International Journal of Engineering Education Vol. 33, No. 3, pp. 1070–1085, 2017
Printed in Great Britain
0949-149X/91 $3.00+0.00

Getting a Hold on the Problem in a Problem-Based Learning Environment*

JETTE EGELUND HOLGAARD, AIDA GUERRA and ANETTE KOLMOS
Aalborg Centre for Problem Based Learning in Engineering Science and Sustainability under the auspices of UNESCO, Aalborg University, Vester Havnepromenade 5,1 DK-9000 Aalborg, Denmark. E-mail: jeh@plan.aau.dk, ag@plan.aau.dk, ak@plan.aau.dk

LONE STUB PETERSEN
Department of Development and Planning, Aalborg University, Denmark, Vester Havnepromenade 5,1 DK-9000 Aalborg, Denmark. E-mail: lonep@plan.aau.dk

When engineering students work in a problem-based learning environment they learn how to act as problem solvers by solving real life problems through the development of technological solutions. Problem solving is at the core of engineering practice and problem-based learning models have therefore been emphasised as powerful for engineering education communities to foster employability. However, the approach to problem-based learning differs considerably between different engineering institutions and one of the variables is the extent to which students develop their ability not only to solve pre-defined problems but also to identify, analyse and formulate problems themselves. This is important if the engineers of tomorrow are to work in a more holistic system perspective, as stressed by accreditation bodies, engineering education researchers as well as engineering academies. This conceptual paper presents a five-step model for students to identify, analyse and formulate a problem to be addressed from an engineering perspective. The model is the result of an iterative process, where theoretical as well as empirical inputs have pointed to creating a conceptual model for problem design for both students and staff, which is simple and concrete in its conceptual framing and walks the students through their first experience as problem designers in a sequential step-wise systemic manner. This model has gradually been appropriated to engineering communities by drawing on experience from students and staff in the problem-based learning environment at Aalborg University. Based on this, a five-step model for project design is presented initiating students to (1) relate to the theme, (2) map the problem field, (3) narrow down the problem, (4) analyse the problem in context and (5) formulate the problem. Experience shows that students can manage this step-wise model, but still there is a need to scaffold students during the process of developing problem design skills.

Keywords: problem-based learning; problem design; problem analysis; contextualisation; problem formulation

1. Introduction

A problem-based learning (PBL) environment requires problems to be solved and, regardless of the size of the problem, history has shown that technologies offer a lot of opportunities to address real life problems. At the same time history also is our witness that technology can cause problems which, although they may inspire new technological developments and achievements, could have been foreseen if engineers had taken a system approach to their design and thereby had addressed the problem in a more comprehensive way.

A comprehensive way of addressing problems implies questions like: Where do the engineering problems come from? Why do some problems draw attention and others not? How can we get close to understanding the mechanisms which at one point create the problem and, in another context, resolve the problem? These questions highlight the process of identifying, analysing and formulating problems—or in other words, problem design.

In this article, we view engineers as important problem designers in order to model real life problems in a way that optimises the solution and its impact on a situation, a sector or society at large. Problem design is seen as the process of identification, analysis and formulation of a problem.

1.1 The need for a student-centred and systematic perspective on project design

Looking at the grand challenges of our time to provide sustainable environments and quality of life for the present as well as future generations, there is no doubt that the engineers of tomorrow will face new, and even more complex, challenges. As eloquently put by the American National Academy of Engineers in their "Visions of Engineering" [1, p. 56]:

> Given the uncertain and changing character of the world in which 2020 engineers will work, engineers will need something that cannot be described in a single word. It involves *dynamism*, *agility*, *resilience* and *flexibility*. Not only will technology change quickly, the social- political-economic world in which engineers work will change continuously. In this context, it will not be this or that particular knowledge that engineers will need but rather the ability to learn new things

* Accepted 4 December 2016.

quickly and the ability to apply knowledge to new problems and new contexts.

As the problems increase in complexity and even urgency, it is also more difficult to define the problems and balance the different variables influencing a problem, and thereby more attention is needed to the problem itself. Engineers can call on and enter into close collaboration with specialists, e.g., in considering the market, the environmental or social impact of the products. However, to integrate these considerations into the design process and target the solution, they need to take a system view of technology and to participate in interdisciplinary scientific communities of practice. Students need to learn to analyse the challenges of problem design, or else they might develop a blind spot. Often complex yet well defined and delimited problems seem to be nicely aligned with pre-defined methods, but in reality, this is seldom the case. It is important that engineering students develop and have the ability to transfer problem solving skills for the sake of employability, but it is just as important that they learn to identify, analyse and formulate problems in order to optimise the solution to the context of use and take into consideration the broader societal impacts of technology.

Problem design is one of the cores of problem- and project-based learning models. Whether the curriculum model is a problem-based model with emphasis on cases or it is more a project-based or project-organised model, with focus on projects, there will be an essential phase in the beginning of the learning process that involves identifying problems [2].

For all PBL curriculum models, the starting point for the learning process can have different scopes—the problems can be narrowly formulated in relation to a specific discipline or they can be broader societal problems that the students will have to identify and narrow down. Students might experience pre-defined problems that are formulated by more experienced practitioners—typically academic staff and industry partners—or they can be asked to identify problems within an open field. In the case-based PBL curriculum, there is a need to identify and formulate problems presented in the case, whereas in the open PBL and project-organised curriculum, the need is also to provide methodologies and tools to the students to analyse problems.

Problem analysis is an overlooked phase in the PBL curriculum—and especially models are needed to guide the students in their learning of the problem identification and problem justification. Therefore, the focus in this paper is what we could call student driven problem design. When, why and for whom given situations become problems, this is not information given in academia nor by professionals. On the contrary, the identification of problems is a very complex process and is highly dependent on the scientific and contextual approach. In engineering practice, experienced engineers have to define problems and to prioritise one problem over others and argue that the proposed solution is the best possible under the given conditions.

1.2 Research question and methodology

In this article, we will propose a systematic way in which engineering students can identify, analyse and formulate problems as a part of a PBL process. We do this by developing a conceptual process model for the identification, analysis and formulation of a problem. The development of the model has happened through an iterative process including insights from:

- A literature review considering the problem design to create the baseline for development of the model.
- Case studies from the PBL environment at Aalborg University considering staff and student approaches to PBL. These case studies include in-depth, face-to-face interviews with students and academic staff from two engineering specialisations. The interviews were carried out between May 2012 and January 2013. The case studies are further elaborated by Guerra [3].
- Examples of student outputs in the first year of their bachelor degree training (handed-in assignments and reports). The outputs follow a process where students have been introduced and are moving through the different steps presented in the conceptual model. These examples are selected among many due to their exemplarity and yet simplicity.

In the following, theoretical perspectives and overall experiences from staff and students regarding problem design are presented as the main two sources of inspiration for the conceptual model.

2. The problem design process—theoretical perspectives

Schmidt and Moust [4] argue that the quality of problems presented to students is at least as important as the presence of a qualified tutor, as problems influence almost all elements of learning in a PBL environment. The first obvious question is then: what characterises a quality problem and how can it be designed?

2.1 Problem definitions and problem dynamics

Drawing on different traditions from different facul-

Table 1. The four shades of a problem (based on [5])

Anomaly	Something which deviates from the rule and the usual, something irregular.
Paradox	Two sets of facts meeting in contrast.
Contrast	A tension between two conditions that is the desired and the actual condition.
Contradiction	A simultaneous statement or relations which mutually exclude each other.

ties, Qvist [5, p. 90] formulated a suggestion for a broad definition of a problem that could embrace the above traditions, as follows: "A problem is something, which is documented or argumented as an anomaly, a paradox, a contrast or a contradiction" (see Table 1). This definition provides two basic criteria for something to be called a problem. First of all, a problem is not said to be a problem before it is documented and argued; and secondly the problem holds, in engineering terms, something that calls for some degree of intervention.

The documentation and argumentation criteria relate to a process moving from the unspecific and soft, e.g., something which you would like to know more about, an uncovered wish or a lack of function, to something that is scientifically documented and argued. The problem, in this sense, is more the result than the point of departure for analysis and this still leaves a very diffuse definition of the starting point for the PBL process. The other criterion, that the problem has to fall into the categories of either an anomaly, a paradox, a contrast or a contradiction, is based on a synthesis of previous definitions of a problem. The four problem types are clearly argued, but it is not as clear how to put this rather abstract problem definition into practice.

Another way of defining a problem is by bringing attention to the causes of the problem. A problem can arise from the fact that a group of people consider a certain situation unsatisfactory, or on the other hand that there is a lack of attention to a yet unexplored potential [6]. Thereby a problem is a result of either an explorative process taking into consideration the different perspectives on *what is*, or a creative process imagining *what could be*. The focus on potentials clearly links to what Qvist [5] signifies as a contrast, whereas the so-called unsatisfactory situation can be related to an anomaly, a paradox or a contradiction—however, in this perspective there is not much focus on making such distinction.

2.2 Problem variables

When problems are explicated or formulated in different stages of the problem design, there are different variables to optimise the problem for learning purposes. As noted by Kolmos and de Graaff [2] there has to be a very close relation between the problem design and the learning objectives.

Jonassen [7] distinguish between five characteristics of problems: structuredness, context, complexity, dynamicity and domain specificity of the problem (see Table 2). Aligned with the view on problem "calibration", these problem characteristics are to be seen as a continuum—from the very structured to the ill structured, from practical problems closely interrelated with real life situations to theoretical problems, from complex to simple problems, from stable to dynamic problems, and from disciplinary to interdisciplinary problems. As noted by Jonassen [7], the characteristics are also interrelated, e.g., if the problem is ill structured it is most likely to be complex.

From a student perspective, Sockalingam and Schmidt [8] have made a characterisation of problems by analysing reflective essays from bio-medical students and they refer to two kinds of student responses: features and functions. Whereas features refer to characteristics that are the design elements of the problem, functions refer to the potential or desired outcomes resulting from working on the problem. For the feature characteristics of the problem, students highlighted problem format, clarity, familiarity, difficulty and relevance. Also, addressing student needs, Duch [9] identifies some characteristics of so-called "good" problems including: engaging students, requiring students to make a decision, be complex enough to foster

Table 2. Landscape of characteristics of problems, [3] based on [7]

Structuredness	Variety between ill-structured and well-structured problems. In ill-structured problems, the problem elements and information are unknown, leading to a multiple-solutions solving path. It also implies multiple criteria for assessing the solutions, and uncertainties about what concepts, principles and knowledge are required for problem solving.
Context	The context of the problem represents the situation in which the problem is embedded. Or, context is the situation which is analysed and from which problems are formulated and defined.
Complexity	Problem complexity is related to the number of issues, functions or variables involved in the problem as well as the interactions and predictability of these.
Dynamicity	The dynamicity is related to the way elements, factors and variables that compose the problem change over time.
Domain specificity	Domain specificity is related to problem solving strategies that become specific to certain domains.

collaboration, connect previous with new knowledge; and furthermore, it is stressed that the first stage of a problem should be open ended.

The above differences in the conceptualisation of the constituting elements stress the need not only to look for what could be called the internal quality of the problem, but also what could be called the external quality, considering how it is perceived by students. In the latter respect, much more emphasis is on the learning objectives, the engagement of students and the communicative value of the problem.

2.3 Problem design models

Although PBL has been institutionalised during the last half century, the level of research on problem design is relatively low compared with, e.g., curriculum change, collaborative learning processes and project management. Nevertheless, a few problem design models have been developed to guide problem designers to design effective PBL problems.

Hung [10] presented the 3C3R model including both the so-called core elements that support content and conceptual learning, and also processing components which concern students' cognitive processing and problem solving skills. This model basically highlights three core elements which in short are: (1) *content* alignment with curriculum, (2) assessing the appropriateness of *context*, and (3) *connection* to the disciplinary field of study. The core elements relate to three processing components: (4) a problem solving *researching* process, (5) a *reasoning* process promoting appropriate application of knowledge, and (6) a *reflecting* process to synthesise and integrate the knowledge learned. The three Cs in "content, context and connection" and the three Rs in "researching, reasoning and reflecting" constitutes the 3C3R model. For each of the constituent elements, Hung [10] presents a list of questions to be considered for the problem designer. For example, with regard to content, the designer should, among other things, consider whether the scope of the problem sufficiently supports curriculum standards.

In a more step-wise manner, Duch presents a five-step model to write PBL problems, which in short are as follows [9]:

Step 1. Choose a central idea, concept or principle and relate it to the learning objectives.
Step 2. Relate the idea, concept or principle to a real world context and develop end-of-chapter problems with a storytelling aspect.
Step 3. Introduce and stage the problem with guiding questions, so students can identify the different stages of learning.
Step 4. Write a teacher guide and suggest a combination of different pedagogical settings, e.g., mini-lectures, whole-class discussions, small-group work, etc.
Step 5. Identify the resources needed by students.

Whereas these two models for problem design place staff at the centre of the design process, other perspectives on PBL have argued for the need for students to act as the designers of problems. Algreen-Ussing and Fruensgaard [11] have defined the overall phases of a project as: problem analysis > project delimitation > problem solving > conclusion > implementation. It is stressed that even though the curriculum sets the goals for the project, it is up to the students to formulate how they will achieve these goals, and how they will plan the work process [11]. The link between the curriculum and the problem analysis is created by a theme, and related to this is a so-called initiating problem that calls for further analysis [12].

Kolmos and de Graaff [2] distinguish between a discipline- and teacher-centred approach to PBL where, among other things, the problems are well defined and lectures determine the project, in contrast to an innovative and learner-centred approach where problems are ill defined and lectures support but do not determine the projects. If the learning objectives are openly defined, the problems can also be more ill defined and vice versa [2]. The use of the concept of ill-defined, and not ill-structured, problems, emphasises that the problem in itself might not be clear—we simply might not understand *what* the problem is; whereas the notion of ill-structured problem puts emphasis on clarity when considering *how* we should solve the problem. A related term is a "wicked" problem, as defined by Rittel and Weber [13], where it is unclear where the problem centre lies, and likewise it is less apparent how to intervene. For problem-based projects focused on ill-defined or wicked problems, we therefore typically do not know whether the problem is ill structured or not before it has been analysed. The formulation and the embedded delimitation of the problem thereby becomes an iterative process.

In this understanding, the problem definition in itself is not as important as the feedback mechanisms that cause the problem formulation to change continuously—like a thermostat regulating the temperature by feedback mechanisms, the problem formulation is continuously changing due to new knowledge gained through the problem identification, the problem analysis and also though the problem solving process.

In theory, the problem is never defined, but it is becoming more and more delimited due to greater insight into the problem and its context and by appropriating the problem formulation to the learning objectives which might call for a specific set of

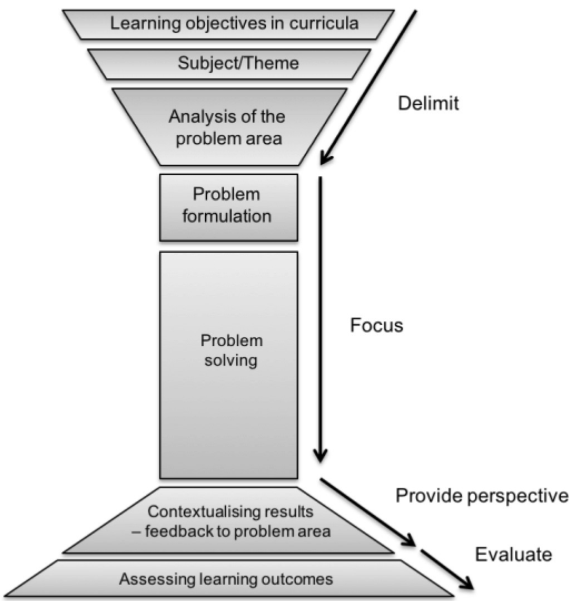

Fig. 1. The problem-based learning project, [15] with inspiration from [14].

disciplinary competencies. Pedersen [14] has illustrated this process of delimitation by a move from a subject/theme to a problem area to a problem formulation. Whereas the subject/theme serves as an area of knowledge, the problem area refers to the theoretical and empirical context that is necessary for defining and explaining the problem clearly and finally this leads to formulating a documented problem [14]. Holgaard, Ryberg, Stegeager, Stentoft and Thomasen [15] have integrated this process into the overall phases of PBL, see Fig. 1.

Regarding the analysis of the problem area, Holgaard, Guerra, Knocke, Kolmos and Andersen [6] have outlined two different approaches—bottom-up and top-down. In a bottom-up approach, students start out by exploring the socio-contextual sites in relation to the subject/theme to elaborate on potential situations which certain groups of people consider unsatisfactory. In the top-down approach students start out with a sense of something that "can be done"—a solution in search of problems, and they then try to appropriate this solution into different socio-contextual settings and in this way, provide the idea with a meaning beyond the scope of the developer.

In a student-centred perspective on problem design, staff design the learning objectives and subject/theme in collaboration with student representatives; whereas the analysis of the problem area and the problem formulation is carried out by the students as a part of the project. In this shift, students are not to solve pre-defined problems—they are to construct their problem by themselves although facilitated by staff. The ownership, and thereby also the responsibility for the quality of the problem, is shifted from staff to students—but in return students learn not only to solve but also to document and formulate a problem in such a way that it can guide the problem solving process.

3. Working with problems and different problem types—a student and staff perspective

In the PBL environment at the Engineering and Science Faculty, Aalborg University, the competence to identify, analyse and formulate problems in contexts is included in every curriculum. As a part of two more comprehensive case studies carried out between May 2012 and January 2013 at Aalborg University, experiences with problem analysis, formulation and solution were gathered to inspire and develop problem design processes. The study included in-depth face-to-face interviews with staff from two engineering specialisations: Urban Planning (7 staff interviewed) and Structural and Civil Engineering (9 staff interviewed), and students from the Urban Planning programme (6 students). This part of the study was explorative in the sense that the revealed attitudes and experiences are merely seen as sources of inspiration for developing the conceptual model.

This study provided the following insights as inspiration for a conceptual model for problem design:

- Problem design is seen as an important yet challenging endeavour for engineering students. Therefore, a model should deconstruct the process to something sequential, concrete and systematic.
- Staff might not be the first in line when students are to point to their preferred problem designers—but they are important facilitators. Therefore, documentation of students' output is important for continual feedback.
- Problem design is provided for what could be called learning restricted innovation. Therefore, as the first step, the model has to clarify the limits of freedom for students to design problems.

The following elaborates on the empirical inspiration and the argumentation behind these three conclusions.

3.1 Problem design as important yet challenging endeavour for engineering students

Being in a PBL environment at Aalborg University, where the problem design is part of every curriculum, places staff in a situation where they not only have to design problems but also are supposed, at least in some stages of the curriculum, to facilitate the design of problems. In the interviews staff underline the importance of that, as follows:

"*I think it's so important for our students to be able to reflect critically about how to define problems*" (Staff 1).

However, staff also recognise that the problem design may be a challenge for students, as can be seen in the following quote from a staff member from Structural and Civil Engineering:

"*I find it for technical engineers, in the field I am working and teaching in, it is . . . we have to put a lot of effort in this problem formulation. And while we are very good in creating the solutions, the problematising s something, I find this . . . sometimes you have really filled them with questions. So this I think is the main obstacle, I can see. Well . . . I think they are very good at the other things.*" (Staff 2)

Engineers are to some degree characterised as people who:

"*want to calculate*" (Staff 3)

and it is somewhat challenging for them to include a broader analytical perspective on the problem. One staff member even states:

"*We are really, really good at ignoring the context*" (Staff 4).

This seems also to be influenced by the fact that some semesters are more designed to socialise students into a discipline and therefore the focus is on rather well defined and structured problems. However, students might not be ready for this kind of shift from the structured to the ill structured, from having experiences bubbled inside the university to the more contextual interaction with the outside world. A staff member expresses it this way:

"*They are in the master[s degree course] now and you think if you are an engineer out in the real world you have to sit down, and you have to find out what is the problem. And when you know what the problem is, what can solve this problem. So we are telling the students: 'You have to recognise the problems and come to us, and say what you need and then we teach', because it is like the real world now. And the students say: 'Oh no! You have to teach us all that you know because we cannot find out what we need.' They are quite afraid of this approach to teaching.*" (Staff 3)

Therefore, even though problem design might be seen as important, it is also seen as a challenging endeavour for engineering students. One of the ways to make it less challenging might be to translate the problem design models to something that is more manageable in an engineering perspective—the following quote expresses this approach in an almost exemplary way:

"*I mean a big part of being engineer, I think, is to take a complex problem and then simplify it down to something you can actually calculate. And understand, break down in pieces, not so that . . . it always has to be done in pieces, you can make complex structures and whatever. But you need to be able to understand it and also you need to be able to develop, you could say, the ability to have an overview of the complex project and understand it.*" (Staff 4).

This inspired the model for project design for engineering students to be simple and concrete in its conceptual framing and to make sure that the process is clearly broken down to be sequential, step-wise and systematic.

3.2 Staff might not be the first in the line of preferred problem designers—but are important facilitators

The study indicates that students are in favour of real life problems with unique solutions, as they have meaning besides "just" learning, as one student expresses it:

"*One of the ways to promote this study is by saying we are working with real problems and that in itself implies you are solving a problem. And not something the teachers just made up. I know a lot of engineering students, specially in the first year, they solve problems that have been already solved but they can't solve it in the most logical, or cheapest way. They have to do it this way, because that is just what they need to learn.*" (Student 1).

In terms of providing real life problems staff can only serve as authentic problem designers when drawing from an academic research context, as is the case in research-based approaches [16], e.g., providing problems derived from ongoing research projects. However, the study also indicates that staff have different preferences (like in research) when it comes to the design of problems:

"*A lot depends on people that are responsible for the course. Some people like to create very open, broad questions, that are not necessarily designed for answers but they are designed to try to stimulate students to think. Other people have a more focused approach, where they take a particular case and they say: 'We will discuss this case. Here's a case of planning intervention, it either works or not, and we are going to look into why.' There are different approaches. There is some stuff that is very theoretical, that is not grounded in practical examples.*" (Staff 5).

No doubt different types of problems will challenge the students more and provide learning, and no doubt sometimes, as for disciplinary projects, the projects might be more structured and even predefined by staff. There are, however, also examples where staff and students co-construct problems, like in the following example of a so-called project café where:

"*We met Monday afternoon, I sort of presented what the semester is about, give a few ideas for projects and some time to discuss. Then we meet again on Friday, with the aim to form the groups, so they have sort of 5 days to talk about and discuss among themselves what could be* *exciting as projects. Actually they come with the projects themselves and what they would like to do.*'' (Staff 6).

In other cases, it is more open and the students are only facilitated to look for a problem, as in this case:

''*That's why we sort of (sometimes) try to engage them in an early pile of interviews, for instance, to go out to the field, to really get a sense of what it is this all about. Then they start to develop more interest, more ownership of their projects.*'' (Staff 7).

In any case, and taking into consideration the challenges that students face when entering the role as problem designers, there are clear indications that the scaffolding provided by staff is important for the students' ability to cope with problem design. Staff might not be the preferred problem designers, but they are important facilitators. This has inspired the conceptual model in the way that it is made applicable for both students and staff and it is taken into consideration that documentation of students' ongoing output from the problem design process is important for continual feedback from peers as well as staff.

3.3 Problem design for what could be called learning restricted innovation

Besides working with real life problems, students were also motivated by the idea of creating new knowledge and making contributions to knowledge in the field. One of the students explained:

''*I think in most cases we have had an idea of what the results may be, and a good idea often. But I am not saying that you can predict the results always. One thing I like about this is that you are not just doing an assignment. You are trying to solve a problem that nobody before you knew about. I have had a censor who—when he saw the project—apparently he had done something similar. But we didn't know that and we couldn't contact him because we knew he was our censor. But he hadn't used that particular method so he hadn't seen other possibilities of what we were trying to do, so he found that very interesting. We suddenly created something new, and I think that is interesting I must say.*'' (Student 1).

This range of possibilities not only to define a problem but also to address the problem is valued. As another student stated:

''*I've learned that, first of all, we don't have one answer to any problem but we can solve it in many ways*''. (Student 2).

This call for innovation is a very strong motivator and is mentioned by both staff and students and even related specifically to being an engineer, but at the same time the restrictions of being in a student environment is mentioned. In every innovative process, there is learning—but here the restriction added is that the curriculum calls for a specific type of learning. The following quote from a staff member illustrates this:

''*So in my head, PBL is not PBL if it doesn't have an innovative aspect in itself in the process of doing it. Of course it may not be innovative in re-creating the framework because you cannot continue to innovate it. Otherwise it is not PBL [. . .] But of course you won't say to students, 'Here is a problem and there are unlimited ways to solve it.' You have to limit yourself somehow—but at some point you make the problem formulation so well defined and limited that there is not space for the students to do anything but the same thing they did in the last semester. If you look in to different years, year one, two, three and four, they produce exactly the same type of problem, there is no problem orientation. They have not reflected on what they did last year. It is a mechanical process.*'' (Staff 1).

As noted, even in cases of what this staff member calls ''real'' PBL, where students work from ill-defined and ill-structured problems, there are not unlimited trajectories—they have to navigate inside the trajectory of the curriculum, and this is an ongoing challenge as the problem and the project develops, as described:

''*When you work in a project it tends to sometimes go in some directions which you didn't anticipate from the start and, maybe, sometimes it is a really bad idea . . .but sometimes, at least, when you are a supervisor you also say, 'Ok, that is very interesting, what they are working out here . . .' and they maybe should be allowed to do that but we just, as supervisors, have to be sure that they at least fulfil what is written in the curriculum.*'' (Staff 8).

Problem design is therefore targeted to what we could be calling or to what could be called learning restricted innovation, and this has inspired the model to clarify the limits of freedom for students to design problems as the very first step. The learning objectives should motivate the problem design process so that the problem, as it develops, is refined and subject for delimitation, and all the time in alignment with the learning objectives—thereby the problem formulation will serve as a compass for the project to stay on track.

4. A conceptual model for problem identification, analysis and formulation

Inspired by the revealed attitudes and experiences from staff and students in the PBL environment at Aalborg University, as well other researchers' approaches, e.g., [9, 11], we set out to make a *step-wise* model for students to identify, analyse and formulate a problem with staff facilitation. As several researchers point to the importance of students relating to a theme, as well as their ability to analyse and formulate the problem, we have incorporated these three steps in the model.

However, we have found a need to add two more phases to emphasise the process of moving from a broad theme to an initiating problem and start-up of a process analysis. Therefore, we have added two

Table 3. An overview matrix with the five steps, key purpose and sources of inspiration

Step	Purpose	Sources of inspiration
Relating to a theme	Clarifying the boundaries to (1) align with the learning objectives and (2) provide overview of interacting domains.	[2–3, 9–12, 14]
Mapping the problem field	To screen for opportunities in order not to focus on one problem area by chance, but get an overview of what the theme can offer.	[3, 9]
Narrowing down the problems	To evaluate, narrow down and select one problem to focus on out of several problem areas and problems revealed in the problem field.	[3,14]
Problem analysis and contextualisation	Analysing the chosen problem, substantiate claims and expand the knowledge of the problem to pinpoint specific motivations for action.	[3, 6, 10–11]
Problem formulation	To clearly state the point of departure for the problem solving process—creating the bridge between the problem analysis and the problem solving process.	[2, 5–9, 14–15]

phases to the model for the students to map the problem field, and narrow down the problems in the problem field to one specific initiative. We use the terms problem field to stress that it is broader than the problem area. The problem area is defined as:

> "*the theoretical and empirical context that makes the research problem a research problem. In other words, the knowledge I have of the world, or a part of it, which is necessary for defining and explaining the problem clearly*." [14, p. 24].

Thereby, the problem area corresponds to the problem analysis. Instead we define the problem field as the field of opportunities and problems that can be linked to a theme [14]. Thereby a problem field can include several problem areas.

Another focus in the proposed conceptual framework has been to propose concrete methods and procedures for students and staff in order to make the conceptual model applicable. This serves two purposes; first of all, it provides structures to frame the often diffuse problem seeking process, and secondly these structures provide what Wenger [17] would call a boundary object—a shared known structure that will target the communication around these explorative or creative processes within the groups and in student/staff interaction.

An overview of the five steps, their purpose and the sources of inspiration to include them, is provided in Table 3. In the following, the five steps are presented with elaboration of purpose and context, potential tools proving structures to frame the process as well as exemplification of implementation in the PBL learning environment at Aalborg University.

The different steps of problem design can be seen as the first steps in a PBL approach. Fig. 2 provides an overview of the different steps, whereas steps 1–5 relate to the problem design process, and the following steps related to problem solving, feedback to the problem area as well as reporting on the findings. In the following we will elaborate on the five steps of problem design.

4.1 Step 1: Relating to a theme

Pedersen [14, p. 25] defines a subject or a theme as a wider and not very precisely defined area of knowledge. When students' work is subject based they read about the subject, they describe and then formulate personal considerations to add their own experience/attitude to the subject [11, p. 37]. The theme, understood as an area of knowledge, can be seen as a playground in which students can unfold their learning potential, and the main purpose of limiting this playground is to place students where they can find a purpose for the discipline of study. For example, a theme for computer scientists could be assistive technology, and there are already examples of computer aided technologies targeted towards this area.

By borrowing a basic model developed for evaluation purposes by Mehlbye, Rieper and Togebye [18] picturing the target area and the approach to address this, students can deconstruct and present an overview of the theme and the approaches needed to obtain the learning objectives. It can be that the learning objective is open for whatever approach the students might find appropriate, but seldom is it completely open as the curriculum most likely demands a certain type of disciplinary knowledge.

However, as students have to be in what Vygotsky [19] termed the proximal zone of development, it is important that the area of knowledge is not too wide or includes too complex areas of knowledge—the playground should, in other words, be suitable for the level of development. This can be decided by relating the learning objectives to the considered knowledge domain.

Figure 3 shows an example from computer science, again taking the example of assistive technology. Assisting technology, as a theme, is deconstructed into different issues of investigation e.g., emergencies or adaption. The chosen approach to address the theme is user-driven design, prototyping

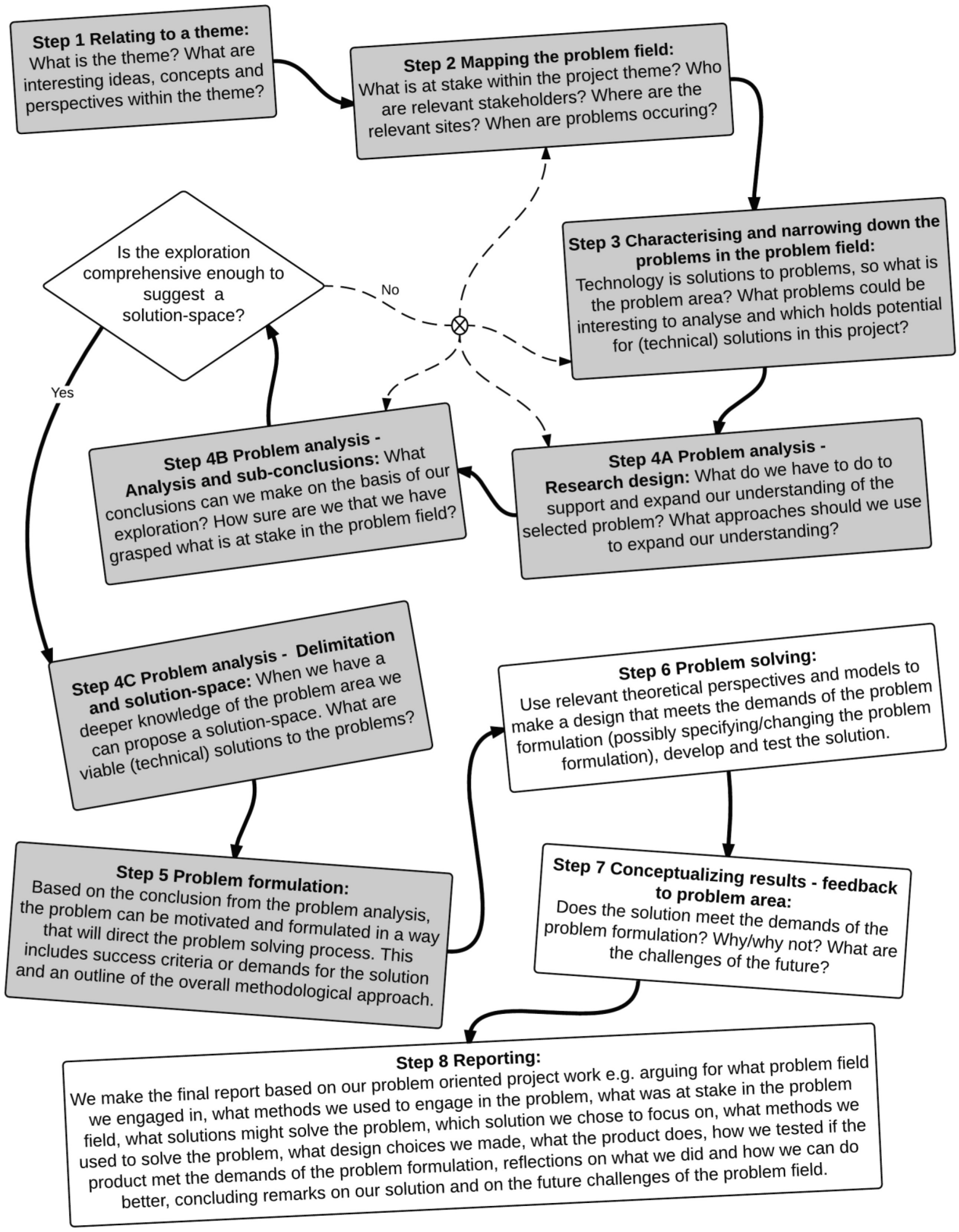

Fig. 2. Guiding steps of problem-based learning. The grey boxes (steps 1–5) indicate problem design steps.

and testing—which in this case is among the requirements in the curriculum. Thereby, students are challenged to link a narrower field of study with the required approach. On other occasions in might be the other way around.

When students are in this initiating phase there is a risk that they will use too much time and resources on deconstructing the theme—this is their safe-zone as they really do not have to move from rather traditional ways of learning into the possible new form of PBL. Therefore, it is crucial to facilitate students in time planning already at this stage. Another crucial element for the facilitator is to act as expert when it comes to assessing the appropriateness of what could be called sub-themes. If the facilitator, for example, assesses it to be too time consuming for the students to gain insight into cognitive impairments, when they also have to make an application and test it in a user context, this is the time to say so.

4.2 Step 2: Mapping the problem field

In the second step, students need to map the problem field. Here the classic "Five Ws and one H" (5W1H: why, what, when, where, who and how) questioning method is applied to let the students expand their understanding of the problem. The model is a tool for letting students define their own

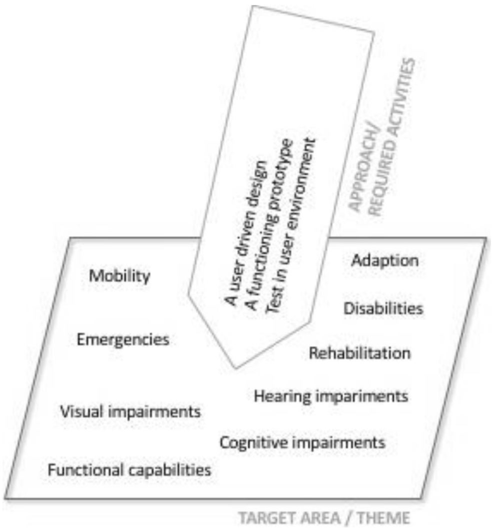

Fig. 3. An overview of the theme and relation to the required activities to obtain the learning objectives, inspired by [18].

problems and thereby reflects an approach within the ill-defined problem perspective to PBL. The 5W1H model comes out of a rhetorical questioning tradition dating back to ancient Greece. The formulation of the 5W1H problem solving method, also called the "Kipling Method", was pinpointed by Rudyard Kipling in 1902 in an introductory poem to the tale of "The Elephant's Child" [20]:

I keep six honest serving-men
(They taught me all I knew);
Their names are What and Why and When
And How and Where and Who.

The questions of what, why, when, where, who and how are posed in order to explore the context of a phenomenon, event or problem and have been used methodologically and developed in many contexts like journalism [21], computer science [22], management [23] etc. The strength of the questioning method is in its simplicity and generality and it can therefore be used in very different fields, where the aim is to understand a broader context. The generality is also its weakness, as it can seem trivial. However, when expanding the model slightly to fit the field of application its strength re-emerges.

In order to adjust the model to the educational setting of guiding the students in their problem-oriented project work some key terms have been added to help the students associate with the scientific investigative field. The expanded 5W1H model (Fig. 4) has the following investigative elements:

1. What: Conceptualisation
2. Why: Relevance
3. Who: Stakeholders
4. Where: Place, site, context
5. When: State of the art
6. How: Problems to be addressed

The questions in Fig. 4 are given priority numbers in order to guide the students to start where Step 1 ended, meaning that the students have generated a list of concepts included in the theme. However, the model is presented as a mind map which underlines the fact that all the elements interact and that the analysis is an iterative and back-and-forth process as reflections on one element inevitably will lead to new reflections.

In the following we elaborate and exemplify the six questions in Fig. 4 based on how we have presented it for students in a PBL environment. In the exemplification, we relate to the theme of assistive technology as in Step 1.

What—Conceptualisation: "What" relates to key concepts which are important for understanding the theme. These key concepts can be found in the target area presented in Step 1 and can be further elaborated in the tree structure. As noted in Fig. 2, assistive technology can be deconstructed and related to concepts like functional capabilities, visual impairments, mobility and so on. Mobility

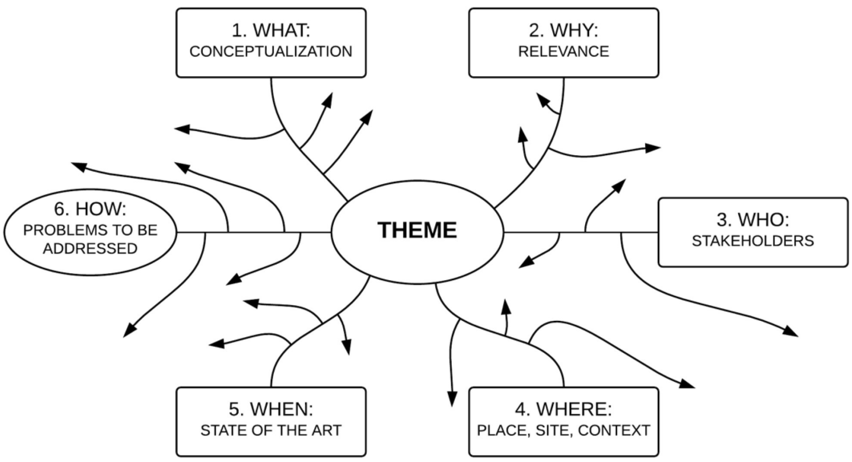

Fig. 4. The 5W1H model for analysis of the theme: to create a problem field.

can be deconstructed into walking, driving a car, taking public transportation and so on. What, however, also includes existing technologies, like electronic wheelchairs, lifts, etc.

Why—Relevance: Knowing about the theme will create a basis for considering why it is relevant to consider the theme—the reasons can range from a societal perspective e.g., being socio-cultural, ethical or socio-economic to personal motivations based on students' experiences. The students are encouraged to be critical and think not only about the technical knowledge within a problem field. For example, and in relation to mobility, there could be ethical considerations regarding equality of people, there could be economic reasons considering the inclusion of disabled people in the workforce and so on.

Who—Stakeholders: "Who" incites students to identify different stakeholders that are or could be related to the theme. Students should be encouraged to expand the view from users and producers to a broader set of stakeholders that might affect and be affected by the state and development of this knowledge area. In addition to the users, who could be families, elderly persons, wheelchair users, etc. and the companies that develop technologies within the field of assistive technologies, other stakeholders could be patient/disability organisations, online communities of users, ministries of health and transportation, transportation companies, shops, transportation researchers, etc.

Where—The site and its context: "Where" relates to the sites where the knowledge is created or brought into practice. Who, where and when are closely interrelated and will often inform each other. Students are encouraged not just to consider the specific site where knowledge comes into play, but also the broader organisational or socio-cultural context. In relation to assistive technologies "Where" could be at home, on the bus or train or in the city, it could also be at ministry level, developing rules and regulations in relation to physically impaired people and mobility or in-patient or disability organisations engaged in improving the situation for their members. Going further into detail might reveal interesting sites with challenges for the physically impaired e.g., public transportation or shops.

When—State of the art: "When" relates to the situations and practices in which the knowledge of the theme is created, unfolded and has an impact. Typically, students will take a state of the art perspective considering current and dominant practices and the state of the art in coping with this at a certain point in time. In relation to the considerations on mobility and the physically impaired the focus could be on different situations e.g., when disabled people are using public transportation in rush-hours or when they are shopping during a crowded sale. We are now getting closer to the context of use of technology.

How—Problems to be addressed: Lastly, the students are encouraged to reflect on which problems are handled and which are in need of being handled. Here students are encouraged to think of problems not only as knowledge gaps, but also as a potential platform to be rebuilt or expanded. Creativity techniques most often come into play while considering how different challenges and problems are or need to be handled. One problem could be lack of access for physically impaired people which would present different types of problems depending on whether it is accessibility to public transportation, shopping, theatres etc. In other words, problems are designed by combining the elements in the problem field.

As mentioned above, it is recommended that facilitators provide an introduction to the model and include concrete examples of the use of the model related to the specific field of study. After an introduction, students return to their project groups where they use brain-storming and make mind-maps in relation to their theme. The students are assisted by a teacher who assists them in the screening process by providing feedback during their group work. If students have just started at the university, the facilitator should take into consideration that the challenge they face might not only be related to the framing and reflection, they also have to expand their understanding of the complexity of a problem field.

4.3 Step 3: Narrowing down the problems in the problem field

As an output of Step 2 there should be a list of problems that could be addressed under the proposed theme. Now the groups have to narrow down the problem field to one initiating problem that can be analysed in more detail in order for the analysis to be manageable. Whereas the risk of students just going with the first problem coming into their minds is considered in Step 2, this step will take care of the risk that based on the overview of the problem field students will select a problem due to personal interest alone, leaving out the implications this will have on the project. No doubt, and as noted by Duch [9], the problem should engage students, but other variables can impact motivation during the project and learning experience, like:

- *Alignment with learning objectives*—even though the knowledge area has been considered in relation to the learning objectives, the problems derived might have more or less potential for fulfilling the learning objectives. For example, it might be questioned whether the problems can in fact be addressed with the required methods.

- *Access to knowledge*—even though a problem is aligned with the learning objectives it is possible that the access to knowledge is limited. For example, the access to knowledge for a user-driven design is easier if the users are located nearby, and have the time, interest and trust to participate. Another example is if three of the group members have worked on similar problems in other projects, and thereby have established a knowledge base and network.
- *Time available*—an overall time estimation, taking into consideration the number of students in the group, might give a hint of whether the problem is realistically solved within the given timeframe, and if not whether it is possible to delimit the problem to something realistic and still reach the learning objective.
- *Budget*—if the project, for example, needs prototyping, the budget for making prototypes should be considered. If user-driven design is needed and the detected problem is in Africa while the group is situated in Denmark, some travel expenses have to be considered, and so on.
- *Possibility to impact*—the possibility of having an impact outside the group by making this project can be considered. If, for example, industry partners have highlighted the problem, there could be a possibility for project collaboration, which again could provide a possibility for having an impact on the organisational level. The possibility to have an impact on real life processes can be a motivator for learning—and besides that it can contribute to the outreach activities of the university.
- *Contextual reach*—for incremental technical innovation the problem might not even be visible in the use context—it might be a "lab problem" in other words. At the other end of the continuum the problem might not only be of great influence in the use context, it might also have a far-reaching and broader socio-cultural impact. The students should be encouraged to assess what is at stake, and if it is "too much" it should be assessed whether it is possible to delimit the problem and still fulfil the learning objectives.

For most cases, the time available for this exercise is limited, and therefore the facilitators should support the students in a structured process. Some students like to make evaluation matrices and quantify the assessment of the different problems, other students prefer to discuss the different possibilities more qualitatively and end up with a consensus of where to go—other students might choose both ways. In every case, this step provides the students with a considered selection of an initiating problem that will reduce the risk of using a lot of resources to analyse an initiating problem that is simply not suited to the particular study context.

4.4 Step 4: Problem analysis and contextualisation

When moving on to the problem analysis the 5W1H model becomes relevant again. Now the students need to reflect on the problem that they identified as relevant through the first steps of the process while reflecting on the problem field. Further the students need to expand the analysis by considering how to substantiate their claims and expand their knowledge of the problem. They therefore need to regard what methods they want to use to collect and analyse the problem.

In order to get more depth in their analysis and be inspired to move forward the students are introduced to some additional questions to reflect on in relation to the 5W1H model. The following questions are provided:

- *Why: relevance*—Why is this problem occurring? Why is it a relevant problem? What will happen if this problem is not solved? What are the symptoms? What are the impacts, etc?
- *What: conceptualisation*—What concepts do I have to know more about to be able to understand the problem?
- *Who: stakeholders*—Who is causing the problem? Who says this is a problem? Who is impacted by this problem? Who has an influence on the problem, etc.?
- *Where: place, site, context*—Where does this problem occur? Where does this problem have an impact, etc.?
- *When: state of the art*—When does this problem occur? When did this problem first begin to occur, etc.?
- *How: what are the possible solutions*—How are people currently handling the problem? How can other technologies help to solve this problem? What new technology needs to be developed to solve this problem, etc.?

Please note that there are no numbers attached to the different questions, as students are starting differently depending on the type of initiating problem. If the students have chosen an initiating problem that asks for what Holgaard, Guerra, Knocke, Kolmos and Andersen [6] termed a bottom-up problem analysis they would most likely start by elaborating on the why. With a top-down approach, where students start out with a sense of something that "can be done", they thereby have a possible solution in search of a problem. In that case, they will start by elaborating on the "how" and the "why" might be the last question to be addressed.

The students are presented with the expanded model and encouraged to move further in their analysis by considering literature to substantiate their analysis and to point to areas where they lack scientific knowledge. Where brain-storming was adequate in the initial screening of the problem field in Step 2, the students now need to get into how an argument is supported when carrying out a project within a scientific framework.

The analysis, in other words, needs to be substantiated by a scientific methodological approach. At the Faculty of Engineering and Science at Aalborg University students are introduced to different methods that can be used in the problem analysis. In Fig. 5 the different methods, models and perspectives are listed in relation to the 5W1H questions. On the left side are the methodological methods of research design, literature review and sociological methods and critical reflections on these needed in order to explore the contextual field of the problem—guided by the initial problem formulation. On the right side are the different models and theories for contextual analyses that the students are introduced to during the course. These are needed in order to support the analytical work moving from the screening level of Step 2 to a qualified and argumentative sound foundation of the problem analysis.

The methods support a problem analysis within an ill-defined problem field. The analysis has the aim of providing insight into what is at stake in order to provide a well-argued foundation for proposing a solution space (a range of possible solutions) for Step 5.

In the technology assessment, students might assess existing technology in light of the user needs and broader societal perspectives they have revealed. This analysis as well as the criteria given by the study context (see Step 3) can be brought together with the output of the creative process (related to the "how") where new solutions are proposed, creating a so-called solution space. In this way, possible solution patterns that call for further technical analysis are revealed. Thereby the primary output from Step 4 is a problem so delimited that it calls for a targeted design, implementation and evaluation.

Step 5: Problem formulation

In Step 5 the students will use the conclusions from the problem analysis to formulate the motivation

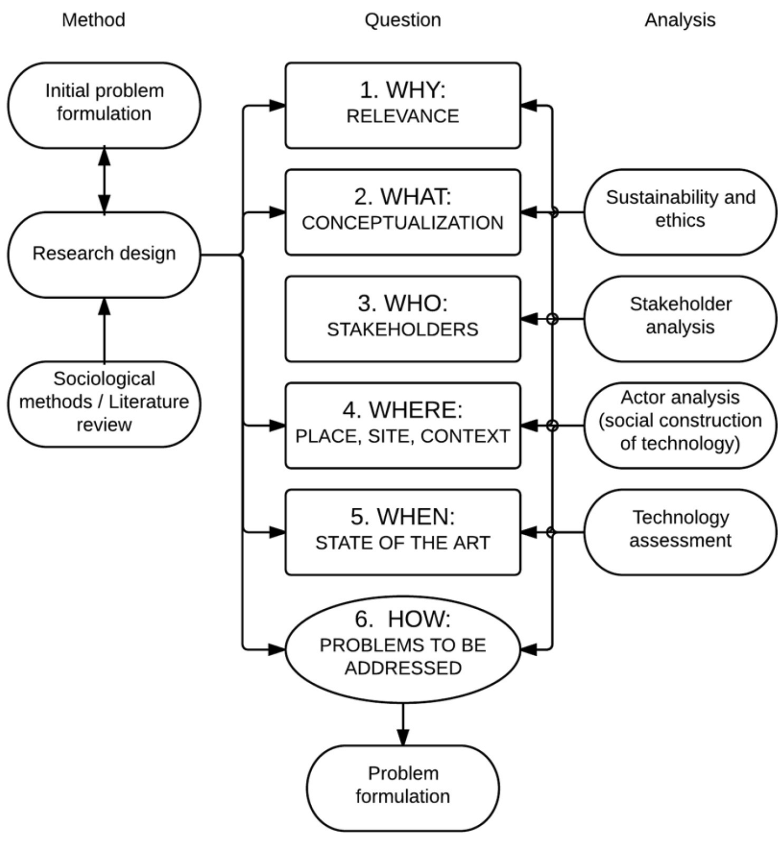

Fig. 5. Methods and analytical models and theories needed in the problem analysis to support and substantiate the use of the 5W1H model.

for a research question. The motivation includes clear statements of the need for problem solving. Based on the motivation, an overall question, and potential sub-questions, can be formulated to guide the problem solving process. Based on this question it should be possible for students to outline the overall methodology. The facilitator should encourage students to present this, e.g., in a simple flow diagram and have it visible at all time—for the students to keep track—or re-direct their track along the way.

Based on literature review and experiences from different faculties, Holgaard, Ryberg, Stegager, Stentoft and Thomassen [15] conclude that a problem formulation should be: challenging, documented, clear and unambiguous, guiding, open for research, durable within a given timeframe, ethically sound, interesting and relevant for the study. Compared with the list of criteria for selecting an initiating problem, the basic difference lies in the documentation provided by the process analysis; and instead of serving as a compass for a problem analysis like the initiating problem, the problem formulation serves as a compass for the problem solving process.

Let us provide an example of a delimitation and problem formulation based on the above chosen theme for exemplification: assistive technology.

Motivation: Based on the analysis the group found that people using wheelchairs have a range of challenges when shopping. Shops can have steps which exclude them from entering, the shops can be too small and too densely packed with products for the wheelchair user to navigate in the shop. Products can be placed where they are not within reach from a wheelchair and if there is a lack of assistance in a shop, it can limit the shopping experience. There is no legislation for the design of shops to support disabled people inside the shops. The organisation for physically disabled people explained in an interview that they were working on a system for rating accessibility of different venues including shops. This system is under development, but it is possible to use this organisation to define ''appropriate and accessible shops''. In the solution space the groups considered designing an app to integrate the technology in a mobile device that could be used during the shopping experience. On the basis of the problem analysis the following *problem formulation* was chosen:

How can an app support wheelchair users in finding appropriate and accessible shops?

Listed *sub-questions* were:

1. What is needed to complete our understanding of the context of use?
2. What features are needed to support the users at home and on the street?
3. What different solutions can meet the requirements of the users?
4. How can we select the best solution for implementation?
5. How do we implement the solution in the most efficient way?
6. How can we evaluate the designs against the requirements to design a solution that meets users' requirements?
7. What implications does our solution have for other interested parties as well as users?

On the basis of the problem formulation, the group chose an *overall methodological approach* based on the methods and theories within their field of study. This could, in this case, be inspired by the standard (ISO 9241-210) for human-centred design for interactive systems, supplemented by overall considerations of the type of knowledge needed. This direct future considerations considering appropriate development methods in designing a system for the target group, as well as methods to test the system, both technically and/or in relation to user demands.

5. Conclusion and final remarks

When working in a PBL environment, the students not only need to learn to solve problems, they also need to learn how to identify, analyse and formulate the problem in context, as problems do not just magically appear in a format that calls for specific engineering solutions. It is an iterative process, because having more knowledge about a theme, a problem, a possible solution and what is at stake, changes the students' perspectives and thereby the trajectories to viable solutions. In this article, we have presented a conceptual five-step model for students to identify, analyse and formulate a problem to be addressed from an engineering perspective. The model is based on theoretical as well as empirical inputs that have pointed to a conceptual model for problem design for both students and staff, which is (1) simple and concrete in its conceptual framing, (2) walks the students through their first experience as problem designers in a sequential step-wise systemic manner, and (3) draws attention to the process of moving from a broad theme to an initiating problem and starting up a process analysis.

The conceptual model for project design includes five steps initiating students to (1) relate to the theme, (2) map the problem field, (3) narrow down the problem, (4) analyse the problem in context, and (5) formulate the problem. Experience shows that students can manage this step-wise model, but there is still a need to scaffold students during the process of developing problem design skills.

When transferring this model into practice it is first of all important that both students and staff are introduced to this conceptual framework and, secondly, staff members have to select the theme carefully to initiate the process. The theme has to provide students with the possibility to enter into a rich problem field, with different problem areas and a possibility to relate to technical innovation within the field of study. As a rule of thumb, a good theme is a theme where the staff members, due to their experience, can brainstorm through the different steps and come up with at least a dozen possible problems that call for technical developments, which at the same time will satisfy the requirements of the curriculum. Third, a status seminar after each step with the students is recommended as this provides an opportunity for students to get inspiration from fellow students working in the same field, which enriches the problem design process. Last but not least, timing is of great importance. If students have too long a time for e.g., the problem analysis, they might dig too deep, but if the time is too limited, the analysis will be superficial. In all cases, staff should make sure that the appropriate time is provided to address the depth indicated in the intended learning outcomes of the study.

It can be a complex process to identify, analyse and formulate a problem, and this should draw attention to the need for facilitating this process. The self-directed learning element in the PBL environment calls for the students to make their own decisions—and in the first stages they typically do that with a relatively limited ground of experience as well as little time to establish firm scientific ground for every decision. To provide pre-defined structures to gather an overview based on screenings and to facilitate ongoing evaluation based on pre-defined criteria is one way to scaffold the process. However, it also has to be considered that instructions might not be enough to handle the frustration of being asked to make decisions on shaky ground—some face-to-face facilitation is most likely needed. It is much less frustrating to let others make the decision, although it might turn out to be less engaging.

The complexity embedded in the process to reach a problem formulation, however, should also draw attention to whether the initial steps of the mode should be included in every project model in a curriculum. Some variance in the use of the model will occur due to different interpretations by different teachers and the way different groups of students work. The core of the model is the same, however: to encourage the student to explore the context of the problem field they engage in. Variations occur when, e.g., the problem field is defined in a project proposal. In this case, the students are likely to spend less time on understanding the problem field and defining the initial problem. Another variation occurs when the project is not focused on developing but analysing an existing solution. Here the theme is more like a subject, e.g., if the students are required to do a usability test of an existing technology. However, in this case students still need to figure out the relevance of their chosen technology, understand the context and provide relevant requirements in order to design their usability test and give suggestions for improvements.

Sometimes it might be appropriate to place the focus on other learning objectives, by presenting the students with a set problem, or limit their scope by project proposals or even a fixed set of user requirements. On the other hand, if students do not experience clear attention to the process of problem identification, analysis and formulation in the curriculum, then students as well as staff might be caught up in a disciplinary bubble, working on narrow research problems grown in the backyard of the university. These are important in a PBL study as well, but as not every student ends up in academia, it is far too limited a focus to assure employability of our students.

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Jette Egelund Holgaard is associate professor within the field of Sustainability, technology and organizational learning at the Department of Development of Planning; Aalborg University, Denmark. She holds a PhD in Environmental Communication. She is affiliated to the Aalborg Centre for Problem Based Learning (PBL) in Engineering Science and sustainability. Her current research focuses on how to make use of a PBL framework to enhance problem based learning, contextualisation and innovation for sustainability in engineering education.

Lone Stub Petersen is associate professor within Organizational change, Socio-technical studies and Health Informatics at the Department of Planning, Aalborg University, Denmark. Petersen holds a PhD in Health Informatics. Her current research focuses on interdisciplinary competencies in technology projects and citizens perspectives on Health Informatics.

Aida Guerra is assistant professor within the field of Problem Based Learning (PBL) and Engineering Education for Sustainable Development at the Department of Planning and the Aalborg Centre for Problem Based Learning in Engineering Education, under the auspices of UNESCO, Aalborg University, Denmark. Dr Guerra holds a PhD in PBL and Sustainable Development in Science and Engineering Education. Dr. Guerra current research focuses on how to make use of a PBL framework to enhance engineering education for sustainable development.

Anette Kolmos is professor in Engineering Education and Problem Based Learning and Chairholder for UNESCO in Problem Based Learning in Engineering Education, Aalborg University, Denmark and the head of the Aalborg Centre for Problem Based Learning in Engineering Education, under the auspices of UNESCO. She is furthermore guest professor at KTH Royal Institute of Technology and at UTM University Technology Malaysia 2011–2013. President of SEFI 2009–2011 (European Society for Engineering Education). She is Associate Editor for the *European Journal of Engineering Education* and was Associated Editor for *Journal of Engineering Education* (ASEE). During the last 20 years, Dr. Kolmos has researched the following areas, primarily within Engineering Education: development and evaluation of project based and problem based curriculum, change from traditional to project organized and problem based curriculum, development of transferable skills in PBL and project work, and methods for staff development.