Breukelen, De Vries, & Smeets, 2016) and to establish any further enhancement due to re-modifications.

Data collection

To investigate students' change in conceptual understanding, the pre-post-exam developed for the first study was used. 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 3-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.

Analysis

The pre-post-exams, processed for each LBD 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 $\langle g \rangle$: the ratio of the actual average gain (%post – %pre) to the maximum possible average gain (100 – %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 1 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 case of one-way ANOVA eta-squared η^2 was calculated and for the *t* tests, Cohen's *d*. Additionally, a post-hoc power analysis was used to identify whether the research design had enough statistical power.

The assessment of design outcomes in case of the modified and remodified approach, based on the 3-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 k*w* was 0.70). The assessment results for each approach are presented in Table 2 by the relative distribution of awarded scores per design specification and for all specifications.

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 2 shows the exam results and corresponding gains complemented by the Cronbach's alpha values that assume sufficient internal consistency.

Table 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

Note. SD = standard deviation; Quest. = question; Gain: $\langle g \rangle$ = (%post - %pre) / (100 - %pre) (Hake, 1998)
[a] Results adopted from Van Breukelen, De Vries, and Schure (2016)

Analysing the pre- and post-scores (paired samples *t* test) within each group, there is a significant increase in all cases: $t(76) = -18.18$; $p < 0.001$, $t(109) = -35.60$; $p < 0.001$, $t(126) = -37.29$; $p < 0.001$. In studying the gains, it is obvious that the modified approach resulted in much better learning gains compared to 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 re-modifications 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 to the traditional approach ($p < 0.001$). The test also confirmed a statistical difference between the modified and remodified approaches ($p = 0.004$). Finally, post-hoc power analysis revealed a power of 87 percent in the case of the modified and remodified interventions. 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.

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%) that only managed a low learning gain in case of the traditional approach. Due to the 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 re-modifications 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).

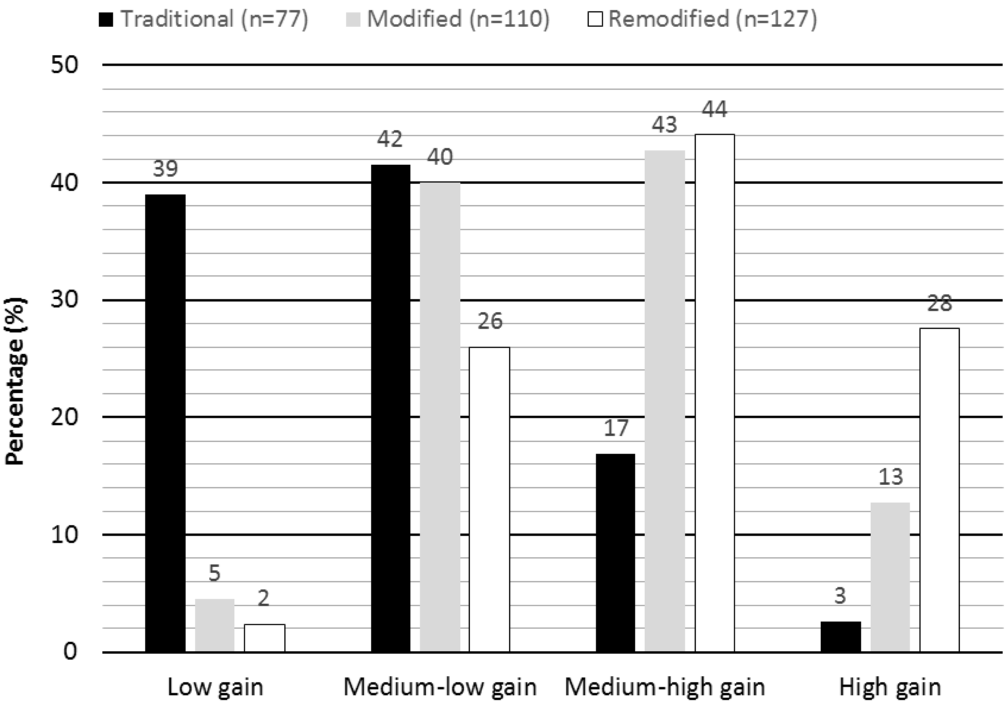


Figure 5. Relative distribution of gains

Note. Gains: 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 three approaches. Based on all specifications the success rate (+) is just above 70 percent for all interventions. For the science-based specifications (1-4) this percentage is even around 80 percent. This suggests that a solid improvement of conceptual learning does not automatically lead to more sophisticated design outcomes and that a limited amount of conceptual understanding is sufficient for proper design realisation. Table 3 shows how the final designs were scored by the experts.

Table 3. Assessment of design outcomes

Design specification (See Appendix: Table A2)	Relative distribution of scores awarded								
	Traditional (25 designs)			Modified (28 designs)			Remodified (32 designs)		
	+	o	-	+	o	-	+	o	-
(1) Main power switch operation	90%	8%	2%	86%	7%	7%	84%	10%	6%
(2) Floor pad design & operation light bulb 1	80%	16%	4%	79%	14%	7%	78%	16%	6%
(3) Floor pad design & operation light bulb 2	82%	16%	2%	82%	11%	7%	75%	16%	9%
(4) Floor pad design & operation buzzer	84%	14%	2%	71%	18%	11%	78%	19%	3%
(5) Restricted amount of used materials	96%	4%	0%	93%	7%	0%	94%	3%	3%
(6) Durability & solidity	42%	54%	4%	46%	43%	11%	50%	38%	12%

(7) Nice design (eye candy)	40%	44%	16%	43%	46%	11%	56%	28%	16%
Total	74%	22%	4%	71%	21%	8%	74%	18%	8%

Notes: + = successful; o = partially successful; - = unsuccessful

Discussion

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 also 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%) 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 re-modifications (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: To what extent will the FITS model further enhance concept learning and provide a successful approach for interdisciplinary teaching? Compared to students who were challenged by 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%) and suggests that the additional re-modifications 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 re-contextualisation 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 is also a main reason for limiting 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.

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APPENDIX: Detailed information on the adopted traditional LBD task

Table A1. Stages and activities

Stages [time]	Activities[a]	Final products[b]
1. Introducing the Challenge and Context [15-20 min]	Introduction of context, design challenge, activities, organisation, learning sources, time schedules, materials, objectives, etc.	
2. Understanding the Challenge, Messing About, White boarding [50-60 min]	• Exploration of the challenge, context and objectives (G) • Writing down ideas, (research) questions and hypotheses (G): what to do and learn? • White boarding: sharing results; feedback session (C)	Design diary stage 2 • Flip chart for white boarding (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 of results: 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) • Experiment poster (G)
4. Establishing Design Rules of Thumb [20-30 min]	• Determination of design rules using experiment results (C) • Focus on the science content: 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 and 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: realisation of the design solution (G) • Testing the design: realization of design specifications (G) • Gallery walk: determine shortcomings; feedback/reflection (C) • Adjustments of the design rules and design solutions (C/G)	Design diary stage 6 • Prototype design (G)
7. Iterative Redesign [50-60 min]	• Iteration of previous 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 design solution (G) • Final reflection (individual)

Note. Reprinted from Van Breukelen, De Vries, and Schure (2016). C = class activity or product; G = design group activity or product.

[a] Available resources: electronic learning environment (ELE), smartphones, laptops, tablets, Microsoft Office software, internet access,
materials and tools for design realisation, materials for conducting experiments

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

Table A2. Design specifications and materials

Design specifications
1. The readily available push button serves as main power switch.
2. One self-designed floor pad, recognizable by a circular form, should flash a light by being stepped on.
3. One self-designed floor pad, recognizable by a triangular form, should flash a second light by being stepped on.
4. To sound the buzzer. two self-designed floor pads, cross and rectangular shaped, must be pushed on simultaneously (with two feet).
5. It is not allowed to use more design materials than available.
6. The dance pad consists of one piece and can be used frequently without failure.
7. The dance pad has a nice design (eye candy) and is easy to use.

Material	Quantity	Material	Quantity
1,5-volt AA battery	2	push button	1
AA battery holder	1	light bulb	2
Aluminium foil	1 roll	light bulb holder	2
cardboard (4 colours)	1 sheet (50x70 cm) per colour	buzzer	1
tape (single- & double-sided)	1 roll	electrical wire	500 cm

Note. Reprinted from Van Breukelen, De Vries, and Schure (2016).

Table A3. Scientific objectives and initial appearance

DC Electric Circuit 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 components on current flow (through a battery): parallel components increase and series components decrease current flow.	• Similar to objective 1
4. Recognizing and designing series, parallel and combined circuits and, with respect to this, identifying	• Operation is based on proper wiring. Students have

and describing circuit operation.	to meet design specifications 1 - 4. • Wiring can be studied by experimentation.
5. Students know that conductors and insulators influence current flow: conductors enable current flow while insulators impede current flow.	• Students have to design floor pads by combining conducting and insulating materials (design specifications 2 - 4).
6. Students know that circuits (in daily life) have a purpose in converting an input in an output (action).	• The dance pad is a daily life example of a system based on an electric circuit.

Note. Reprinted from Van Breukelen, De Vries, and Schure (2016).