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Enhancing Critical Thinking in a PBL Environment*

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Engineering education accreditation bodies emphasize the need for competencies beyond technical expertise. Critical thinking is one of these competencies, which is also considered as a precursor for the development of other competencies such as multidisciplinary collaboration, problem-solving skills and lifelong learning. There is an urgent need to enhance engineering students' critical thinking and one way to do this is to make use of active, student-centred learning approaches such as Problem Based Learning (PBL). This study aims to provide a model for understanding and enhancing critical thinking in a PBL environment. The development of the model takes its point of departure from a conceptual model for critical thinking that is concretized in a PBL context by including theoretical as well as empirical perspectives. The empirical study was conducted at the Faculty of Engineering and Science, Aalborg University (Denmark), which has more than 30 years of experience in educating engineers in a PBL environment. Based on the results, a model for critical thinking in a PBL environment is outlined emphasizing a problem-solving process grounded in open and real life problems as well as a self-directed, collaborative and team-based learning environment. The model also includes recommendations to overcome challenges detected in the empirical study, especially those related to the scaffolding of group collaboration and the use of theory in a self-directed learning environment based on real life problems.

Keywords: engineering education; critical thinking; problem based learning; decision making

1. Introduction

Contemporary society poses new challenges for engineering education. Educators, researchers and international organizations have been debating what kind of engineering education is needed for the 21st century. The 21st century engineer is challenged by societal requests to manage the unpredictable impacts of technology on social, economic and environmental systems, to innovate and provide technological breakthroughs at a fast rate, and to adjust to increasing globalization and the complexity of knowledge systems [1–4]. Engineering education is called upon to address these challenges by rethinking educational approaches and goals. For example, engineering students not only have to master the fundamentals of a particular engineering discipline (e.g. STEM) but also to develop other kind of competencies such as critical thinking, communication, teamwork, problem-solving skills, self-assessment, change-management and lifelong learning skills [3, 5]. In the literature these competencies are referred to as process competencies, transferable skills or soft skills and are developed along with the application of knowledge and, therefore, call for an active, student-centred learning approach. Among these competencies is critical thinking, which is considered to be a core goal of contemporary education [6], including engineering education.

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1.1 The need for critical thinking in engineering education

Engineering education accreditation bodies, international and governmental organizations emphasize the need for competencies beyond the technical expertise as part of a professional qualification profile [1–2, 7–10]. Critical thinking is one of these competencies and it is also considered a precursor for the development of others, namely multidisciplinary collaboration, problem-solving skills and lifelong learning [5].

The criteria for engineering programs provided by the Accreditation Board for Engineering and Technology (ABET) [7] does not explicitly refer to critical thinking as a learning outcome. The general program outcomes are: communicate effectively, work in multidisciplinary teams, understand the impact of engineering solutions in global and society in general, and be able to engage in lifelong learning or self-directed continuous professional development. However some engineering programs include specific criteria where critical thinking is explicitly stated as the ability '*to conduct laboratory experiments and to critically analyze and interpret data in more than one major environmental engineering focus areas, e.g., air, water, land, environmental health*' [7, p. 301]. The European accreditation framework, EUR-ACE, states that for the second cycle of studies, within the dimension of knowledge and understanding, students should be able to have '*a critical awareness of the forefront of their branch*' [8, p. 5].

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The Tuning-AHELO Project [11] presented a conceptual framework for the expected/desired learning outcomes for engineering education based on both ABET and EUR-ACE. The project emphasizes the development of critical and self-critical abilities, namely the students' ability to critically assess results, produce critical information through, for example, modelling, critically review target systems and make critical judgements [11]. This is referred to as a part of an innovative curriculum for engineering education in the European context. The *Global Engineer* [2], a document that elaborates on the skills needed for engineering education in UK higher education, argues that more than technical and scientific knowledge is needed in order to address the uncertainty and complexity of present society. In this document, the authors point out that critical thinking, multi-disciplinarity, team working, the ability to work across cultures and contexts, systems thinking and strong inter-personal and communication skills are just as relevant to international development practice [2, p. 3].

The Engineer of 2020: Visions of Engineering for the New Century [1, p. 54–57] outlines the following attributes for future engineers: strong analytical skills, exhibit practical ingenuity (skills in planning, combining and adapting), creativity (invention, innovation, thinking outside the box, art), communication to engage with multiple stakeholders, overall business, management and leadership skills, high ethical standards and professionalism as well as dynamic, flexible and lifelong learning potential.

According to Felder & Brent [12], the goal of engineering education should be to bring students to a certain stage of intellectual development in which they recognize that knowledge is not certain and begin to make judgements on the basis of evidence (e.g. theoretical or empirical). This stage is named intelligent confusion where students recognize that all '*knowledge is contextual and becoming sophisticated in their use of evidence to make judgments. Students start to behave as expert engineers*' [12, p. 269]. In the opposite stage, that of "ignorant certainty", students see knowledge as certain or unquestionable where figures of authority hold all the answers. This last view of knowledge carries a certain intellectual inertia against the need for innovation and creativity, which is considered crucial for today's engineering profession. In consequence, engineering education should re-think its educational approaches and methods to allow for an intellectual development, which enables students to critically question existing knowledge and to seek evidence for testing its validity [5, 12].

Through critical thinking, students develop a conscious awareness of the knowledge learned, question it, find evidence from different sources to support arguments and decisions, but also integrate new knowledge gained from the experience of being involved in a learning process. In this sense, critical thinking gains further relevance by allowing students to transform their experience of learning into new knowledge and to relate it to the existing knowledge [5, 12–13].

All the above stresses the need for critical thinking as part of the learning outcomes for engineering students, which means that learning environments should provide the conditions for students to enhance and strengthen their critical thinking abilities. However, studies have shown that educators find it hard to define what critical thinking is and how it can be developed within the learning process [14].

1.2 Research question

The above highlights the urgent need to enhance engineering students' critical thinking skills but, at the same time, it also shows that critical thinking is a competence among, and in interplay with other competencies that will challenge the engineering education of tomorrow, such as: multi-disciplinarity, team-work, system thinking, communication, analysis, practical ingenuity and creativity—the so-called process competencies. Problem Based Learning (PBL) is an example of an active, student centred methodology suitable for developing students' critical thinking and other process competencies [15–16]. Yet even though an active and student-centred learning environment is an established and appropriate condition for the development of process-competencies, the awareness and understanding of what critical thinking is and implies for students does not necessarily follow. In search of a framework to initiate such discussions, the authors have identified a gap between the rather abstract theoretical frameworks with epistemological perspectives at the one end, and prescriptive frameworks stating what students should do from a rather instrumental perspective at the other. Both types of frameworks are, without doubt, important to the enhancement of critical thinking but, whereas the epistemological frameworks have limitations in terms of out-reach to staff and students in the engineering community, prescriptive frameworks do not necessarily relate to the activities aligned with the chosen pedagogical model, e.g. PBL. There seems to a missing link that takes into consideration the particularities of the educational models in the prospect of critical thinking.

Based on these considerations we ask the following research question:

> *What characterizes and enhances critical thinking for engineering students in a PBL environment?*

In order to address this question, this paper begins by presenting a literature review regarding critical thinking as a means of synthesizing and capturing a "down to earth" understanding of the concept. Following this, the principles of PBL are presented and related to critical thinking by drawing on an empirical study conducted at the Faculty of Engineering and Science, Aalborg University (Denmark).

2. Critical thinking and PBL—a literature review

The following literature review will address the concepts of critical thinking and problem based learning (PBL) respectively and in combination.

2.1 Critical thinking as a concept

The importance of critical thinking in engineering education has been widely agreed and the need to educate engineers to become critical and reflective practitioners has been emphasized, i.e. by stressing that professionals should be capable of reflecting on their own practice [13, 17].

Based on [6, 13–14, 17–21] critical thinking can be defined as cognitive or intellectual acts, of questioning, examining, revising and/or judging something or someone. Critical thinking also relies on a set of criteria in order to revise and judge, carried by arguments, reasons and evidence based on knowledge, experiences and inquiry processes [6, 14, 19–20]. For Schön [17] critical thinking can be defined as a continuous process of reviewing models, theories and ideas applied to a context at different levels (e.g. individual, community and/or social levels). Furthermore, this continuous process requires different levels of abstraction where more factors and systems can be included to increase the complexity of reasoning. Several authors have simplified this complexity of reasoning by defining critical thinking through perspectives or developmental models [21–23].

Mogensen [22], for example, defines four perspectives of critical thinking: epistemological, dialectical, holistic and transformative. These perspectives highlight the multiplicity and increasing complexity of critical thinking by pointing to the different levels and structures questioned. These perspectives move from cognitive acts carried out individually (epistemological), to a more social perspective where knowledge is socially constructed and derives from different people with more or less different views (dialectical). The holistic perspective views critical thinking as not only related to cognition and intellect, but as integrating cognitive, emotional and social dimensions. This is also aligned with Illeris' [24] concept of learning which involves cognitive, social and emotional dimensions. Last, but not least, the transformative perspective takes in other levels of abstraction; it moves from individual to other wider structures (e.g. political, environmental, economic, cultural, etc.) on which society is built. By criticizing these structures and their interconnections, students' worldviews and values may also change. This supports the promise of the intellectual empowerment of students to obtain a wider perspective rather than just reflecting on past actions and resuming future ones. This is also aligned with a transformative perspective of learning [25] which leads students to transform their worldview, values and current practices. Mogensen [22] refers to critical thinking as an important skill to assist students to deal with society's increasing complexity and urgency by strengthening their "*reflective and critical approach to the structural levels of society as well as the scientific and the personal levels, and the connection between them*" [22, p. 429]. The interconnection between the different structural levels aligns with Schön's [17] view of increasing complexity and abstraction, emphasizing a more holistic and system approach to critical thinking.

Another way to conceptualize critical thinking is presented by Barnett [21] who proposes three levels of critical thinking: critical thinking, critical thought, and critique. Critical thinking concerns cognitive tasks carried out by the individual, and this is very much aligned with the epistemological perspective described by Mogensen [22]. On the other hand, critical thought is collaborative and involves taking into consideration the perspectives and points of view of others. At this level students navigate within the discipline of study. The critique level refers to criticism towards the discipline, its social value and construction. At this level several perspectives are accepted and may lead to cognitive and personal transformation. This means that students' worldview, values and/or epistemological assumptions may change in light of new evidence or arguments.

A third example of a conceptual model for critical thinking is the reflective judgment model proposed by King and Kitchener [23]. The reflective judgment model includes two dimensions. The first dimension regards people's different assumptions and views on knowledge, whereas the second concerns how people mobilize and use knowledge to justify their own judgments. The reflective judgment model is also a developmental model where the two dimensions (view of knowledge and concept of justification) evolve along three and seven stages of development: pre-reflective thinking (includes three stages), quasi-reflective judgment (includes two stages) and reflective thinking (includes two stages). At the pre-reflective thinking level, students assume knowledge as certain and unquestionable, all problems are well structured and all questions are answered by one single answer. At this level, students do not use evidence to reason or support conclusions. At the quasi-reflective level, students develop an awareness that knowledge is uncertain, constructed and relies on evidence. Also, students may assume that different perspectives and assumptions rely on different types of evidence. In contrast, the reflective thinkers regard knowledge as contextual and perceive knowledge as constructed and reconstructed in the light of new evidence. According to this model, students move from a stage of ignorant certainty towards an intelligent confusion where they recognize that knowledge is contextual and they become sophisticated in their use of evidence to make judgements. '*Students start to behave as expert engineers*' [23, p. 269]. In the stage of ignorant certainty, students see knowledge as certain and unquestionable where figures of authority hold all the answers [5].

In sum, critical thinking is defined as cognitive acts, carried out individuals and collectively, with the aim of examining, revising, assessing and/or judging social constructs as theories, models and/or ideas based on arguments, reasons and/or evidence. Critical thinking also includes several levels of abstraction and complexity which are conceptualized through perspectives and developmental models.

2.2 Problem based learning: core principles

Problem Based Learning (PBL) as learning pedagogy poses the possibility of enhancing the development of critical and, thereby, reflective thinking as it is grounded in constructivist theories of learning. Constructivist learning approaches advocate that students construct their development based on relevant learning experiences. These constructions and developments are thought to happen when students are active in their learning process, reflect on their learning experiences (individual or collective), and try to generalize from them [13]. Nowadays, more and more higher education institutions are implementing PBL in their teaching and learning approaches. The implementation occurs at different levels in part or in the entire curriculum [26–27].

The PBL process is driven by a problem. A team of students set out to question and analyze real life situations, contexts or cases, in order to formulate a narrower problem to be solved with contributions from their specific field. In this process, students mobilize prior knowledge, assess the knowledge needed and, furthermore, monitor and construct (individually and collaboratively) new knowledge [15, 28–29]. As the PBL process takes its point of departure from real life problems, learning happen in relation to a specific context. By solving the problem students also develop a deeper and strategic approach to learning which is characterized, for example, by understanding the relationship between new ideas and prior knowledge, the ability to manage resources in the problem solving process, and also by the interaction between theory and practice [15, 30]. One of the drivers for PBL practice in the 1970s was to equip students with "ready to use" professional skills along with disciplinary knowledge. PBL emphasizes the relationship between theory and practice by bringing real problems into educational contexts that students solve by use of appropriate theoretical frameworks and methodologies [31–32].

PBL is participant-directed, meaning that, based on a diagnosis of learning needs, students formulate learning goals and identify learning resources, create strategies to learn new knowledge, develop knowledge about their own learning preferences and styles, and reflect on, and evaluate the appropriateness of new knowledge [31]. A PBL environment allows students to become independent learners, which is the basis for lifelong learning. Students acknowledge their own learning preferences and styles and they learn "how to learn" [30, 33].

PBL is also team-based and thereby promotes collaborative learning. Collaborative learning is more than just working together to achieve established goals, it is also a matter of structuring interdependence among team members, their roles and functions [34]. In PBL, learning occurs between peers and through collaboration. Students are to engage in activities that support the learning process of others and promote reflection and self-assessment of their own knowledge [34–35]. For example, by supporting each other's learning in the team, students come to reflect on existing knowledge and knowledge gaps, learning styles, and communication skills by continuously testing concepts, principles and theories with peers.

2.3 Relating problem based learning and critical thinking

Without specific reference to PBL, critical thinking theorists have emphasized that real life problems can trigger critical thinking. Mogensen [22] sees critical thinking as a competence to act through involvement in real problematic situations. In this context critical thinking enables students to question, judge and make choices among the existing possibilities. For the author, critical thinking establishes an important link between the language of critique (e.g. one takes responsibility and is motivated to be involved in a problematic situation) and the language of possibility (e.g. one finds the solution, or solutions, or makes a solution possible). The language of critique and the language of possibility (by solving complex social problems) aligns with the view of critical thinking as a promise of intellectual empowerment, creativity and innovation [20].

King and Kitchener [23] also relate to the process of solving badly structured problems with reflective thinking. For example, the view of knowledge and the concept of justification relates to how they mobilize and use knowledge to justify their own judgments about problems. To deal with problematic situations, students need knowledge and a set of criteria for making judgments and evaluations as well as for developing arguments to support their decisions. Furthermore, students may have to realize that different people have different assumptions about knowledge and its use for judgment, argumentation and justification purposes [22–23].

With specific reference to PBL, the development of process competencies and critical thinking has also been related to learning principles and activities/tasks that students carry out in a PBL environment [15]. Critical thinking is considered to be one of the process competencies developed by students in a PBL environment and throughout the entire problem-solving process where students have to make decisions and justify them as well as manage the project (i.e. management of people, time, resources) [36–37]. This is supported by Pan & Allison [16] who concluded that the link between critical thinking, PBL and Environmental Building education can be created by fostering critical thinking in the creation, development, justification, implementation and evaluation of design solutions for a project. Therefore, critical thinking is not one step in the PBL process—it is an on-going process that takes place alongside the PBL process.

At a conceptual level, Savin-Baden [38] has presented a constellation of PBL for critical understanding. Here, "*PBL is a vehicle to bridge the gap between models of thinking and actions*" and provide students with skills to "*see the relationship between their personal stance and the propositional knowledge of the discipline*" [38, p. 207]. This work points to PBL constellations that enhance students' critical thinking skills—without specifying the implied cognitive or collaborative acts of students.

In the following we, therefore, turn to an empirical study of student and staff perceptions of critical thinking in a PBL learning environment.

3. Capturing student and staff perspectives on critical thinking

This empirical part of the study, which was conducted at the Faculty of Engineering and Science, Aalborg University (Denmark), aims to investigate the ways in which PBL enhances students' critical thinking. Aalborg University has been problem-based and project organized since its foundation in 1974. In all bachelor and master's programs, from the moment they enrol students learn by identifying, analyzing and solving real problems. Since 2010, the curriculum has been organized in a project module of 15 ECTS and three courses of 5 ECTS each. The Aalborg PBL model is defined as problem oriented, project organized, participant directed, team-based and relates theory with practice [39]. For this reason Aalborg University constitutes a suitable place to conduct the study.

The next section presents the methodology used in the study and this is followed by a discussion of the results of the study.

3.1 Research methods

Figure 1 illustrates the research methodology by presenting the data collection and analysis process. The data were collected through semi-structured interviews aimed at two types of responses: (1) answer open questions and (2) filling out a checklist and thinking out loud whilst doing so. The purpose of the interview design is to triangulate the data gathered from the open-ended questions on interviewees' perspectives on critical thinking, and on their completion comments on the checklist.

The interview process was designed to begin with the open questions (i.e. the first part of the interview script), after which the checklist was presented for the interviewees to fill out (i.e. the second part of interview script). According to Cohen et al [40] such combined scripts enable the researchers to attain two types of responses: unstructured responses and structured responses.

All the interviewees were from the 2nd semester of the M.Sc. Urban Planning and Management (UPM) program from the Faculty of Engineering and Science. The interviews took place in the Spring of 2012. The researchers aimed to interview all the students and facilitators from the entire second semester of the master's program. Therefore the numbered of interviewees was to be 22 (4 facilitators and 18 students). All the interviewees were contacted by e-mail and only a total of 9 were available to participate in the study. Table 1 summarizes the number of interviewees intended and the numbered of interviews achieved, i.e. conducted. Two of the facilitators interviewed were also lecturers on the courses in the same semester.

The interviews were conducted face-to-face and lasted approximately one and a half hours. Permission was asked to record the interview and researchers also guaranteed the anonymity of interviewees when presenting and reporting the study's results.

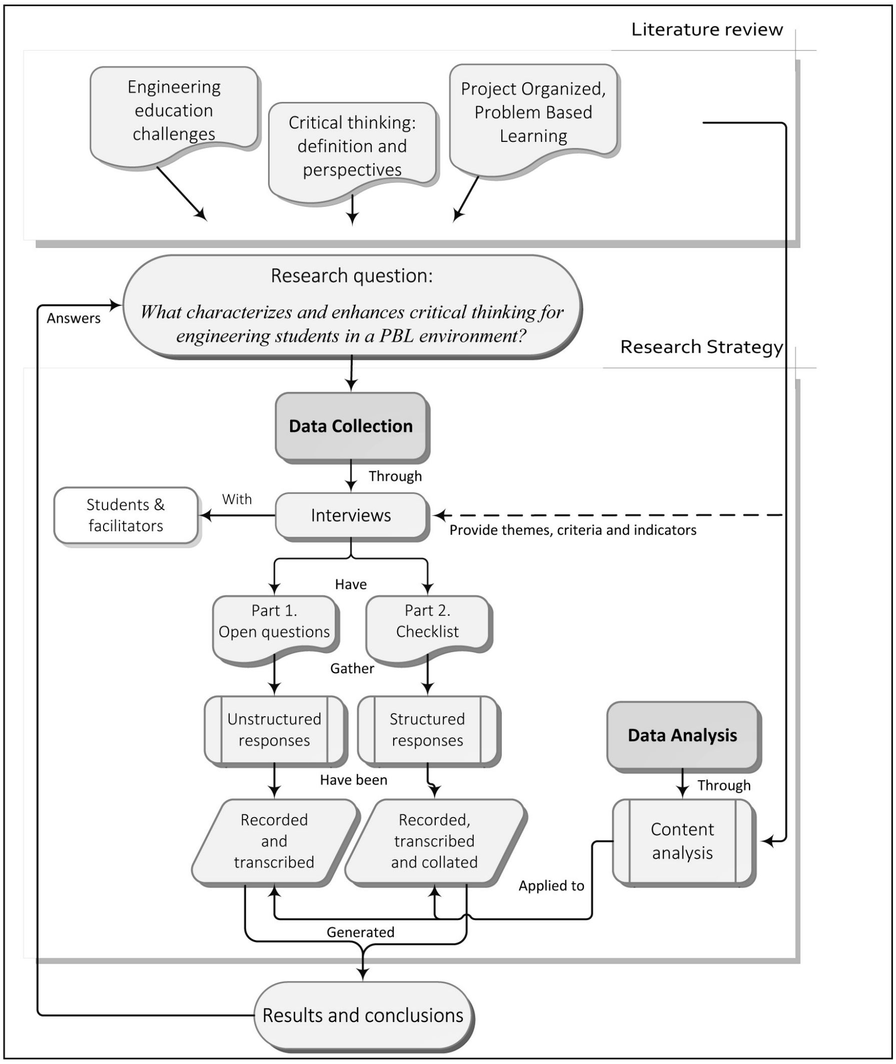

Fig. 1. Research methodology chart.

Table 1. Interviewees and total number of interviews conducted

Interviewees	Intended	Achieved
Facilitators	4	4
Students	18 students (from 5 groups)	5 students (from 4 groups)
Total interviews	22	9

The open-ended questions and un-structured responses

The open ended questions were divided into three themes in order to try to unfold how the students and staff picture the PBL process in general, the organization of the curriculum around problems, and the problem-solving approach more specifically. Table 2 summarizes the interview design, types of responses, and examples of initial questions for the interview script.

The interviews were transcribed and content analyzed. The overall coding process was carried out by reading through the transcripts and coding segments that related to critical thinking by using the themes, criteria and indicators generated from the literature review.

Table 3 presents an example of the themes, which clustered the criteria and indicators for the content analysis. The two themes are: definition of critical thinking and context of critical thinking. The theme "definition of critical thinking" (1), for example, includes criteria such as cognitive acts (1.1) and, in relation to this criteria, indicators are listed for these cognitive acts (1.1.1–1.1.3). Some indicators were generated on the basis of the literature review, whilst others were added during the coding and related to specific criteria.

The checklist

The responses gathered through the checklist show the kind of activities/tasks that are carried out through the learning process and that may enhance

Table 2. Strategy for data collection using open-ended questions

Strategy for data collection	Response type	Interview themes	Example of question(s)
Semi-structured Interview	Unstructured through open questions	PBL process	What is the potential of the PBL approach? What are the challenges of the PBL approach?
		Curriculum organized around problems	What is the relationship between courses and project work?
		Problem solving approach	How, and by whom, are problems chosen/ formulated? How is the problem solving process carried out?

Table 3. Examples of themes, criteria and indicators for content analysis of interview's unstructured responses

Themes	Example of criteria	Example of indicators
1. Definitions of critical thinking	1.1. Cognitive acts [20,23,41] 1.2. Informed/ reflective judgment [14,20] 1.3 View of knowledge & use for justification [23].	1.1.1. Question, assess, evaluate, judge, revise, etc. 1.1.2. Based on criteria, reasons, evidence and arguments 1.1.3. Knowledge as certain, contextual, limited, etc.
2. Context of critical thinking	2.1. Problem area/ scenario [23,41] 2.2. Problem solving process [20] 2.3. Process of inquiry 2.4. Collaborative [42] 2.5. Decision making and participatory	2.1.1. Real and ill structured cases, type of problems, problem formulation, etc. 2.2.1. Set goals, strategies, goals, provide solutions, etc. 2.3.1 Research methodologies, data collection, data analysis, etc. 2.4.1 Team, group work, includes other perspectives, etc.

students' critical thinking. The checklist includes sentences that describe examples of activities/tasks that students may be involved in during the problem solving/project work processes.

The checklist was constructed based on the four perspectives of critical thinking provided by Mogensen [22] and combined with activities/tasks derived from the literature review. Table 4 presents descriptions of activities/tasks that characterize each perspective, and their respective codes. The activities and tasks mentioned in the second column of Table 4 are the same as those that composed the checklists presented to interviewees.

To fill out the checklist, the interviewees were asked to pinpoint up to five of the most important tasks carried out during project work, and to comment out loud whilst filling in the checklists. The completion of the checklist was recorded in case the interviewee made relevant comments or add-ons. The comments were divided into groups: general comments and specific comments. The general comments are related to the overall checklist whereas specific comments are related to specific activities listed. Only the most important comments were transcribed and coded.

3.2 Results

The study of student and staff perspectives on critical thinking in the context of the PBL environment conducted in the Faculty of Engineering and

Table 4. Perspectives of critical thinking, activities/tasks and codes for the checklist

Perspective of critical thinking	Activities/tasks	Codes
A. Epistemological	Identify factual and normative aspects of the problem	A.1
	Explain, understand and questioning the factual and normative aspects of the problem	A.2
	Analyzing and assessing the factual and normative aspects of the problem in order to outline strategies	A.3
	Individual questioning and examining of the settings around the problem	A.4
B. Dialectical	Different points of views on each case	B.1
	Recognition that knowledge is dependent on latent interests and values	B.2
	Recognition that progress and development take place by challenging, querying, criticizing and breaking down parts of existing parts to reconstruct a new and alternative one.	B.3
	Rebuilt new practices without the deficiencies and errors of previous one.	B.4
	Consistent criteria of assessment for oneself and others (e.g. group acknowledges each member's potential, skills, knowledge and opinions)	B.5
C. Holistic	Thinking involves emotions, feelings, intuition, and reason	C.1
	Urge to transform an intention to act into a real action to promote change	C.2
D. Transformative	Transformation of values and beliefs	D.1
	Change own point of view of existing economic, political, scientific and environmental structures and mechanisms	D.2
	Community (group) analysis as well as assess alternative possibilities and strategies	D.3

Science, shows that students and staff see critical thinking as linked to a contextual view of knowledge driven by multi-perspectives and diversity as well as values and beliefs. Furthermore, critical thinking activities were linked to different stages of the PBL process, primarily to problem identification, analysis and formulation. In the following we elaborate on the results of the study, which is put into perspective in the subsequent discussion.

Critical thinking is linked to a contextual view of knowledge

Interviewees highlighted the contextual view of knowledge. As the following example shows, facilitator F1 argues that students do not just learn about theories; they also have to be able to choose among different theories and apply them to the context.

> *Instead of just learning a theory and what it is about, it is more about enabling them to choose between different theories, which one is more appropriate to this setting, or situation. And then, also to be able to go beyond the theories, and be able to think critically about "oh right, this is just a theory and in practice we may have to do different things or combine different theories in new ways".* (Facilitator F1)

The above emphasizes the mobilization and use of theories in a real context—it is not just any theory but an appropriate theory considering the specific context. Furthermore, the interviewee also underlines the need for the "reconstruction" of theories in terms of their application and limitations for practice. Students also share this view of knowledge. For example, student S1 supports the view of facilitator F1 by pointing out that theories are never 100 percent true and when used in an inquiry process their limitations emerge.

> *[. . .] Theories are never 100 percent and you find out, when you do empirical work, that you miss something, which lacks or limits one's knowledge. But suddenly it pops up and say I was not aware of that, or theories haven't been aware of that. It is actually an interesting area.* (Student S1)

According to facilitator F1 and student S1, the learning process is thus not limited to the application and understanding of a theory in context as it also includes awareness of theoretical limitations and understanding that the choice and application of theory is context dependent. The context referred to is the real life context in which the problems have evolved and are identified and, therefore, it relates to the PBL principle of having a strong relationship between theory and practice.

Student S1 also highlighted that students develop a kind of strategic knowledge where they learn to structure the problem-solving process. Furthermore, it is recognised that this process is not linear but, rather, iterative.

> *Strategic knowledge, you know, somehow structures the process. You know when you should do what but at the same time you never know. [. . .] You always jump back and forward all the time. And of course, it is also about knowing when to apply the knowledge that you get from theory.* (Student S1)

Student S5 shares the view of student S1 and adds that being able to apply the acquired knowledge to a specific context allows for a better understanding of theories and their limitations:

> *But if you every day only see chalk on the blackboard and equations and they are not connected with pictures, with stories, then it is difficult to understand. In this master's I was given the opportunity to connect, especially in a course where an example was always given; he would always end by [. . .] this is how you can use, here is a case where it has been used, and we have to present ourselves and reflect about a certain problem, or areas or whatever.* (Student S5)

Even though the above interviewees' quotes stress a contextual view of knowledge, which characterizes the reflective thinking at the 3rd level of the reflective judgment model [23], they are recognizing that it complicates the learning. Facilitator F4 points out that some students struggle to select proper theories and make use of them in their project work.

> *Students become a little overwhelmed in actually bringing forward some of the theories, carrying them forward into the project and being able to make use of them. (Facilitator F4)*

Whereas all students interviewed in this study had been educated in a PBL environment since undertaking their bachelor program which gave them three years of "practice" the same cannot be said of all students enrolled in the master's program. The master's program is an international program and enrolls students from different countries and educational backgrounds. For King and Kitchener [23] students' reflective thinking develops from a level of pre-reflective (e.g. knowledge is viewed as certain and unquestionable) towards the levels of quasi-reflective thinking (e.g. recognition that uncertainty is part of the knowing process) and reflective thinking (e.g. use of evidence and reason to support judgments and understanding of the relationship between knowledge and context). It is likely that for students entering the master's program with no prior PBL experience, the challenges of relating theory with practise is even harder to overcome.

Critical thinking involves different perspectives and views

A further outcome of this study relates to the different perspectives on critical thinking based on the checklist. The outcome mostly relates to a dialectical perspective on critical thinking in two ways. First, and in relation to contextualisation, emphasis is placed on students bringing several points of views/perspectives to the same case. The dialectical perspective thereby refers to the development and progress as it assumes a self-correctness by challenging and querying current practices and constructs. Second, the dialectical perspective emphasises that critical thinking not only involves an individual standpoint, but also collective and participatory actions. It implies that each individual appreciates other people's ways of thinking, is aware of the limits of their own knowledge, and believe that arguing for a case can bring new learning [22].

At Aalborg University (AAU), PBL is fostered in a team-based and project organized environment where students solve problems collaboratively. Several master's programs are international, which means mixing students familiar with PBL with students who have no prior acquaintance with the AAU PBL model. Students external to AAU and Denmark can enroll on these programs, which mean that some of the groups may have a high degree of cultural diversity. When questioned about the challenges of being educated in a PBL environment, students pointed to the cultural and educational diversity of the student body:

> *In the master's programs you have cultural differences, it is just the language barriers sometimes, and expectations and cultures of how you work and how you think. It is definitely a challenge but you also learn something, but that's hard.* (Student S1)

As can be seen from the quote, cultural diversity is also viewed as a challenge in a positive sense—as an opportunity for learning. The challenge is to allocate time getting to know the different cultures and, at the same time, handling personal differences in working styles, take on new team roles and properly solving the problem at hand. When addressing the challenges of PBL, collaborating in a PBL environment comes up as a key response:

> *In some ways it is to cooperate I would say. Find this balance between who is the leader, do we have a leader? How do we cooperate, how can we divide work equally, is it even possible? And that people are engaged to the same extent in the project. I think these are some of the main challenges, to creating really good fellows in a group; what is really needed when you do this PBL because it's fundamental for creating good projects.* (Student S1)

Facilitators corroborate students' concerns about group collaboration and point to the learning potential in diverse groups but, furthermore, facilitator F4 stresses that the communication aspects of PBL also influences the decision making process in the groups.

> *Different planning traditions merge to work on a specific problem [. . .] and the challenge was that people have different ideas, they come up with different perspectives and the one that has the strongest personality, and probably more leadership skills, takes over the others. The others find it quite difficult to develop arguments to create a space within the group and to put forward their ideas.* (Facilitator F4)

Facilitator F4 here points out that personality, like natural leadership, might hinder the possibility of developing the proper arguments to put forward ideas. Nevertheless, facilitator F4 acknowledges that if a group is able to create a good dynamic and overcome the challenges posed, it can have enriching ideas and discussions.

> *So if there is appropriate group dynamics, and by appropriate I say a lot of really enriching discussions when they really get engaged in discussion and open up ideas without ... I mean leaving behind their stubbornness or their personal issues. I think they end up learning far more than in the typical traditional way of lecturing just because of the fact that they exercise it.* (Facilitator F4)

In international group-work this brings new opportunities for students to reflect beyond their knowledge, values and ways of working. The matter of contrasting perspectives also enables students to develop awareness of the fact that different people might give different meanings to the same object, situation or theory depending on their values, prior experiences, interpretations and motivations. Student S1 explains this in the following way:

> *You have different points of view in a case. You might think that a justification is an interesting subject, and two of you in the group think it is interesting. So you think you two think the same, but in end you may have two different interpretations of what is justification in the specific case.* (Student S1)

Student S3 shares the view of student S1 and adds to the picture that collaborative learning shapes the way students construct their knowledge.

> *When we started we all had the same level of knowledge of group-work, project work. You develop your knowledge of that together, but now people come from outside, and have never tried before so it had to adjust to that. Give some of your knowledge but also gain some.* (Student S3)

With the increased mobility of students and globalization of the engineering profession, the dialectical perspective of critical thinking presents itself as a relevant and promising platform for developing critical thinking skills. For example, students have the opportunity to broaden their understanding and comprehension of different cultures of work, educational backgrounds and systems, all of which can provide new dimensions/perspectives to critical thinking. Yet to achieve the synergies of diversity, student S4 points out that it is important to know the reasons behind one's behavior and to understand the context in which one's fellow student has grown and was educated:

> *Find why this person's logic and way of rationalizing things and connecting with other things such as culture, religion, and so on, what is affecting this person's values.* (Student S4)

To summarize, it can be argued that collaborative learning in a PBL environment draws attention to the dialectical perspective on critical thinking. In fact, this is supported by the checklist, as the dialectical perspective was the one chosen by most. All interviewees, with the exception of student S4, considered that knowledge is dependent on latent interest and values, and that progress and development take place by challenging and breaking down current practices to reconstruct new ones.

Critical thinking also includes beliefs and a promise for transformative learning

Critical thinking is also understood as more than cognitive and intellectual tasks; it has a moral and motivational orientation. Students are motivated to be involved and make decisions about what is to be considered as right or wrong [20]. The holistic perspective of critical thinking argues that critical thinking involves both feelings and reason [22]. Some of the interviewees, namely student S1 and student S2, pointed out that many of the situations they find themselves engaged in involve feelings:

> *I think in many situations there is a feeling behind it. In my case it's a mixture of rational thinking saying how it should be because it's best for everyone and, of course, it depends on the case. There are also feelings involved.* (Student S1)

Student S1 emphasizes a mix between reason and emotion, which drives a way of doing things for everyone involved. In this program, students have the opportunity to choose the problem and situation they want to work with; they independently formulate problems and select methods to solve them. Student 2 stresses that feelings and emotions are also a source of reasoning when students make these decisions:

> *Thinking involves emotions, feelings, intuition and reasoning. I am very emotionally driven, I feel like more in my stomach now than in the books or in my head. Probably because it is very rooted in the personal values we talked about as well. It is very internal somehow.* (Student S2)

The above quotes, especially the one from student 1, relate to a holistic perspective on critical thinking as it is recognized that sometimes students' decisions are driven by feelings and intuition, and this implies a will to make things better, to make changes.

Moving to the next perspective on critical thinking, the transformative perspective regards transformation of values and worldviews as taking place during the learning process. These transformations include different levels of abstraction at the individual level (e.g. attitudes, worldviews and values) and at the structural level (e.g. political, economic, or social). Even though student S4 is not sure that his values and beliefs have changed during education in a PBL environment, he is sure that more aspects are taken into consideration about the way the world is seen:

> *I am not really sure whether my values and beliefs change during a project. I may vary the ways I look into a specific thing but I still belief in one way to do things. And I don't recall . . . Of course it has changed during my education here. We have been taught a lot of things that may differ from how the world sees things, but it is not something I really focus on, it just happens.* (Student S4)

The above quote exemplifies the uncertainty or the lack of awareness of inner transformation of personal values and beliefs, whereas this student is very aware that he has expanded the frame of reference for reflecting on his own values and beliefs. Some authors regard critical thinking as a promise of the empowerment of students to change and transform. This perspective assumes a relevant role in contemporary engineering education as engineers are called upon to take a stand, for example, regarding the sustainability crisis. Due to the flexibility and adaptability students have to undertake when working in a PBL environment, it can be argued that a PBL environment strengthens the students abilities to address social challenges such as sustainability [18, 25].

Critical thinking to problematize or too problematic?

Based on the literature review it was stated that critical thinking is not one step in the PBL process—it is an on-going process alongside the PBL process. PBL can in itself be considered as a critical and reflective process where students experience and actively construct their development by engaging in different tasks/activities. Examples of such are problematizing (i.e. problem identification, analysis and formulation), problem solving (i.e. inquiry process) or arguing for best solution(s) (i.e. based on contextual criteria and evidence). Problematizing is a core element which defines PBL practiced, and it is recognized by interviewees as a key to enhance critical thinking.

Facilitator F2 relates critical thinking to the formulation of a problem as students' work is based on explorative investigations that generate hypotheses and assumptions to be tested and proven through an inquiry process:

> *I think it is linked with this problem formulation. They start by exploring something and then we see "ok this*

kind of problem" and move to hypothesis . . . there is some criticism . . . (Facilitator F2)

This process of exploring a problem, or analyzing a problem can be contained in a critical stance towards "what is", "why this is" and "what could be different"—and at that stage the students might not have considered theories, methods or even possible answers. As student 2 explains:

> *I have been part of IDA* [ref. to engineering association] *and the planning part of that invited some people that have been working with public participation, and in a quite extreme way. They described their model and then I was just wondering whether that was actually a good idea because it seems that the planners didn't have any control or responsibility. I think I just want to dig into the problem area* [ref. to semester theme—power] *and see if it could be a good idea, or not and in which cases. I didn't have any answers in my head, I was just curious.* (Student S2)

So, even though problematizing is important for enhancing critical thinking skills, it is also a challenge for students who may struggle with the formulations, with establishing a methodological approach, and with applying the proper theories. As facilitator F4 explains:

> *The analysis sometimes is extremely soft, too narrow, too fluffy because they didn't problematize well and because they didn't follow a methodological approach that really sounds right to be able to analyze it better. And then they don't know how to integrate the theory and probably they chose the wrong theories because they never knew what the problem was all about.* (Facilitator F4)

According to facilitator F4, students also need to develop a methodological approach to analysis as well as to the choice of theory they choose to use and apply. Thereby, problematizing requires critical thinking.

The diversity of problems and the way problems are presented to students also present possibilities for enhancing critical thinking. According to Jonassen [29] problematic situations can be more or less structured, more or less contextual, more or less complex, which leads to different problems and, consequently, the development of different skills and competencies. Interviewee F3 points out that different problems are brought into education for different purposes. Some are very open questions with the aim of stimulating students' thinking, whilst others have more narrow approaches with the aim of understanding the reasons behind current behaviors and practices.

> *Some people like to create very open, broad questions that are not necessarily designed for answers but they are designed to stimulate students to think. Other people have more focused approaches where they take a particular case and they say "we will desiccate this case. Here's a case of planning intervention, it either works or not, and we are going to look at why".* (Facilitator F3)

So even though it may limit the possibility for self-directed learning in the first phase of the project, facilitators can also choose to limit the degree of freedom (i.e. by presenting a more narrow problem field) or focus specifically on one part of the PBL process. Undoubtedly, problem analysis and formulation enhance students' critical and reflective thinking but students might need to address these challenges step-by-step with clear learning objectives—and then develop their PBL skills to manage a comprehensive PBL process.

However, there is also the risk that the PBL process in itself is not questioned. In the interviews, students recognized that during their three years of study in this particular PBL environment, they had developed a kind of mechanical way of formulating and solving problems. Student 1 explains:

> *Like everything, it becomes mechanic. You just do it without really thinking why you do it, but it is how it's done.* (Student S1)

Student S2 shares the above point of view in the following quote, referring to characteristics of the problem solving approach:

> *Tacit knowledge—that we become experts in doing it. Maybe when we meet in this international environment I think it is pretty healthy for us because then we see it. I actually realize how brainwashed I've been. It is not that I don't like it or anything, it is other ways of looking into it.* (Student S2)

This quote underlines the point that even though PBL offers students a self-directed learning environment, PBL is an institution in itself, which staff and students tend to internalize and take for granted. For students to face this challenge and benefit from the embedded learning potential, group constellations with diverse cultural, as well as educational, background offer opportunities.

4. Discussion

In the above section we have addressed the rather complex concept of critical thinking and pointed to opportunities and challenges in using PBL to enhance competence. A reflection on the use of a checklist confronting students and facilitators with critical thinking perspectives, however, has resulted in the suggestion of a need to translate critical thinking into something more tangible in an engineering education context. In order to do so, we propose to make the conceptual framework visual and to present it in a more simple way.

Inspired by Laswell [42] and his very simple way of modelling the complex nature of communication by asking "who says what to whom in what channel with what effect", in terms of critical thinking we can ask: "Who is thinking critically about what with

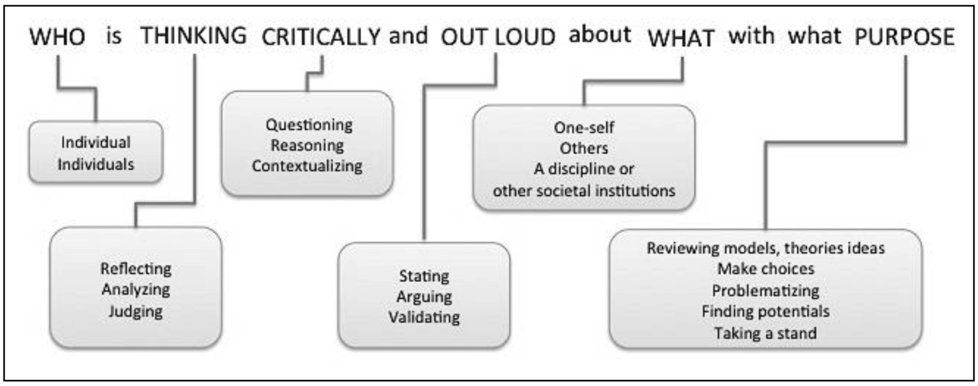

Fig. 2. One way to understanding critical thinking.

what purpose"? However, because "who" can be both one individual and a number of individuals we have to add a social dimension to the picture which implies that the "thinking" has been communicated—as in a usability test the thinkers have to "think out loud" to move the concept onto the dialectical stage. Fig. 2 visualizes this model related to the key-concepts presented in the literature review.

At the next level, we have investigated critical thinking specifically in relation to PBL. Fig. 3 visualizes the critical thinking model (Fig. 2) in this context. The figure illustrates the strong relationship between critical thinking and problem identification, analysis and formulation, but is also stresses that PBL processes combine thinking with acting (problem solving).

It should also be noted that "who" not only includes students (as one could be tempted to think in a self-directed learning environment) but also facilitators (especially when confronted with ignorant certainty) have a role to participate actively in the dialectic process taking place in the groups and, importantly, to introduce the questions to foster discussions that involve scientific, contextual, as well as motivational arguments. Furthermore, stakeholders, who have a stake in the real life problem addressed, might also have a say, as many PBL projects are carried out with stakeholder interaction. Furthermore, due to the collaborative environment, critical thinking has to be based on shared values and interests (or at least acceptance of group values and some interests), group negotiations and agreements, activities that will probably require some scaffolding.

5. Conclusion

Critical and reflective thinking has particular significance for contemporary higher education and for the specific case of engineering education where the need to develop critical thinking is emphasized by accreditation bodies as well as international and governmental organizations. In this study, we have drawn attention to the need to bridge the gap between rather abstract theoretical frameworks on the one hand, and prescriptive frameworks on the other, and we do so by linking to the pedagogical model at an institutional level. We have accepted the challenge to provide a conceptual model for critical thinking that is concretized in a PBL context, as PBL has been argued to provide a suitable environment for enhancing critical thinking. Through the literature reviews we presented different perspec-

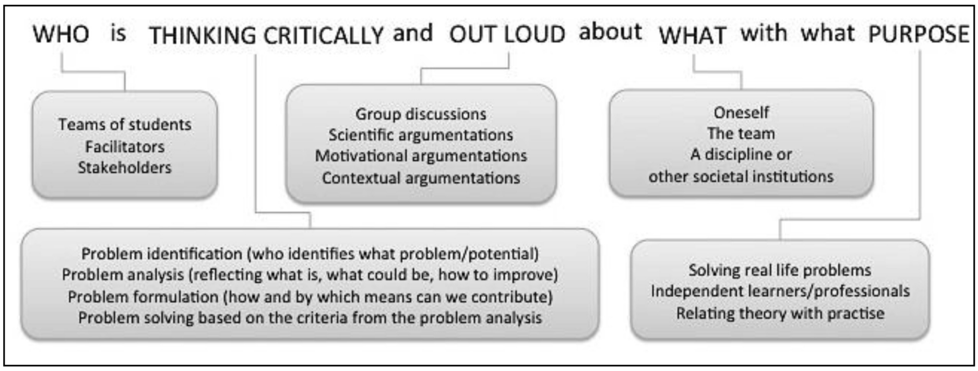

Fig. 3. One way of understanding critical thinking in a PBL context.

tives on critical thinking in itself and also in relation to PBL, and our empirical research has explored how engineering staff and students experience critical thinking in their everyday practice. The empirical study was conducted at the Faculty of Engineering and Science, Aalborg University (Denmark), a faculty with more than 30 years experience of educating engineers in a PBL environment.

The study shows that the PBL principles of theory and practice interaction and their context in real life problems foster a critical stance towards theories and open up reflective thinking. The identification of the problem itself starts with students exploring and questioning different views. As the problem is uniquely tied to a specific context the methods for analyzing and solving the problem are themselves open to question. The collaborative learning environment provides a basis for the dialectical perspectives of critical thinking, both in terms of problem analysis (including the different interests related to the problem), and in the teamwork related to decision-making that is required throughout the project. This has been shown to form a base for idea-generation, critical thinking "out loud", and discussion. Self-directed strategies for problem identification, analysis and solutions, at the same time, foster a critical stance towards the work-plan as it is continuously revised due to the unforeseen nature of real life problems. Furthermore, self-directed learning allows students to include personal values and beliefs, which are also demonstrated in the way in which some students characterize thinking—as a mix between reason and emotion.

However, enhancement of critical thinking in a PBL learning environment also poses considerable challenges to students. First of all, students face the challenge of selecting theories and methodologies that are appropriate for addressing a concrete problem in its context. Second, it appears that some students find it difficult to cope with the diversity in the groups and to manage the decision-making process to make reasonable decisions for the projects—diversity can be due to different cultural backgrounds, different interpretations of what constitutes justification and occasionally different levels of expertise in working in a problem-based learning environment. Third, when talking about self-directed learning one could ask "who is the self", because when working in a group this may effectively mean the one with the strongest personality and probably more leadership skills.

All these challenges are, at the same time, possibilities for learning. Theory/practice relations hold potential for critically assessing what students learn when compared with the needs facing their profession or society at large. One consequence of diversity within groups is that perspectives, and what students from a given culture or with a give educational background have internalized and take for granted, are questioned. Furthermore, group collaboration holds potential for the development of students' communication skills—to collaborate, to negotiate, to make change.

Last, but not least, this paper presents a model for critical thinking in a PBL environment—as a modest attempt to engage engineering educators to ask: "*WHO is THINKING CRITICALLY and OUT LOUD about WHAT and with what PURPOSE*" within their educational context—and to critically think about how PBL could inspire the development of critical thinking skills among their students.

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