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Avoid, Control, Succumb, or Balance: Engineering Students' Approaches to a Wicked Sustainability Problem

Johanna Lönngren[1] · **Åke Ingerman**[2] · **Magdalena Svanström**[1]

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Abstract Wicked sustainability problems (WSPs) are an important and particularly challenging type of problem. Science and engineering education can play an important role in preparing students to deal with such problems, but current educational practice may not adequately prepare students to do so. We address this gap by providing insights related to students' abilities to address WSPs. Specifically, we aim to (I) describe key constituents of engineering students' approaches to a WSP, (II) evaluate these approaches in relation to the normative context of education for sustainable development (ESD), and (III) identify relevant aspects of learning related to WSPs. Aim I is addressed through a phenomenographic study, while aims II and III are addressed by relating the results to research literature about human problem solving, sustainable development, and ESD. We describe four qualitatively different ways of approaching a specific WSP, as the outcome of the phenomenographic study: A. *Simplify and avoid*, B. *Divide and control*, C. *Isolate and succumb*, and D. *Integrate and balance*. We identify approach D as the most appropriate approach in the context of ESD, while A and C are not. On this basis, we identify three learning objectives related to students' abilities to address WSPs: learn to use a fully integrative approach, distinguish WSPs from tame and well-structured problems, and understand and consider the normative context of SD. Finally, we provide recommendations for how these learning objectives can be used to guide the design of science and engineering educational activities.

Keywords Engineering students · Ill-structured problems · Phenomenography · Science and engineering education · Wicked sustainability problems

✉ Johanna Lönngren
johanna.lonngren@chalmers.se

1 Chalmers University of Technology, Gothenburg, Sweden

2 University of Gothenburg, Gothenburg, Sweden

Introduction

The use of complex and ill-structured real-world problems in science and engineering education is advocated for different reasons. For example, engaging students in discussions about such problems has been suggested to render education more relevant to the students and thus increase students' interest in science and engineering (Aikenhead 2003). It may also facilitate students' development of moral reasoning and informed decision-making skills and prepare them for active participation in democratic societies (Gallagher 1971; Pedretti and Nazir 2011). Finally, using such problems offers a venue for engaging students with social and environmental questions, which is increasingly recognized as an important aspect of science and engineering education (Aikenhead 2003; Pedretti and Nazir 2011; Wals et al. 2014).

Jonassen (2000) analyzed a large number and variety of problems that are and can be used in education. He categorized problems according to their level of complexity, structuredness, and domain-specificity. He describes problem complexity as "defined by the number of issues, functions or variables involved in the problem; the degree of connectivity among those properties; the type of functional relationships among those properties; and the stability among the properties of the problem over time" (p. 67). Highly complex problems require efficient problem-solving strategies. Complex problems can be either well-structured or ill-structured. Well-structured problems have knowable and comprehensive solutions and thus lend themselves to "the application of a limited number of regular and well-structured rules and principles that are organized in predictive and prescriptive ways" (p. 67). Ill-structured problems, on the other hand, are characterized by uncertainty and the need to make judgments. Finally, Jonassen notes that most ill-structured problems are highly domain-specific. Thus, general (domain-independent) problem-solving approaches are not useful for addressing ill-structured problems (see also Kitchener 1983).

In this paper, we focus on problems that are highly complex, ill-structured, and domain-specific. We further narrow our focus to problems that are discussed in relation to sustainable development (SD). To describe these kinds of problems, we use the term *wicked sustainability problems* (WSPs). The term "wicked problems" (as opposed to "tame problems") was originally introduced by Rittel and Webber (1973) to describe problems in the context of design and social planning. Since then, researchers have continued using and developing the concept in the design (education) research community (e.g., Buchanan 1992; Cross 1984; Nelson 2003), as well as in other contexts, such as SD and education for sustainable development (ESD) (cf. Hischemöller and Gupta 1999; Seager et al. 2012; Tomkinson 2011). In some contexts, the term "ill-structured problems" has a similar meaning to "wicked problems" (e.g., research on ill-structured problem-solving in design by Dorst 2006 and Schön 1990). The present paper is primarily grounded in the use of the concept of "wicked problems" in the contexts of SD and ESD. Where appropriate, however, we also draw on discussions of wicked and ill-structured problem solving in the contexts of science and engineering education, design, and cognitive science.

Seager et al. (2012) describe five characteristics of wicked problems in the realm of SD:

1. developing a clear and unambiguous problem formulation is difficult if not impossible;
2. for each problem, there are multiple ways of addressing the problem that are not necessarily compatible with each other;
3. time frames are open-ended, which means that there is no single point in time at which the adequacy of a proposed solution can be definitively evaluated since the circumstances of problem and solution are subject to constant change and evolution;

4. each problem is novel and unique, i.e., pre-developed, generic approaches cannot be used to deal with them; and
5. competing value systems or objectives are present, which makes unambiguously "good" solutions practically impossible.

For our description of WSPs, we regard the fifth characteristic as particularly important because WSPs (by definition) are embedded in the normative context of SD. SD itself is a highly ambiguous and contested concept (Connelly 2007; Kates et al. 2005); this implies that the variability, ambiguity, and incompatibility of value systems and objectives may be exceptionally high in this context.

Not all SD problems are necessarily wicked problems, but global challenges such as climate change, poverty, resource scarcity, environmental degradation, and global health problems certainly are. Dealing with WSPs such as these is crucial for SD. Science and engineering education can play an important role in preparing students to deal with problems such as WSPs (Kates et al. 2005; Pedretti and Nazir 2011; Wals et al. 2014; Wiek et al. 2011). In fact, engineering students are highly motivated to contribute to environmental and social causes (Haase 2013), and engineering practice is commonly viewed as a "service" to society (Wisnioski 2012, p. 95). At the same time, students are not adequately trained to contribute to such causes. For example, students in engineering (and to some extent, the natural sciences) have been found to be more likely than those studying humanities, arts, and social sciences to hold naïve beliefs about the certainty of knowledge (Paulson and Wells 1998). Such beliefs do not support productive engagement with WSPs (King and Kitchener 1994). Indeed, they have been found to be negatively correlated with the ability to solve ill-structured problems, since they "[preclude a] thorough analysis of alternative solutions" (Schraw et al. 1995, p. 535). Despite these findings, little attention has been paid to students' approaches to ill-structured and wicked problems (Douglas et al. 2012).

While problem-solving plays an important role in science and engineering education (see e.g., Jonassen et al. 2006; Stewart and Rudolph 2001), students mainly learn to solve well-structured problems. However, performance on solving well-structured problems has been reported to be unrelated to students' ability to address ill-structured problems (Schraw et al. 1995). Dealing with ill-structured problems requires, among other things, the reconciliation of conflicting goals, multiple forms of problem representation, and multiple solution methods (Jonassen et al. 2006). Ill-structured problems cannot be addressed by merely using linear and pre-defined problem-solving processes, from a definite problem definition to a final, optimal solution. Rather, the understanding of the problem itself will change during an iterative problem-solving process (Dorst 2006). Jonassen et al. (2006) suggest that current practice in science and engineering education does not adequately prepare students to address ill-structured problems (and thus WSPs) in these ways (see also Seager et al. 2012). As scientific knowledge about how to prepare students for dealing with WSPs is limited, educators have to rely on their own intuition and anecdotal evidence as they attempt to develop appropriate teaching strategies.

In this paper, we aim to address this lack of research by providing insights related to students' abilities to address WSPs. In this way, we also aim to contribute to an empirical and theoretical basis for better aligning science and engineering education with the aims of ESD.

Specifically, our aim is threefold:

I. to describe key constituents of engineering students' approaches to a WSP in terms of different levels of complexity of understanding the problem;

II. to evaluate these approaches with respect to what may be considered appropriate in the normative context of ESD; and
III. to identify relevant aspects of learning related to WSPs in the context of engineering ESD.

We address this aim with a phenomenographic research approach (Marton 2015; Marton and Booth 1997), which we describe in the second section, "Methods." The phenomenographic analysis resulted in four qualitatively different ways of approaching a specific WSP— we describe these in the third section, "Results." In the fourth section, "Discussion of Approaches", we discuss the results, and in the fifth section, "Methodological Considerations", we discuss limitations of phenomenographic research in general and limitations of our study in particular. We also briefly discuss implications of our study for other phenomenographic research studies. In the sixth section, "Implications for Teaching and Learning", we provide suggestions for what could be appropriate objects of learning in order to develop science and engineering students' capability to productively tackle WSPs.

Methods

We chose to employ a phenomenographic research approach because it allowed us to gain empirical and theoretical insights in line with the aim of our study. Phenomenographic research aims to contribute to pedagogical development by providing a description of qualitatively different ways in which students understand specific educational phenomena. In these descriptions, phenomenographic researchers attempt to identify the most important and relevant features of students' ways of understanding a phenomenon. These descriptions are a resource for educators who wish to improve their teaching related to this phenomenon (Collier-Reed and Ingerman 2013; Marton 2015; Marton and Booth 1997).

Another reason for choosing a phenomenographic approach was the empirical and explorative character of such an approach. Phenomenographic research is inductive and provides opportunities for developing new theories and contributing new knowledge (Svensson 1997). It is particularly valuable for the present study because it is "especially suitable for situations where there exist no or very little prior knowledge on the topic" (Kinnunen and Simon 2012, p. 199), as is the case in relation to students' approaches to WSPs. In addition, changes to science and engineering education are necessary in order to respond to the urgency and complexity of sustainability issues (Wals et al. 2014). Such changes cannot be achieved through purely deductive educational research, since such research would focus on confirming or falsifying traditional approaches.

There is no widely accepted methodological procedure in phenomenography (Kinnunen and Simon 2012) as is the case in, for example, grounded theory. Therefore, considerable variation exists between methodological approaches in phenomenography (Åkerlind 2005). However, all phenomenographic research shares an explorative and analytical focus in data generation and analysis (Svensson 1997). In what follows, we describe the methods employed in this particular study.

Empirical Material

In planning and conducting the study that underlies this paper, we aimed at creating rich empirical material that would be well suited for phenomenographic analysis. For this purpose, we chose to conduct semi-structured in-depth interviews. The first author conducted these interviews in the spring of 2012. Informants for the study were chosen from a group of Swedish students who were in their third year of a (5-year long) Master of Science in Engineering program. At the time of the study, the students were enrolled in a mandatory course on SD, called "the course." The course was delivered in parallel with one other course at the end of the students' undergraduate education, and it spanned a period of 8 weeks. During the course, students were engaged in discussions about the WSP of global warming. The interviewer was involved in the course as a lecturer and facilitator, but she did not have any functions related to student assessment. Twenty-four out of 44 course participants expressed an interest in participating in the study. Out of these, we invited 14 students to participate in the interviews, and ten were ultimately able to contribute to the study.

To allow for a phenomenographic analysis of the material, we had to ensure that all interviews had a common focus on the same "phenomenon." Therefore, we chose to conduct the interviews towards the end of the SD course. This allowed the participants to develop a shared background as they practiced addressing the WSP of climate change during the course, and as they together experienced the stark contrast between this course and more traditional, lecture-based courses in their engineering program. A common focus in phenomenographic interviews can also be established by structuring the interviews around specific tasks that are performed during the interview (Collier-Reed and Ingerman 2013). For our study, we chose to structure our interviews around a specific WSP and a discussion of what could be possible ways of dealing with it. For the following two reasons, we chose the WSP of water shortage in Jordan.

First, sustainable water resource management has been recognized elsewhere as a wicked problem (Hearnshaw et al. 2011; see also Dimenäs and Alexandersson (2012) for a discussion of the suitability of water as a topic in holistic ESD). The particular problem of water shortage in Jordan also satisfies all the characteristics of WSPs as described in the Introduction: (1) *It is not possible to unambiguosly define the problem.* Is the problem simply that the quantity of available water is insufficient? Is it that resources are distributed unevenly? Or is the problem really about overpopulation, climate change, or regional conflicts? (2) *There are multiple ways of addressing the problem that are not necessarily compatible with each other.* For example, the problem could be addressed by building desalination plants in order to "create" larger quantities of potable water. Alternatively, one could attempt to combat climate change, which is one contributing factor to increasingly severe water shortage in the region. These approaches could of course be combined. However, desalination is an energy-intensive approach to combat water shortage. It may thus counteract attempts to reduce global warming. (3) *The time frame of the problem is open-ended*, i.e., it is unclear when the problem should be solved. Should we strive to provide enough water for the current population, or should we aim to create a situation that is sustainable in the longer term? (4) *The problem is unique.* While water shortage is a common problem in many parts of the world, the local geographical, political, economic, and cultural situation is unique for the specific area. It is therefore not possible to merely implement a standard solution that has been successful (by some standard) in another region. (5) *Competing value systems and objectives are present.* Striving to achieve a "sustainable situation" could have many different meanings in the context of water shortage in Jordan. On a general level of discussions about what would be a "sustainable situation", environmental sustainability could be foregrounded by focusing on preserving local and global ecological systems. Alternatively, economic sustainability could be the main focus; in that case, ensuring adequate water supply to local industry could be the main priority. A focus on social sustainability could mean that the main aim is to ensure distributional justice and a stable political situation in the area. But even within each of these foci of SD, competing objectives will be present. For example, while aiming for social sustainability and distributional justice, one could assume that all Jordan people have the right to the same amount of water. An alternative, conflicting, position could be that water should be distributed according to need.

Second, in contrast to the global problems that were mentioned as examples of WSPs in the "Introduction" (e.g., climate change), the problem of water shortage in Jordan is more local and confined. This made it possible to cover a large number of relevant aspects of the problem during the interviews. The presence of relatively well-defined boundary conditions (e.g., statistics about the current and projected water needs in Jordan, information about the local climate, and the political situation in the area) also made it possible to discuss conflicts and dilemmas that arise in the concrete situation. Finally, choosing such a problem ensured that the focus of the individual interviews was similar and thus that the participants discussed a common phenomenon.

Before the first interviews, we conducted two pilot interviews with graduate students who were involved in teaching the course. On the basis of these pilot interviews, we adapted the interview procedure and materials. Prior to the study, we also obtained written, informed consent from all participants in accordance with the Swedish ethical regulations and guidelines for research of this type (The Ministry of Education and Cultural Affairs 2003).

Each of the ten interviews lasted for approximately 1 hour and proceeded through five distinct phases in a semi-structured manner. The interviews were audio- and video-recorded and later transcribed verbatim by the interviewer.

Phase 1: Reading and Reflecting

As an introduction to each interview, the interviewer described the structure and aim of the interview. She stated that participants were not expected to give "correct" answers and that the researchers were mainly interested in the participants' ways of dealing with, reasoning about, and relating to a sustainability problem. The participants then received a short description of the WSP of water shortage in Jordan. They also received six idealized solution alternatives that had been formulated with the aim to stimulate the consideration of multiple perspectives on the problem (Appendix 1). Finally, participants were given a schematic map and a satellite image depicting the Jordan Valley. With the help of these texts and images, a common focus for all interviews was established.

All participants first read and reflected on the material in silence. Once the participants had come to an initial understanding of the problem and the provided solutions, they gave an account of which of the provided solution alternatives they saw as most suitable for dealing with the problem. They also described their reasoning behind their choices. The purpose of this phase of the interview was to allow the participants to establish a relationship towards the problem and the solution alternatives. Transcripts from this phase were not included in the analysis, since expressing an understanding of a phenomenon requires that one has already established a relationship to it. In the case of problems as complex as this, establishing a relationship can be expected to take some time.

Phase 2: Problematizations

The interviewer then proceeded to ask critical questions related to the participants' argumentation. This phase of the interview is here called "problematizations." It lasted between 15 and

29 min and served the purpose of rendering the complexity of the problem visible for the participants and to stimulate deeper reflection.

During this phase of the interview, the interviewer used a set of "prompt trails" (Francis 1996 in Collier-Reed et al. 2009, p. 349) to highlight new perspectives (e.g., contrasting values or differing expectations on a reasonable standard of living) and complicated boundary conditions (e.g., economic and ecological limits or unintended social and ecological effects). The prompt trails consisted of follow-up questions that aimed to challenge the participants to develop a more complex understanding of the problem and the provided solution alternatives. This method helped to avoid leading questions or suggestions of "appropriate" perspectives on the problem. The following are examples of questions that were part of the prompt trails and that were frequently asked during this stage of the interview:

- "Do you see any problems with this solution alternative?"
- "Where shall we get the energy for the desalination process from?"
- "If we choose this solution alternative, do you think it [the water] will be enough?"
- "What should we do to make sure that we have water in the short term?"
- "But, [acknowledging that this is a problematic situation], what should we actually do [about the problem]?"

The problematizations often caused the participants to deepen their reflections on the problem and the different solution alternatives. In some cases, the interviewer did not find verbal prompts sufficiently powerful. In these cases, she used photographic images and diagrams to trigger further reflection. For example, she used a picture of people protesting against the construction of desalination plants to highlight social aspects of the desalination approach, and a schematic explanation of the effects of groundwater depletion on water availability to problematize some participants' suggestions to dig deeper wells.

Phase 3: Free Solution

After these problematizations, the interviewer explicitly encouraged the participants to disengage with the provided solution alternatives by asking them to think freely about possible ways of dealing with the problem. The purpose of this phase was to encourage participants to go beyond the suggested solution alternatives and to develop a more holistic approach to the problem.

Phase 4: Role-Playing

Participants were then involved in two role-playing activities to allow them to experience different perspectives on the problem. This phase of the interview was not included in the analysis, since it was not possible to separate participants' reflections about the WSP from their attempts to play the given roles.

Phase 5: Reflection About the Problem

Finally, the interviewer asked two questions related to the participants' meta-understanding of the problem: "How did you experience the problem [of water shortage in Jordan]?" and "Are you often confronted with similar problems in your [engineering] education?" This phase aimed to encourage participants to reflect on the nature of the problem as a WSP in contrast with tame and well-structured problems, which are common in engineering education (Jonassen et al. 2006).

Analysis

The purpose of phenomenographic analysis is to identify qualitatively different *ways of understanding* a chosen phenomenon. In the phenomenographic literature, the terms "ways of understanding", "conceptions", and "ways of experiencing" are commonly used. For our study, however, we use the term "approaches" to highlight the interactive nature of the interviews and the active engagement of the students in addressing the WSP.

To identify different approaches towards a phenomenon, phenomenographic analysis needs to proceed on the collective level rather than through an analysis of the individuals' experiences. Therefore, the analysis requires creating a collective *pool of meaning* (Marton and Booth 1997) from the empirical material. This pool contains a collection of transcript excerpts that constitute the units of meaning in the analysis. Each extract is re-contextualized in the whole of the material, and thus seen as meaningful in relation to the entire set of excerpts in the pool (Åkerlind 2005; Marton and Booth 1997). In our study, both the description of the phenomenon and the scope of the pool of meaning co-evolved with the development of the categories of description and the outcome space. In this section, we describe how we analyzed our empirical material (which was introduced in the "Empirical Material" section).

To begin our analysis, we printed all interview transcripts and cut them into pieces representing units of meaning, i.e., expressions of distinct approaches towards the phenomenon of the study. For the phenomenographic analysis, we needed to focus on similarities and differences between *meanings* and *structures of understanding* that are expressed in relation to the chosen phenomenon (Marton and Pong 2005). We chose to start by focusing on *meanings*, i.e., by interpreting what the expressed content in the excerpts signified in relation to the phenomenon.

We randomly chose three out of ten transcripts for the first round of categorization, adding the remaining transcripts once we had developed an initial understanding of which kinds of similarities and differences in meaning could be critical for the participants' approaches to our phenomenon. We continued to work with the categorization in an iterative manner through a total of nine rounds of analysis. For each round of analysis, we also developed a better understanding of the phenomenon in the study, which in turn required narrowing the pool of meaning from which we constructed our categories. For this purpose, we excluded all excerpts from the first (*reading and reflecting*) and fourth (*role-playing*) phases of the interview. We also excluded those excerpts from the remaining three phases (*problematizations*, *free solution*, and *reflection about the problem*) that were not clearly and directly related to the phenomenon (e.g., statements about secondary problems that arise when solution alternatives are applied to the original problem). We reprinted and recut the entire material twice during the analysis process to ensure that the pool of meaning matched our developing understanding of the phenomenon.

Throughout our analysis, we regularly consulted the phenomenographic literature to identify remaining issues with our categories and outcome space. In particular, three key questions from the literature guided the later stages of our analysis: (1) What structural and referential (i.e., related to meaning) aspects of the phenomenon are experienced in each of the approaches to the WSP? (2) What is the internal structure of each of the approaches? And (3) what kind of variation is present? I.e., what are the most salient differences between the approaches?

In phenomenographic research, it is common to use *dialogic reliability checks* rather than *coder dependability checks* (i.e., checking that different researchers would independently arrive at identical results) to ensure the quality of the results. The latter has been criticized as unreasonable since "the original finding of the categories of description is a form of discovery, and discoveries do not have to be replicable" (Marton 1986, p.35), and since the descriptions developed in phenomenographic research are "dependent on the perspective of the researcher and the empirical and theoretical context of the research" (Svensson 1997, p. 168). In addition to constant discussions among the authors, we therefore chose to elicit critical feedback on the preliminary outcome space at a seminar with the local phenomenography research group.

Finally, our analysis resulted in a set of four distinct *categories of description* (Åkerlind 2005; Marton and Booth 1997) that were organized in the outcome space in an order of increasing complexity of understanding of the phenomenon. Each category is described in terms of the students' understanding of (a) the problem, (b) the solution, and (c) possible ways of addressing the problem. We developed both structural and contextual descriptions and illustrated these descriptions with empirical examples from the pool of meaning ("Results"). At this point, all authors agreed that the outcome space fulfilled the quality criteria of phenomenographic research as described by Marton and Booth 1997: the categories of description that form the outcome space are (1) *valid*, i.e., they adequately represent the approaches found in the empirical material, (2) *parsimonious*, i.e., there are no redundant categories, (3) *mutually exclusive*, i.e., no single data excerpt can be ascribed to two different categories, and (4) *logically related to each other*, i.e., the outcome space is structured in such a way that logical relationships are identified between individual categories. Finally, we confirmed the potential of the results to contribute to educational practice (Collier-Reed and Ingerman 2013) in discussions with educators who practice ESD in the context of engineering education (e.g., as described in Lönngren and Svanström 2015).

The Phenomenon

As mentioned in "Analysis", we found that our understanding of the phenomenon co-evolved with the development of the phenomenographic categories, i.e., it was not possible to fully articulate the phenomenon in advance of the study. The reason for this is that the phenomenon in a phenomenographic study is not necessarily what the researchers decide to research; rather, the phenomenon is what the participants *come to* focus on during the phenomenographic interview.

The phenomenon in the present study is complex; it is more than just the problem as it is described in the problem description. Rather, it is a result of a number of specific artifacts and contexts that influenced the interviews. Most obviously, the phenomenon is influenced by the interview situation, i.e., the provided physical materials (problem description, solution alternatives, maps, and pictures) and the discussion between interviewer and participant (the different phases of the interview) (see "Empirical Material" for a detailed description).

Another obvious influence on the focus of the interviews is the context of the chosen WSP itself. Since the problem is an actual real-world problem, participants enter the interview situation with previous experiences and knowledge that influence how they understand and approach the problem. For example, students may have knowledge about water scarcity problems in other regions of the world, the political situation in Jordan, geographical and ecological conditions in the Jordan Valley, and/or different kinds of solution approaches that are currently used to deal with water scarcity problems.

At a more indirect level, the phenomenon was influenced by the participants' current educational context. All participants were pursuing an engineering degree that was mainly composed of "traditional" courses. These courses were based on lectures, laboratory work, and written exams; textbook problems that were to be solved with the help of mathematical algorithms were the norm. The WSP of water shortage in Jordan provided a striking contrast to the kinds of problems that the students were accustomed to in their engineering degree.

However, at the time of the study, all participants were participating in the abovementioned course on SD. This course was case- and project-based and was focused on the WSP of climate change. Thus, when we conducted the interviews, participants had already had an opportunity to engage with another WSP and experienced the contrasts between solving textbook problems and dealing with a WSP. During the interviews, participants commonly commented about the SD course without explicitly being asked to do so. We interpret these comments as a clear indication that their experiences from the course influenced how they perceived, and engaged with, the WSP of water shortage in Jordan.

Acknowledging the complexity of the phenomenon and its contexts, we will from now on refer to the phenomenon simply as "the WSP of water shortage in Jordan" or "the WSP."

Results

As described in "Analysis", the analysis of the interview transcripts resulted in an outcome space that comprises four distinct approaches to the WSP of water shortage in Jordan. In this section, we describe similarities and differences between these approaches in terms of their meaning and their structural characteristics. In this context, meaning refers to the participants' understanding of what the water scarcity problem is about and what kinds of solutions could be appropriate for dealing with the problem. The structural descriptions are more abstract; they focus on the aspects of the problem and possible solutions that participants focused on during the interviews, and how those aspects are related to each other.

To illustrate the descriptions of the four categories, we provide excerpts from the interview transcripts. In all empirical excerpts, an ellipsis indicates that a part of the original quote is omitted. Underlined text denotes words or syllables that were accentuated by the speaker, and a pair of square brackets surrounds text that we have added to clarify the meaning of quotes that are taken out of the context of the interview. We have omitted filler words, stuttering, and word repetitions unless we deemed them to be relevant for understanding the essence of a quote. We have also bolded some parts of the text to highlight particularly illustrative parts of the quotes in the context of the descriptions of the categories. We first describe each of the four approaches separately (Approach A: Simplify and Avoid, Approach B: Divide and Control, Approach C: Isolate and Succumb, and Approach D: Integrate and Balance). Then, we summarize the similarities and differences between the approaches ("The Outcome Space").

Approach A: Simplify and Avoid

In some parts of the interviews, participants talk about the phenomenon in inarticulate and inconcrete ways. In these instances, participants see water scarcity in Jordan as something that is problematic, but they do not actually provide an explanation of what it is that is seen as problematic. Similarly, an appropriate solution to the problem is described vaguely as something that ensures that everybody has enough water and that there are no negative impacts on anybody. When participants use this approach, they do not see how the problem could be addressed, but they still expect and even require a complete solution. The understanding that is represented in this approach lacks both structure and meaning.

An excerpt from the *problematizations* phase in interview 9 illustrates this approach. The excerpt is preceded by a discussion with the interviewer in which problematic aspects of each of the provided solution alternatives have been uncovered and problematized. Among other things, the possibility was discussed that some people might become ill or die as a result of an acute lack of water if no solution is found. After this discussion, the participant concludes that "**there's gonna be problems whatever [alternative] you choose.**" The interviewer does not want to drop the issue that easily and asks, "But what should they do then?" In response to this question, the participant repeats that "there's gonna be problems whatever you do" and adds, "It's hard to satisfy everybody." The interviewer keeps probing for the participants' underlying understanding by pushing her to take a stance on how to choose *whom* to satisfy if it is not possible to satisfy *everybody*. The participant answers in a vague and evasive way, without referring to possible conflicts of interest. She states that the solution should satisfy "as many [people] as possible" and that it should provide "water both now and in the future":

P9: Eh, I think one should satisfy **as many [people] as possible**.

JL: So we're going to count numbers of lives [saved] then?

P9: Yeah, numbers, numbers of lives (inaudible).

JL: And does it matter when they live?

P9: What do you mean, when they live?

JL: I'm thinking, whether they should dig deeper wells now so that those who live now can get water, or— (inaudible)

P9: or whether they should take a more long-term approach, so that those in the future get [water]. Long-term solutions are usually good, aren't they? The best would be if they could do both long-term and short-term things, which don't inhibit each other, at the same time. So that they [the people in Jordan] can get water both now and in the future.

The interviewer keeps pushing the participant to elaborate on her understanding of the phenomenon by discussing possible negative consequences of different solution approaches. After this discussion, the participant concludes in the *free solution* phase: "If one could find a solution that satisfies everybody and that doesn't cause any problems—that would have been good. But it's not so easy to find such solutions." The interviewer continues by asking about how to deal with the disadvantages of these imperfect solutions:

JL: If different solutions do cause different problems, how should one choose which of these problems are [considered] worse than others?

P9: Well, those—; you'd have to check—; I mean, **if the negative consequences exceed the positive [consequences], then it's not a good alternative**. So it's kind of, well, you choose the least of two evils.

JL: How would you evaluate what is the least evil?

P9: Ehm, well, if it affects a lot of people negatively, then it's not good. The best thing would be if it affects as few, as few people negatively as possible.

In essence, the participant is saying that *if something is bad then it is bad, and if it is good, then it is good*. By using empty words, she avoids judging the relative acceptability of different negative consequences that may be the result of different solution approaches. When participants use this approach, they *avoid* dealing with normative aspects of the WSP by *simplifying* the problem to "something problematic" that should be eliminated with some kind of solution that attends to everything that is bad. When participants use this approach, they do not clearly articulate what they mean when they talk about the problem and/or possible solutions.

Approach B: Divide and Control

In a large number of excerpts, participants take an instrumental approach to the given problem. They describe the problem as a lack of water that needs to be addressed by providing *more* water or by redistributing available water. Optimization and regulation efforts are expected to make water usage more effective. Thus, water needs are to be reduced, and water supplies are to be matched to the remaining water needs.

For example, in the *problematizations* phase of interview 8, the participant suggests the construction of desalination plants as a solution to the problem of water shortage in Jordan. The interviewer problematizes this solution approach from different perspectives, such as high costs and energy needs for desalination processes. She also shows a picture of people protesting against desalination, their argument being that replacing the (excessive) use of groundwater with desalination would lead to higher water prices and unfair water distribution practices. The aim of this intervention is to highlight non-technological aspects of the situation, and thus to challenge the participant to view the problem in a less instrumental manner. However, the participant responds by once again exclusively focusing on the availability of water and pointing to the impossibility of continuing to overexploit groundwater resources indefinitely. While this reflection is correct, it also reflects a reductionistic view of the problem as only defined by a quantitative lack of water, and a view of technological solutions as isolated from their social and political contexts. The interviewer continues to probe for the participant's understanding of the phenomenon:

JL: What do you see as the difference [between the negative impacts caused by groundwater overexploitation and desalination respectively]?

P8: Mostly, I think, because [if we use desalination] we will at least have water. And then there will be other problems, like how we're going to get the energy [for the desalination processes]. But **that's kind of a problem that people work with somewhere else**. If we keep digging [deeper wells], and the groundwater is depleted, then we'll still be in the same situation that we don't have any water. (…) So I think it's mostly that **[with desalination] (…) they'll at least have water. And then [somebody else] can do something about the other problems.**

The above quote clearly illustrates the reductionistic focus that underlies this approach. Participant 8 views the problem as something that needs to be carefully *controlled* and ultimately overcome with the help of smart solutions. He assumes the problem to be *divisible* into several independent parts that can be solved individually and independently, by different people in different places. Consequently, even the solution is expected to be a cluster of independent parts. This was also expressed by participant 3 in the *free solution* phase of the interview: "So I would suggest **not to look for one big solution, but many small [ones], which solve the problem in its entirety**."

The suggested solution approaches in this category are instrumental. Technological approaches, such as desalination or transportation of water, are generally preferred, but some participants also suggest non-technical approaches, such as information campaigns to change peoples' "disrespectful" (participant 3, *free solution*) attitudes and behaviors in the face of acute water scarcity. Such campaigns are expected to lead to more restrictive use of water resources.

A further example of instrumental approaches to the situation is found in the *problematizations* phase of the interview with participant 6, who suggests the use of solution alternative 6, which aims to fairly distribute the available, renewable water resources:

JL: If we choose [solution] alternative six, do you think it [the water] will be enough?

P6, without hesitation: No.

JL: What will happen with those who are not getting enough?

P6, without hesitation: They will die.

JL: And that-

P6: Wrong answer, or what? I mean, if they don't get enough water, they'll die. That's terrible (…), but it **becomes statistics**.

By reducing the problem to statistical metrics, participant 6 avoids engaging with the complexity and ambiguity of the situation. Political and social aspects are ignored, and the solution is found through rigorous, mathematical calculations.

When participants use a *divide and control* approach, they make an effort to identify multiple aspects of the problem and of possible solutions. They also try to relate individual aspects of the problem to individual aspects of the solution—and yet they view the problem as composed of isolated parts that are not related to each other.

Finally, a *divide and control* approach to the WSP is goal-directed. When participants use this approach, they express a general sense of responsibility for finding a solution. This should be contrasted with the non-committal *simplify and avoid* approach and the lack of proactivity in the *isolate and succumb* approach (as described in the next section).

Approach C: Isolate and Succumb

In some excerpts, participants express a more complex understanding of the problem while still assuming that it should be possible to find a "correct" solution. Instead of defining the problem merely as a lack of water as in the *divide and control* approach, it is viewed more broadly as a low quality of life that is the result of water scarcity. It is considered a "global problem" in which "there are a lot of human lives to consider [and] people might die if you make the wrong decision" (participant 9, *reflection about the problem*). A hypothetical solution to this problem is viewed as providing enough water for all people in Jordan without causing serious negative side effects to ecosystems, international relations, or the economy. Ultimately, such a solution is expected to raise the quality of life of the people in Jordan without harming anybody. In the face of realizing that it is impossible to completely avoid negative effects, and that "**there isn't any perfect solution (…) that could be good for everybody**" (participant 9, *reflection about the problem*), some participants attempt to identify quantitative metrics for success, which would be in line with an instrumental approach to addressing the problem. In the *problematizations* phase of the interview, participant 4 reflects on the numerous dilemmas that arise as one tries to solve the problem of water shortage in Jordan. She tries to identify criteria for weighing different solution approaches against each other:

> P4: I guess what we want to strive for is the **highest level of happiness for the largest number of people** in some way.
>
> JL: How would you measure that?
>
> P4: Well, in **the number of dead people**, if we are to look at it in a blatant way. But on the other hand, if that makes [the situation] worse for a large part of the population, that might not be—. No, **it's hard to measure happiness**. Oh, I'm kind of **stuck** right now. There's so much one doesn't think about.

Besides realizing the impossibility of quantitatively evaluating the appropriateness of different solution approaches, participants who use this approach also realize the systemic nature of the problem. This is illustrated by a quote from participant 10. In the *free solution* phase of the interview, she reflects on the reasons for why it may be so difficult to find a perfect solution to the problem. She notes that water resources are limited and need to be shared within the system and that this in turn creates ethical dilemmas that cannot be solved with instrumental approaches such as reducing water consumption:

> P10: There is no obvious solution. (…) There is no inexhaustible source of water where you can just go and fetch water. Whatever you [do], **you always have to take water from somewhere and to somewhere else**. And in Jordan's case, they need more water than they can take from the area where they live, really. So it'll be problematic where this extra water should come from. Whether it's best to take [water] from places where there is more water, but [from where] you have to transport it over long distances, and which would cost a lot of money, or whether they should take it from places that actually don't have so much water [which then will be] completely depleted. That's a big problem. **But the best would maybe be if they could reduce their water consumption without causing anything to suffer because of that. But that's also wishful thinking.**

Participant 10 continues to reflect on the importance of water for the Jordan people, considering drinking water and hygiene. She also reflects on the effects of water shortage on industry and thus on the economic situation of the state: she mentions that if the industry suffers, the state will have less money. With less money, it is not possible to supply as much water for the people, thus causing a "vicious cycle." In the end, the participant concludes once again that nothing can be done.

This focus on possible side effects of different solution alternatives, along with an awareness of uncertainties created by the socio-economic context of the problem, creates an insurmountable tension between the ways in which participants understand the problem and the solution: while the problem is understood as a system of interconnected parts, the solution is thought of as a cluster of independent, *isolatable* parts. Participants perceive this tension as unsolvable, and they *succumb* rather than proactively attempting to do something about the problem.

Approach D: Integrate and Balance

Finally, some excerpts from the interviews indicate an understanding of the WSP as an integrated whole. In this approach, the problem is perceived as being about much more than just increasing the amount of available water. It consists of technical as well as ecological and social challenges that are interconnected in complex ways. These connections are seen as producing powerful conflicts of interest related to water scarcity. Thus, the problem is not seen as something that can be solved, but as a problematic situation that should be managed with a holistic focus.

An appropriate way of managing the problem is understood as finding a way to *balance* different stakeholders' needs, while at the same time raising the average quality of life of all stakeholders. *Integrative* approaches are suggested that address the problem at a deeper level than would have been possible with isolated solution approaches. Participant 4, for example, suggests using technological innovation to increase the amount of available water, while at the same time ensuring that the distribution of this water is politically controlled to accommodate different stakeholders' needs. When she is prompted to think beyond the provided solution alternatives in the *free solution* phase, participant 4 is first tempted to give up in the face of the overwhelming complexity of the situation. She ties the problem to both global warming and an increasing population in the country and does not seem to be able to see a way of addressing this complex problem. Eventually, however, she suggests an integrative combination of several solution alternatives:

> P4: I think I would have wanted to **combine** some of these [solution approaches], maybe. I mean, an allocation plan, definitely; I would have wanted to do that in order to be able to be sustainable in the long run, somehow; but combined with desalination plants in that case. Because it's kind of the same principle there [as mentioned before], **a quick fix with a plan for long-term sustainability incorporated**. That way I think you'd use technology in the right way; because then there's still an ambition to change the attitude towards the problem.

The interviewer's question about why participant 4 wants to combine different solution approaches spurs the participant to reflect on how to achieve fair distribution of the water resources. The participant wants to avoid a situation where only the economically well-off can afford enough water to live a decent life. Once again, she addresses this problem through an integration of different approaches:

> P4: Maybe one could combine, nationalize this [the water obtained from desalination plants] as well; so that it has to be **included in the allocation plan**; so that it's not a free-standing private sector that distributes water to those who pay the most.

Another example for this category is found in the interview with participant 8 in the *reflection about the problem* phase. The participant reflects on the similarities and differences between the problem that is being discussed in the interview on one hand, and problems encountered in traditional engineering education on the other hand. Problems encountered in the participant's educational program are described as problems that are carefully designed for educational purposes. The reason for the problems' existence is that students are supposed to learn something specific:

> P8: You're supposed to learn how physics works or you're supposed to learn how math works, or you're supposed to learn everything you need to be able to build all those things when you're an engineer.

The participant further describes these problems as easily solved with "some kind of calculation" and contrasts them with the problem of water shortage in Jordan; the latter serves as an example of the kinds of problems that the participant expects to encounter in her future professional life:

P8: But that's not really how it is, it doesn't work that way. Because here you might solve a problem in one country, and then you come to the next [country]. Or you might solve a problem in one country, but that might not turn out so well, so you have to continue. And that is what—, that's how it's going to be in real life. It's not like I'm just going to calculate this formula and then we have everything, then you'll all get water. (…) There is so much else. Even if I physically could have, like, this is how you build a sewage treatment plant or a desalination plant or so, but what then? It's not enough to be able to build it, it's not enough to be able to build it in Sweden, or draw a blueprint for what it's supposed to look like with exact dimensions. That is the least of the problems. It might take a lot of time for the person who is doing it, but it's definitely not the most difficult [part of the process].

The above quote illustrates the integrative nature of this approach and an understanding that it is not possible to divide the problem into parts that can be addressed individually. For example, participant 8 points out that it is not possible to solve the problem in isolated countries nor to merely focus on the technical design of a desalination plant, since such isolated "solutions" may indeed cause new problems. She also stresses the importance of considering the local context of the problem.

This approach is similar to the *isolate and succumb* approach with regard to a realization that "it's not always possible to solve such a situation" (participant 2, *problematizations* phase). However, when participants use an *integrate and balance* approach, they realize that moral aspects of the problem, and of approaches to addressing it, cannot be avoided. They also realize that somebody has to take responsibility for managing the conflicts of interest that are the result of different stakeholders' needs:

P2: "If you are in an unsustainable situation, then it will of course affect you in one way or another, [but you still have to] try and **make the best of the situation.**"

With this approach, a solution is not understood as something that solves and thus eliminates the problem. Rather, a solution is experienced as consisting of a number of integrated problem management strategies (i.e., the parts of the solution) that interact with different aspects of the problem. In other words, connections among and between parts of the problem and parts of the solution are discerned.

The Outcome Space

In the *simplify and avoid* approach (A), problem and solution are experienced as diffuse entities that are related in a rather unclear way. In the *divide and control* approach (B), parts (aspects) of problem and solution are discerned and each problem part is matched to one solution part. The solution parts are in turn recombined to form a compound solution. As relationships between the parts of the problem are discerned in the *isolate and succumb* approach (C), direct pairing of problem parts and solution parts is experienced as impossible and relations between these parts are dissolved. This in turn leads to the understanding that it is impossible to solve the problem. Finally, in the *integrate and balance* approach (D), relationships between problem parts and solution parts are discerned and the problem is perceived as something to be managed rather than solved.

These structural descriptions are summarized in Fig. 1. They provide a powerful image of the similarities and differences between the four approaches to the WSP. In the figure, red items (dark grey in the printed version of this article) illustrate either the problem (approaches A and B) or parts of the problem (approaches B, C, and D). Correspondingly, green items (light grey in the printed version) illustrate either the solution (approaches A and B) or parts of the solution (approaches B, C, and D). Double-headed arrows are used to indicate that participants do not necessarily approach the WSP in a linear way by first attempting to define the problem then finding a suitable way of addressing it and finally defining the solution. Table 1 complements Fig. 1 by providing a textual summary of the descriptions of the structural similarities and differences as well as how the specific problem (water shortage in Jordan) is interpreted.

Discussion of Approaches

When participants used a *simplify and avoid* approach during the interviews, their reflections on the WSP were non-committal, evasive, and inconcrete. We conclude that such an approach leads to an avoidance of the problem rather than constructive engagement. This lack of engagement is combined with a lack of understanding of the nature of the problem, indicated by the lack of structure and meaning in this approach. We suggest that a *simplify and avoid* approach is inappropriate for addressing WSPs if the goal is to constructively work towards SD.

A *divide and control* approach towards the WSP involves dividing the problem into parts that can be addressed in isolation from each other. In other words, when participants used this approach, they assumed that the WSP could be reduced to a collection of tame, well-structured problems. But wicked problems cannot be reduced to tame problems (Conklin 2005; Rittel and Webber 1973; Roberts 2000; Spiro et al. 1996); wicked problems have to be dealt with in

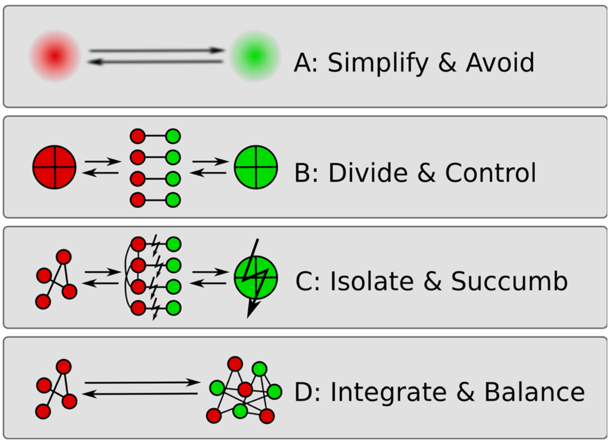

Fig. 1 Illustration of structural similarities and differences between the four distinct approaches to addressing the WSP

Table 1 Summary of contextual and structural descriptions of the categories

		Understanding of the problem	Understanding of the solution	Understanding of ways to address the problem
A	Meaning	Something problematic	Something good: enough water for everybody without any negative consequences	Not sure how to solve the problem
	Structure	Diffuse entity	Diffuse entity	Simplify and avoid
B	Meaning	Not enough water	Optimization of the amount of available water relative to the amount needed through, e.g., desalination, water transport, more effective water usage, or information	Provide more water
	Structure	Cluster of several independent parts	Cluster of several independent parts	Divide and control
C	Meaning	Low quality of life due to water scarcity	Not possible to provide enough water for everybody in Jordan without causing serious negative side effects to, e.g., ecosystems, international relations, Jordan's economy, or the quality of life of the Jordanian people	Cannot do anything
	Structure	System of several inter-connected parts	Should be a cluster of several independent parts, but does not exist	Isolate and succumb
D	Meaning	Conflicts of interest related to water scarcity	A balance between different stakeholders' needs while raising the average quality of life related to water shortage through, e.g., politically controlled distribution of technologically increased production of water based on an assessment of stakeholders' needs and rights	Manage water shortage
	Structure	System of several inter-connected parts	Integrated system of interconnected parts of both problem and solution	Integrate and balance

fundamentally different ways, by applying different skills and assumptions than what is needed in the process of solving well-structured problems (Kitchener 1983; Schraw et al. 1995). For example, solving well-structured problems has been suggested to require extensive cognitive resources such as logical thinking, an ability to memorize, and access to effective problem-solving strategies (Simon and Newell 1971). Addressing ill-structured problems, on the other hand, has been suggested to require recognizing the systemic and normative dimensions of such problems (Kitchener 1983; King and Kitchener 1994). A *divide and control* approach utilizes the cognitive resources that have been associated with well-structured problem-solving, but it neglects the systemic and normative nature of WSPs. Thus, while such an approach may be useful for solving well-structured and tame problems, it is not optimal for addressing WSPs.

Education is inherently normative since it always aims to achieve some kind of learning. Therefore, educational researchers need to explicitly state and problematize their philosophical assumptions about what education is (Jickling 2009). In the study underlying this paper, we have used a phenomenographic research approach. In such an approach, the aim of education is seen as supporting students to develop more complex ways of understanding the world and their relationships to it. At the same time, our research is based in the field of ESD, where "the most critical check for the adequacy of the [ESD] competencies is the degree to which graduates can improve sustainability in the world" (Wiek et al. 2011, p. 214), i.e., the aim of education is seen as contributing to SD. The *isolate and succumb* approach that was identified in our phenomenographic study clearly illustrates the tension between the two normative contexts of phenomenography and ESD. On the one hand, an *isolate and succumb* approach suggests a more complex understanding of the WSP than a *divide and control* approach because it entails an appreciation of the complexity and the systemic nature of the problem. On the other hand, an *isolate and succumb* approach does not contribute to SD because students become paralyzed by the overwhelming complexity of the problem and the impossibility of identifying an optimal solution. Thus, despite its instrumental nature, a *divide and control* approach may sometimes be more appropriate for dealing with WSPs than the more complex *isolate and succumb* approach.

When participants in our study used an *integrate and balance* approach towards the given WSP, they recognized the interconnectedness of problem and solution. They understood that it is impossible to tame the problem by addressing parts of the problem in isolation. They understood that WSPs cannot be solved once and for all but need to be addressed in an iterative manner. Among the four approaches identified in our study, the *integrate and balance* approach is most in line with the characteristics of WSPs as described by Seager et al. (2012, see "Introduction"). In addition, the approach is based on the most complex understanding of the problem, while also enabling students to see constructive ways of dealing with the problem and thus to "improve sustainability in the world" (Wiek et al. 2011, p. 214). Therefore, we suggest that an *integrate and balance* approach is most appropriate for addressing WSPs, from the point of view of research on human problem-solving, phenomenographic research, *and* ESD.

Methodological Considerations

Phenomenography is not a positivist research approach and does not aim to reveal objective "truth" (Collier-Reed et al. 2009). Consequently, we do not argue that we have found the absolute truth about engineering students' approaches to WSPs. Rather, we stress the usefulness of our description for educational practice. To increase the accessibility of the results for educational practice, we will discuss implications for teaching and learning in the next section. First, we want to discuss a number of methodological considerations that the reader should keep in mind when attempting to transfer the results to other contexts.

General Limitations to Phenomenographic Research

Obviously, no research approach can address all kinds of questions; phenomenography is no exception. For example, since phenomenographic analysis is performed on a collective level, and since the particular way in which a phenomenon is experienced is context-dependent, it is not possible to draw conclusions about individual participants' general (i.e., context-independent) understanding of the phenomenon. This also means that it is not possible to interpret the categories of description (in our study, approaches A through D) as levels of learning that individual students could be claimed to have reached or failed to reach at the time of the interview.

Another implication of the collective analysis is that phenomenography is blind to process. For example, information about whether an approach was used at the beginning or near the end of an interview is lost when individual excerpts are combined in the pool of meaning. Consequently, phenomenography does not provide insight into students' development *during* the interview.

Specific Limitations in the Present Study

As discussed in "The Phenomenon", the phenomenon in our study must be seen as directly related to the interview context. Therefore, it was inevitable that the interview design influenced the kinds of results that we could obtain in our study. On the most general level, the interview design influenced the overall structure of the phenomenon. The WSP was introduced through a problem description and a set of solution alternatives. Thus, the problem, possible ways of addressing the problem, and potential solutions were foregrounded in the discussion (Fig. 2). It is therefore not surprising that these three elements emerged as salient structural aspects of the participants' approaches to the WSP.

Further, the frequency with which the four approaches occurred in the analyzed material differed significantly. There were very few instances in which participants used a *simplify and avoid* approach, while a *divide and control* approach was used frequently. Due to the qualitative nature of this study, these frequencies should not be seen as evidence that one approach is more common than the other (although it is our anecdotal experience from engineering education practice that engineering students are trained to favor a *divide and control* approach as a default approach to any problem they encounter). But the imbalance between the frequencies of occurrence entails that our description of the *divide and control* approach is much more stable and well-developed than that of the *simplify and avoid* approach. The latter should therefore be seen as preliminary.

Finally, the interview design influenced the kinds of approaches to the WSP that were possible to adopt during the interview. For example, the fact that interview participants were chosen from students who were enrolled in a course during which they were working with another WSP may have contributed to the low number of instances in which participants used a *simplify and avoid* approach during the interviews, and thus the relative instability of the description of this category. Further, using a set of predefined solution alternatives as a basis for our interviews may have favored a *divide and control* approach to the problem at the beginning of the interviews and may therefore explain why this approach was commonly used by the participants. During the *problematizations* phase of the interview, the interviewer constantly challenged the participants' reflections about the problem by specifically highlighting problematic aspects with whatever solutions the participants suggested. This procedure may have favored an *isolate and succumb* approach. In fact, the interviewer's own

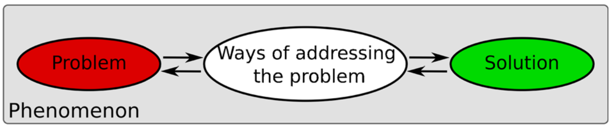

Fig. 2 The participants talk about the phenomenon in terms of their understanding of the problem, ways of addressing the problem, and the nature of potential solutions

understanding of WSPs was mostly in line with an *isolate and succumb* approach prior to this study. Therefore, it was surprising to find that participants transcended the limitations introduced by the interviewer (i.e., favoring an *isolate and succumb* approach) and adopted an *integrate and balance* approach to address the WSP during some parts of the interviews. This unexpected result also illustrates that the interview design merely *influenced the nature of the results* but that it did not *determine the actual results* of the study.

Implications for Phenomenographic Research

Phenomenographic research shares a common focus on pedagogical questions, as well as common philosophical and theoretical assumptions. Therefore, individual studies in this tradition contribute to a relatively strong phenomenographic "research program" (Svensson 1997, p. 167). This allows researchers (to some extent) to transcend the specific contexts of individual studies and explore the generality of phenomenographic results across varying contexts (Collier-Reed and Ingerman 2013).

One important question for phenomenographic research is to clarify what it means to "learn" (e.g., Marton and Booth 1997). Marton (2015) describes learning as developing "more powerful" ways of understanding:

> In pedagogical contexts, you must assume that one way of seeing a particular situation is more powerful in relation to a certain aim than another. Why would you otherwise try to help others to develop a particular way of seeing and particular ways of acting? (p. 84)

A more powerful understanding in this context is an understanding that opens up possibilities to act, e.g., to address a particular kind of problem in meaningful ways. Marton (ibid.) equates a "more powerful" understanding of a phenomenon with a more "complex" understanding. This description of learning builds on the assumption that a more complex understanding of a phenomenon (i.e., perceiving more aspects of it and more relationships between these aspects) automatically opens up more powerful ways of acting than a less complex understanding.

The present study challenges this assumption, at least in the context of ESD. In ESD, the purpose of education is not only to develop more complex ways of understanding but also to ultimately contribute to SD. As discussed in "Discussion of Approaches", a more complex understanding of a WSP (approach C) can be less powerful for the aim of addressing the problem than a less complex understanding (approach B). This result suggests that phenomenographic descriptions of learning could be further developed.

Implications for Teaching and Learning

One of the aims of this paper is to identify relevant aspects of learning related to WSPs in the context of science and engineering ESD. In this section, we relate the results from the phenomenographic study to the literature on human problem-solving, SD, and ESD. On this basis, we suggest that the following learning objectives can guide the design of science and engineering educational activities that aim to prepare students to address WSPs in their future professional lives: (1) learning to use a fully integrative approach when addressing WSPs, (2) learning to distinguish WSPs from tame and well-structured problems, and (3) learning to consider the normative and contested nature of SD and its relevance for WSPs.

Learning to Use a Fully Integrative Approach when Addressing Wicked Sustainability Problems

In "Discussion of Approaches", we argued that *integrate and balance* is the most appropriate approach for addressing WSPs, in light of research on human problem-solving, phenomenographic research, and ESD.

Most participants in our study alternated between different approaches towards the given WSP during the interview. Participants who used an *integrate and balance* approach at some point during the interview also used a *divide and control* and/or *isolate and succumb* approach at other instances in their interviews. In other words, these participants were clearly able to adopt an *integrate and balance* approach, but they only did so under certain conditions that were not present throughout the entire interview. This is a common finding in phenomenographic research, and it highlights the influence of context on students' ways of understanding educational phenomena (cf. Marton and Pong 2005). Because of this finding, we suggest that science and engineering education needs to provide as many opportunities as possible for students to practice using integrative approaches to WSPs. Rather than (only) requiring students to solve tame problems, educators should engage students in discussions about ill-structured, wicked problems. This is in line with findings by Schraw et al. (1995) who concluded that different cognitive processes are involved in addressing well-structured and ill-structured problems. Only through extensive practice can students develop their ability to use integrative approaches.

However, we recognize that scaffolding an integrative understanding of WSPs in the context of formal education is a challenging task for educators. The possibility of understanding the problem as complex while still expecting a simple solution (as in the *isolate and succumb* approach) indicates how difficult it can be for students to adopt a fully integrative approach when addressing a WSP. We suggest that educators should pay particular attention to guiding students through emotionally challenging experiences with WSPs. Participants in our study expressed a high degree of frustration when they attempted to address the problem with an *isolate and succumb* approach (e.g., participant 4 expressing a feeling of being "stuck"). We suggest that explicitly discussing the differences between the four approaches identified in this study may help students understand and overcome some of this frustration.

Finally, using an *integrate and balance* approach to address a WSP requires a certain level of knowledge about the particular problem and its context (cf. Jonassen (2000) about the importance of domain knowledge in problem-solving). In our study, the interviewer provided information about the problem in the form of a problem description, a set of solution alternatives, critical questions, and answers to participants' factual questions. Since every WSP is unique, the knowledge required for addressing a specific WSP is contextual rather than generic. We suggest that students need to learn to identify what knowledge they will need to address a particular problem; thus, not only will they be able to address the WSPs that they have dealt with in class but they will also be able to transfer their learning to other situations.

Learning to Distinguish Wicked Sustainability Problems from Tame and Well-Structured Problems

WSPs require different approaches to tame and well-structured problems (Kitchener 1983; Schraw et al. 1995). Being able to recognize different kinds of problems is a necessary condition for consciously choosing an appropriate approach for addressing a problem. The prevalence of well-structured problems in the context of science education at all levels, and perhaps even more so in engineering education (Jonassen et al. 2006), suggests that students may be trained to uncritically expect such problems. Our own anecdotal experiences from engineering education practice support this suggestion.

We suggest that students' ability to distinguish WSPs from tame and well-structured problems can be strengthened and that this requires providing students with opportunities to discuss the characteristics of WSPs in contrast with those of tame and well-structured problems. In addition, students could benefit from training to adopt a critical and reflexive attitude towards their approaches to addressing different kinds of problems.

Learning to Consider the Normative and Contested Nature of Sustainable Development and Its Relevance for Wicked Sustainability Problems

WSPs are not only "wicked", they also contain the explicitly normative dimension of SD as a desirable goal. This means that any approach to WSPs needs to be in accordance with the principles of SD. However, SD is an ambiguous and contested concept (Connelly 2007; Kates et al. 2005). The ESD literature contains descriptions of students' rudimentary understanding of the ambiguity of the SD concept; we note a striking similarity between these descriptions and our description of the *simplify and avoid* approach to water shortage in Jordan. For example, Carew and Mitchell (2002) suggest that engineering students tend to make "broad sweeping, non-specific statements about taking action or protecting the environment" (p. 357) if they do not have an understanding of what SD means. They describe SD in vague and inconcrete ways: SD is something good that should be achieved or done. Kagawa (2007) suggests that students may see SD as a "good thing" even if they do not understand "either the contested and multi-faceted nature of sustainability nor the holistic nature of the concept as proposed by proponents" (p. 332). When participants in our study used a *simplify and avoid* approach to address the WSP of water shortage in Jordan, their reflections were equally inconcrete. For example, they described potential solutions vaguely, as something good, a situation where everybody is satisfied forever. Thus, a lack of understanding of the nature of SD may be one reason behind students' use of a *simplify and avoid* approach when addressing WSPs.

A failure to recognize the normative and contested nature of SD may also lead to an *isolate and succumb* approach. The wide, and often uncritical, acceptance of the SD concept as a guiding principle (for all areas of life and all parts of society) may cloud the need to clarify interests and values and to define what it actually is one is striving for. Thus, paradoxically, engineering students' high level of motivation to contribute to social and environmental causes (Haase 2013) may render them more susceptible to adopt an unproductive *isolate and succumb* approach: if students strive to contribute to SD without a clear understanding of the ambiguity of the concept, they may expect an "absolutely correct solution" (cf. Kitchener 1983, p. 226) to a WSP. Failing to find such a solution, they may give up trying.

Finally, it is our experience that engineering students have a strong desire to provide technically advanced solutions to any kind of problem that they encounter. This preference for technical solutions may compromise students' ability to address a WSP in socially, environmentally, culturally, and politically acceptable ways. An awareness of the normative context of SD includes an understanding of the many perspectives that need to be taken into account in an *integrate and balance* approach to WSPs (Lönngren et al. (2016) for a discussion of perspectives in ESD).

We suggest that educators should engage students in discussions about the broad understandings of SD and encourage them to develop their own view of what SD means to them personally as well as professionally in the contexts that they may encounter in their specialization. We expect that such a nuanced understanding of the normative and contested nature of SD will support students in using *integrate and balance* approaches to WSPs.

Further Research

As discussed in "Implications for Phenomenographic Research", generality in phenomenographic research can (to some extent) be explored empirically across several phenomenographic studies (Svensson 1997). We suggest that the following phenomenographic studies could facilitate transfer of the results presented in this paper to other contexts: analyses of (1) engineering students' approaches to other WSPs; (2) non-engineering (e.g., science) students' approaches to WSPs; (3) students' approaches to well-structured problems; and (4) students' approaches to WSPs with different interview designs, in group discussions about WSPs, and/or in authentic learning situations.

Since phenomenographic research does not provide a basis for analyzing learning processes, it would be valuable to complement our study with an analysis of how students develop their ability to use an *integrate and balance* approach to WSPs. How do students learn to address WSPs and what does it mean to be able to adopt an integrative approach? To answer this question, we suggest that it is also necessary to study under what conditions students use integrative approaches to address WSPs. Specific questions that should be addressed are, for example: What characteristics of educational situations support the use of integrative approaches? What kinds of specific domain knowledge do students need for different kinds of WSPs, e.g., science and engineering knowledge, knowledge about political systems, knowledge about geography, etc.? And are there any kinds of domain-general knowledge, skills, or attitudes that help students develop integrative approaches to WSPs that they may encounter in their future professional lives? In particular, studying students' development in authentic learning situations could ensure relevance and applicability for educational practice.

We hope that this and other future research will shed light on how science and engineering education can better prepare students for addressing WSPs in integrative and productive ways.

Conclusions

On the basis of a phenomenographic study on engineering students' approaches to a WSP, we have described four qualitatively different approaches to the problem of water shortage in Jordan: (A) *simplify and avoid*, (B) *divide and control*, (C) *isolate and succumb*, and (D) *integrate and balance*. We have evaluated these approaches with respect to what may be considered appropriate in the normative context of ESD and concluded that a fully integrative approach (approach D) is most appropriate in this context. We have further identified approaches A and C as the least appropriate approaches for achieving SD, despite the relatively complex understanding of the problem that underlies approach C. This mismatch between the educational goal of increasing the complexity of students' understanding on one hand, and the productiveness of an understanding for achieving SD on the other hand, highlights the importance of clarifying normative assumptions in science and engineering education. To some extent, this mismatch also challenges one of the basic assumptions of phenomenographic research: the assumption that the goal of education is always to help students develop more complex ways of understanding educational phenomena.

Drawing on our description of approaches A through D, we have further identified three aspects of learning related to WSPs, and we have provided recommendations for supporting such learning in science and engineering education. First, we have suggested that learning to use a fully integrative approach when addressing WSPs can be supported by scaffolding students through emotionally difficult experiences with WSPs, by explicitly discussing the differences between the four approaches identified in this study, and by training students to identify what knowledge they need in order to address specific WSPs. Second, we have pointed out the importance of students learning to distinguish WSPs from tame and well-structured problems. We have argued that such learning requires providing students with opportunities to discuss the characteristics of WSPs in contrast with other kinds of problems and training them to adopt a critical and reflexive attitude towards their approaches to addressing different kinds of problems. Third, we have proposed that students need to learn to consider the normative and contested nature of SD and its relevance for WSPs. For this purpose, we have suggested that educators should engage students in discussions about the broad variety of understandings about SD that exists in society and encourage them to develop their personal view of what SD means to them.

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Appendix 1: Problem Description

Jordan is a country in the Middle East that is classified as an "upper middle-income" country by the World Bank. The country has a stable and growing economy, and a number of free trade agreements with other countries all over the world. The developmental standard and the standard of living are high in a global comparison.

But Jordan's climate is dry, especially in the eastern parts of the country. It is unclear whether there will be enough water to support the 6.5 billion inhabitants in the future. Jordan is one of the world's most vulnerable countries in terms of water shortage.

In 2007, the annual water demand was estimated to be 1505 billion cubic meters. This number is expected to further increase and reach 1635 billion cubic meters in 2020. Today's water resources are estimated to amount to 665 billion cubic meters annually. The difference between assets and demands is currently bridged by overexploiting groundwater resources.

Apart from these natural limits, water supply is also restricted by an agreement among the countries that surround the Jordan Valley: Jordan, Israel, Lebanon, and Syria. According to the "Jordan Unified Water Plan", which was signed in 1955, these countries have specific water allocations that they are allowed to withdraw from the streams in the valley.

Solution Alternatives

1. Dig deeper wells in order to get hold of more groundwater.
2. Build desalination plants in order to make use of the water in the Dead Sea.
3. Import water from, e.g., Sweden and Norway who have a surplus.
4. Breach the Johnston agreement by withdrawing more water from the Jordan Valley.
5. Liberalize the water market to achieve a water price that reflects the balance between assets and demands.
6. Nationalize the water market and limit the water usage to an entirely renewable amount (665 million m^3) through an equitable distribution plan.

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