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ACUIRING THEORETICAL KNOWLEDGE IN CHALLENGE BASED LEARNING (ID 239/1239)

R.Taconis[1]
Eindhoven University of Technology
Eindhoven, the Netherlands

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1 INTRODUCTION

Challenge Based Learning (CBL hereafter) is an educational concept to modernize engineering education e.g. [1] [2]. In CBL students build their knowledge, develop skills and professional attitudes by addressing open real-life challenges in interdisciplinary teams. These challenges mirror professional engineering practice, and are often related to the major challenges of our time [3].

As an educational concept CBL offers a view on how engineering students should learn [4] and underscores a broad range of educational practices and teaching methods such as Problem Based Learning (PBL) [5] and Design Based Learning [6]. This view stools in social constructivist learning theories [7] which view learning as a process of social interaction and participation in a professional community. Thus, it contrasts with classical instruction-based STEM (science, technology, engineering and mathematics) education, which has traditionally been associated with the idea of learning as a primarily cognitive process.

Scientists have identified several positive effects on professional preparation, motivation and a positive attitude towards STEM and the acquisition of practical knowledge and skills. It also brings education closer to (professional) reality.

In STEM and engineering, theoretical knowledge and understanding play an important role, however this depends on the type of engineering domain. Therefore, concerns have been expressed by faculty and students about PBL applied in the field of engineering. Concerning increased workloads, difficulties with implementing CBL in the curricula, but also doubts about its effectiveness in theoretical knowledge accumulation [5] [8]. According to Hung et al. *'Problem-based learning is criticized for its emphasis on facilitating higher order thinking and problem-solving skills at the expense of lower level of knowledge acquisition'* [5, p. 489]. Therefore, we deem it useful to conduct further research on the effectiveness of CBL for theoretical learning in particular. That said, we would like to emphasize that this paper is not intended to criticize CBL, it merely intents to assess its effect on cognitive learning effects of CBL, to identify potential areas of improvement.

1.1 What is CBL?

Various authors have described characteristics of CBL and have relied on a variety of definitions e.g. [3], [9], [10]. Here, CBL is viewed as a 'family of educational approaches' that share key elements [11]:

- open and authentic: learning by working on open-ended 'real world' issues or problems,
- productive: leading to a product or 'solution' with relevance outside the educational context,

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[1] *Corresponding Author*

R. Taconis

r.taconis@tue.nl

- challenging: it is engaging and challenging to students,
- collaborative: requires a (multi-disciplinary) team approach,
- expansive and experiential: students need to acquire additional new knowledge to complete the challenge successfully and will have to learn by doing,
- student agency: it requires (guided) self-directed learning from students,
- developmental: student are trained to be increasingly self-steering and reflective.

Overall, these characteristics apply to all CBL, but the exact mix and specific realization may differ from subtype to subtype. For example, Problem Based Learning (PBL) uses open problems as challenges e.g. [12]–[15], while Design Based Learning (DBL) uses designing something as a challenge e.g. [16]–[20]. Thus defined CBL is used as various universities [5], [10], [15], e.g. [21]–[23] and engineering universities [1], [2], [24].

1.2 A view on an adequate engineering knowledge

Various scholars have described the competencies and knowledge engineers need [25]–[27]. This requires a skill-base that comprises key engineering skills such as analytical thinking, experimenting, problem solving, design skills, and general professional skills. Communication skills and advisory skills for example.

Domain related engineering skills, however, need to be rooted in an adequate engineering knowledge base [28]. The latter should be correct, coherent and well integrated. A commonly held view is that an adequate knowledge base is made up of a number so called cognitive schemata, embedded in a coherent theoretical meta-structure and involving a rich number of internal and external connections. Schemata are defined as functional units of knowledge in which three essential types of knowledge are intimately connected. These are: situational knowledge (serving as active recognition filters indicating 'when' the schema is potentially relevant), declarative knowledge (what concepts, rules formula's apply), and procedural knowledge (containing information on how to apply the declarative knowledge) [28].

Engineering c.q. STEM are characterized by the wide use of complex and abstract concepts. Unlike practical and operational concepts which are defined by what they represent in reality, theoretical concepts are *defined* by their formal mutual relations. These concepts build abstract models and theories, here viewed as configurations of mutually connected concepts. These connections are of various nature e.g. semantic, mathematical or hierarchical [8].

This hierarchical nature causes that the mastery of a particular part in STEM often is essential to understand the following parts. Missing a peace will make it difficult or impossible to learn later on, at which point a very significant repair would be required [8]. In education, this implies a need for a curricular sequence. But for the learner it implies that from time to time a small paradigm shift is needed to accept and integrate a new vision, model or theory. To adopt a new theory, the interconnected configuration must sometimes be understood as a whole, and this requires the restructuring or degradation of already existing ideas. As described in theories of misconceptions and threshold concepts, STEM learning is sometimes not a smooth process of adding up new bits of knowledge [29].

1.3 Building an adequate engineering knowledge base

In general, theoretical learning results from the cognitive activities and metacognitive activities which regulate thinking/learning and operate with/on the students' (theoretical) knowledge [30] [31]. Examples of these are: 'testing ideas' [31] and 'evaluating the value of knowledge' [32]. Various taxonomies have listed cognitive and metacognitive learning activities [31], [33]. Also guidelines for reaching such 'deep learning' through teacher guidance, feedback, example, help and possibly explanation [34] have been formulated [35].

In CBL these are invoked by the challenge. Students primarily perform the (meta-) cognitive activities necessary to complete it. In completing the challenge, students experience the strengths and shortcomings of their current knowledge, which they can then expand ("need to know" [36]). Viewed at the level of learning theory, deep learning in CBL depends on the success with which the challenge elicits appropriate and sufficient (meta-) cognitive activities.

Seen on a more specific level of schema-theory, building an adequate engineering knowledge base in CBL requires a) activities that lead to the construction of new schemata or the completion/refinement of pre-existing ones, and b) activities that lead to building a (theoretical) meta-structure and rich connections adequate for engineering [37]. Examples of the latter are: 'reflecting on (theoretical) knowledge' and testing (theoretical) knowledge for consistency.

2 METHODOLOGY

It is our aim to look for information pointing a direction to optimize CBL for theoretical learning for which the research question are:

1. What are features of challenge based learning tasks that help create an adequate theoretical engineering knowledge base?
2. How can Challenge Based Learning tasks be designed to maximize the acquisition of theoretical knowledge and understanding?

A systematic search and review was performed comprising using the SALSA strategy: Search, AppraisaL, Selection, Synthesis, and Analysis of literature [38].

The search involved: a) theoretical papers underpinning / defining CBL-type education ($n \approx 30$), reviews and meta-studies on CBL-type education (e.g. PBL, DBL, case based learning) ($n \approx 20$). Next to these secondary sources, literature on empirical cases of CBL-type education in various domains in or closely connected to Engineering ($n > 250$) was analysed as primary sources. The papers were searched using keywords in google scholar, with a preference for studies published in the 21st century.

In the appraisal phase, a significant number of the selected studies were found to be less informative regarding theoretical learning. One reason for this was the wide variation in terminology about knowledge and skills, as well as the ambiguous use of these terms. For example, in studies that showed the terms knowledge and theory in the title and summaries, but only drew conclusions in terms of skills. Second, it appeared that many studies fall short in describing key elements (e.g. the assessment procedure or learning outcomes), or aspects we were looking for (e.g. it was not clear whether the learning loop was closed or not).

In the synthesis, a framework has been developed to understand the main features of CBL design that are found relevant for (theoretical) learning in the literature. It was found that several reviews shared co-authors (e.g. [39] and [40]), built on previous reviews (e.g. [41], on [42]), and/or included overlapping sets of experimental studies. This resulted in repeated findings in several studies..

Besides this, research appears dominated by PBL in medical education (e.g. [43]). Similarly, research findings conducted on education in the field of engineering seems to be skewed towards DBL [6] and CDIO-type approaches with the use of open problems [44].

In an effort to overcome the lurking risks and create the best possible overview, empirical evidence was re-examined to 'test' the synthesised framework of features relevant for theoretical learning (see section 0). The analysis focussed on empirical studies that oppose or support the hypothesised impact on (theoretical) learning.

In the analysis, knowledge outcomes were typified using the categories: practical, conceptual, operational, and theoretical [9] [43]. For challenge types the classes were 'engineering methods' [9] supplemented by problem types [22], [45].

Since not all sources are informative on all aspects, the results presented focus on the studies that were deemed informative on the research questions.

3 RESULTS

3.1 Overall picture of CBL learning results

It was found that CBL generally produces positive attitudes towards STEM. Research indicates that it increases motivation, and results in the learning of practical and operational knowledge, skills in applying that knowledge, and professional skills. For practical and operational knowledge PBL appears slightly superior to 'classical education' e.g. [5], [40], [41]. Strobel and van Barneveld claim PBL is superior to 'traditional instruction' with respect to training competent and skilled practitioners, but slightly inferior results on 'standardized tests' [15]. However, learning effects are heavily moderated by various factors in the design and implementation of CBL [43], as well as by student competencies and characteristics.

Only a small number of studies report on learning results that according to our definition count as theoretical. Also, in studies that did report on knowledge acquisition, *theoretical* knowledge is not indicated as a learning outcome (e.g. [15] [41] [46]). The most widely used classification system of Gijbels et al. [41] does not include a category that includes the interrelationships between concepts, as would correspond to our definition of theoretical knowledge. The studies that explicitly relate to theoretical knowledge usually report a learning outcome that is less than that of classical education, or, for example, a negative learning outcome e.g. [20]. While the evidence is incomplete and partly "circumstantial", all this strongly suggests that CBL in general is less effective for theoretical learning – at least without particular additional measures.

3.2 Synthesis: building a framework

3.2.1 Features and typology of CBL

For the review it emerged that two general features of CBL learning could particularly impact (theoretical) learning outcomes:

- Duality CBL learning is a dual process which comprises two sub-processes. First, the process of *task completion*, which consists of collaboration, the production of a final product, and various cognitive and metacognitive activities to achieve this. This is a joint effort, both with regard to the activities and with regard to the outcome, which is (often) assessed at group level. And secondly, the process of *(theoretical) learning*. In this students may have their distinct individual aims [47].
- Complexity CBL classifies as a case of so called 'complex learning' [48]. 'Complex learning aims at the integration of knowledge, skills, and attitudes; the coordination of qualitatively different constituent skills; and the transfer of what is learned to daily life or work settings' [49, p. 5]. The challenges CBL is built around are complex e.g. ill-structured problems or involving design dilemmas. Completing these requires the use of different strategies, such as divergent thinking guided by deliberate methods, creativity, position determination and different schemas [45].

3.2.2 Typology of various CBL learning tasks

In addition to these two general characteristics, the literature showed design choices that can influence (theoretical) learning [43]. Five design features have been identified, in particular since these appear to influence students' (meta-) cognitive activities and schema construction:

- Curricular embedding. This concerns how CBL-tasks are integrated in the curriculum for example: 'stand-alone', 'as a course' next to and orchestrated with appropriate theoretical courses (ladder model), or as a course including which theoretical components useful to completing the challenge (sandwich model). This feature impacts the availability of students' prior knowledge, and provides options for students while searching for knowledge they still miss.
- Open and closed learning loops. Barrows [22] distinguishes between open and closed learning loops. This characteristics specifically concerns the learning sub-process and is relatively independent of the challenge as such being open. A closed learning loop means

that the learning process is triggered by the project (e.g. a 'need to know' [36]) and that the results of an intermittent learning episode is explicitly used for moving forward the project. The task can be open-ended in that the students decide on the particular project they define, how they approach it, and what end-product they define, while the learning loop is closed. This aspect impacts how student search and use knowledge is regulated and used as a source for completing their project.

- Types of challenge/problem. CBL is built around a challenge, issue or problem. These challenge reflects the 'genre' of that engineering domain and focus on a particular professional activities that plays a key role in that domain [50] which we here indicate as particular *engineering methods*. For example, for 'industrial design', Design is the key engineering method, and it is an obvious choice to use in CBL. In building science 'writing an underpinned advice' reflect one of the important professional engineering activities, and could be used in CBL. The type of challenge influences what knowledge students need, how this knowledge needs to be processed (e.g. the (meta-) cognitive activities) and how it is synthesized to create a product.
- Scaffolds. In complex education like CBL, cognitive load and working load that is not directly or indirectly contributing to reaching the learning goals has to be carefully managed or minimized [48]. First by choosing a design with a carefully managed complexity, providing clear (possibly personal) learning aims, and by careful alignment of learning aims, required activities and assessment [51]. But also by providing scaffolds that support students in managing the group process without too much effort, and that allows them to gradually develop the skills necessary to do so as well. Scaffolds influence the availability of cognitive resources to engage in (meta-) cognitive activities and schema construction while doing the challenge, as well as the exact activities undertaken.
- Guidance. Scaffolds need to be supplemented by ample guidance to help reduce extraneous cognitive load [52]. Apart from reducing cognitive load, guidance is critical to help students deepen their discussions and learning [53]. Guidance performs the same functions as scaffolding, but can also influence the depth of theoretical discussions and thinking.
- Multidisciplinarity. Learning in a group can be superior to learning individually, particularly in relatively complex tasks [54]. For effective teamwork, effective collaboration is needed and this is highly facilitated by e.g. creating an interdependence between team members is needed [55]. This affects the availability of know-how, opportunities for peer-to-peer learning and in-depth discussion in the team as they rise to the challenge.
- Alignment of aims, learning process and assessment. This may be generally considered an important feature of successful (engineering) education [51]. Literature indicates that particularly the alignment of the assessment to the learning process is an issue in PBL e.g. [56].

3.3 Analysis: features of CBL and their relation to theoretical learning

Literature was re-examined from an analytical perspective to broaden and test this synthesis where possible

3.3.1 Curricular embedding

Creating a structure of interlocking CBL-activity and instructional episodes is advocated to optimize learning by various authors e.g. [57]. Sipes [58] concluded that (theoretical) learning probably demands the explicit programming of the course content within the challenge, or in a previously programmed knowledge intensive (sub-) task. In the engineering education cases, CBL occurs as a capstone project (theoretical courses preceding the challenge) or using the ladder model (parallel to courses providing relevant content). The sandwich model (small educational episode programmed of maid available on demand during de CBL project) is found less frequent, though this is the classical model of PBL as used in medical education.

3.3.2 Type of challenge: Engineering method

In engineering education, design is de most frequent type of challenge e.g. [16], but solving open-ended problems is also frequently used. Also cases were found using product development [59] or improvement [60], and various forms of decision-making problems in which students are asked to write a study book chapter, paper, underpinned advice or expert report [45, p. 21]. Particular approaches fit to particular domains. For example, reverse engineering was most abundant in computer science e.g. [61].

It was found that design may be less suitable as an 'engineering method' when aiming at theoretical learning. First, because creating a working prototype is so tempting that it actively diverts the student's attention from theoretical learning [20]. And second, because creating a design and / or building a prototype involves a large workload that is largely ‘extraneous’ to theoretical learning. Decision-making problems are advertised as beneficial for (theoretical) learning [45]. Like reverse engineering, this type of challenge implies theoretical deepening in a natural way [43].

3.3.3 Balancing task completion and learning

For theoretical learning, (meta-)cognitive processes must operate on or at least involve theoretical knowledge and it is key that a considerable amount of project time is spent on in depth theoretical discussions [53]. Students have been found to prioritize the task completion process over theoretical learning [46]. In particular when a design has to be realized [20, p. 426] or when time runs out [47].

3.3.4 The learning loop: closed or not

The effects of a closed learning loop on (theoretical) learning are not visible in individual studies, unless explicitly evaluated. For example Moust et al. [62, p. 667] and others have shown how the learning loop in the Maastricht model of PBL is closed. Also Sipes [58] describes a clearly closed learning loop, but in neither case an evaluation of the effect of this particular feature on learning was evaluated. In secondary literature, a closed learning loop is associated with superior learning outcomes [22] [43].

3.3.5 Alignment of aims, activities and assessment

Savin-Baden [56] concludes that in many cases assessment in PBL was found to be disruptive to the intended learning process and that 'many forms of assessment still largely undermine collaborative learning and team processes in PBL’ [56, p. 221]. In line with this Moust [62] argues for a better alignment of assessment to learning process.

It was found that not all studies reviewed are explicit on what exactly is evaluated. A general tendency however seems to be an emphasis on collaborative and group process and the qualities of the product produced. Van den Beemt et al. [3] [63] call for balancing product and process assessment, by assessing elements such as team progress, knowledge and skills at regular checkpoints both individually and on a group level.

Another issue is the alignment of learning goals and assessment. In various studies theoretical learning goals – if present – may be implicit. Also clear theoretical learning aims, and assessment criteria are needed Savin-Baden [56].

3.3.6 Multidisciplinarity

Almost all CBL projects the teams comprised students within one cohort though sometimes with different disciplinary backgrounds. Large differences in expertise have been found to easily cause unbalanced workload divisions [64]. Hence, for effective collaboration, the team members’ background disciplines should be roughly ‘equally’ relevant for completing the task. When supplementary, this will enhance interdependence between team members [55] which can further enhance collaboration. In order to allow discussions and knowledge exchange valuable to the theoretical learning of all team members, the disciplines must have an overlap [65].

3.3.7 Scaffolding and Guidance

Several authors emphasize that students need scaffolding in CBL and offer suggestions on how to do this, such as a 'model-observe-fade' strategy [66] or 'signposting' [63]. Effective guidance by teacher/guide/tutors is a mix of monitoring, facilitation and guarding the groups work and progress. For this, various mechanisms and techniques can be used such as: asking questions, providing a model showing 'how to act professionally', setting goals, providing feedback on results and processes e.g. [5, p. 494]. Various authors emphasise that it is critically important that the teacher should continuously try to make students go in depth [53]. It was found that expert tutor's in PBL perform better than non-experts, as long as the refrain from 'lecturing' [5]. Most empirical studies are not specific about the scaffolds and guidance offered.

3.3.8 Deep learning, schema construction and meta-structure

Deep learning [35] means that students perform cognitive and metacognitive activities involving their theoretical knowledge.

In CBL, cognitive and meta-cognitive activities are principally invoked by the task completion process. If additional explicit (theoretical) learning goals, or additional learning activities are defined, these will add to that. If not, it may therefore be that most (meta-) cognitive activities focus on the task completion process, rather than the theoretical learning process. For example: monitoring progress in task completion, rather than monitoring progress in theoretical learning. The latter would have a far deeper impact on theoretical learning.

Is already mentioned above, various authors (e.g. [53]) stress that a continuous effort of the teacher is needed to deepen student discussions. If students fall short on this, they will develop an incomplete or only partially integrated knowledge base [67]. Van Breukelen concluded that in secondary school DBL that only concept absolutely necessary to complete the design were learned and even concepts that were only slightly more abstract than these were poorly learned [20]. In empirical studies only a few take a schema theoretic perspective.

Hummel and Nadolski propose a strategy to improve schema construction [68]. A few examples use competition [69] that could help knowledge building and integration through comparison [70]. A few studies report that (theoretical) knowledge and its' integration are explicitly addressed in the assessment [62] [20].

3.4 Summary and acknowledgments

This study could only surface the theme of 'theoretical learning in CBL'. In addition, the research is skewed, towards PBL and research in medical education in particular. Also, our focus on theoretical learning as required in STEM is not common in most research on CBL-type education, making direct evidence from empirical studies relatively scarce.

Nevertheless, a clear picture emerges of the power of CBL for training skilled professionals, as well as its shortcomings for acquiring theoretical knowledge in STEM. This study identifies some of the causes of the latter in CBL design and implementation, used here to support advice for optimizing CBL for theoretical learning.

Concerning the acquisition of theoretical knowledge and understanding in STEM (engineering) this study suggests that 'stand-alone' CBL is less effective than 'traditional education'. This suggestion is supported by the following factors: (a) the large cognitive load and workload produced by the project work that is extraneous to theoretical learning, (b) the relatively small cognitive overlap of the cognitive activities needed for 'project completion' and those activities needed for 'theoretical learning', (c) the absence of some cognitive and meta-cognitive activities necessary for schema building and integration in the average CBL-project, (d) implicit or absent assessment of theoretical learning.

While this research suggests the challenges described above associated with the application of CBL in theoretical learning, it also identifies opportunities. Based on our findings, we make the following recommendation for the application of CBL in our field, in addition to general recommendations for good education (e.g. [51], [55]): use a 'closed learning loop' (while the project as such is open-ended), do not overload students, build the challenge around an appropriate 'engineering method', create teams with a composition functional to deep learning, provide in-depth guidance, provide a clear assessment off theoretical learning, and invest in the higher order thinking skills of the students.

When optimizing CBL for acquiring new theoretical knowledge and understanding, a very well controlled design is probably needed with a high-quality implementation that reduces cognitive load and workload, and aligns theoretical learning with task completion, and supplements CBL with additional (meta-) cognitive activities. For theoretical learning, a close interlocking of CBL-activity with instructional episodes is best.

All in all, CBL is a great step in the process of facilitating optimal learning processes for students. However, there are still some hurdles to overcome. We look forward to the future where we can further explore this approach to enhance its use and applicability.