Engineering Students' Conceptualizations of Sustainability

Citation for the original published paper (version of record):
Kabo, J., Nieusma, D., Baillie, C. (2020). Engineering Students' Conceptualizations of Sustainability. Proceedings - Frontiers in Education Conference, FIE, 2020-October.
http://dx.doi.org/10.1109/FIE44824.2020.9274122

(article starts on next page)

Engineering Students' Conceptualizations of Sustainability

Jens Kabo
Communication and Learning in Science
Chalmers University of Technology
Gothenburg, Sweden
jens.kabo@chalmers.se

Dean Nieusma
Engineering, Design, and Society Division
Colorado School of Mines
Golden, CO, USA
nieusma@mines.edu

Caroline Baillie
Shiley Marcos School of Engineering
University of San Diego
San Diego, CA, USA
cbaillie@sandiego.edu

***Abstract*— While the integration of a sustainability lens within engineering education is increasingly urgent, the appropriate conceptual underpinnings for such integration remain under debate. The study presented follows an investigation of one small group of students in a course that addressed sustainability in the context of technology design. Our goal was to explore the range of student conceptions of sustainability. Using a phenomenographic approach, we observed and interviewed students in the course and identified seven categories of sustainability. These findings can be used as parts of a tool for scaffolding students' learning experiences.**

Keywords*— *engineering, sustainability, phenomenography, students

I. Introduction

While the integration of a sustainability lens within engineering education is increasingly urgent, the appropriate conceptual underpinnings for such integration remain unclear. We argue that an important component of such integration is to explore the diversity of ways in which sustainability is understood by students in order to design more relevant and impactful learning experiences in engineering educational contexts. The study presented follows an investigation of one small group of technical students in a course that addressed sustainability in the context of technology design, whose aim was expanding students' appreciation for the concept's complexity. Our goal was not to evaluate the outcomes of the course *per se*, but rather to ask: What range of conceptions is held by the students at a collective level? And can this inform sustainability's integration into engineering education?

In order to achieve our goal, we employed the qualitative research approach, phenomenography, which focuses on the *different ways* students talked about "sustainability", especially in the context technology design. Using this approach, we identified seven qualitatively distinct categories, ranging from "Sustainability as other people's unrealistic ideals" to "Sustainability as integrated problem solving". The categories were organized and related to one another according to three dimensions of variation, which were themselves emergent from the data. As elaborated below, the dimensions of variation overlap with key themes of the course, most notably including the recognition that multiple dimensions of sustainability often exist in tension with one another, sometimes fundamentally so.

While several studies exist that explore sustainability, including some that focus on students' conceptions and others using phenomenography as research methodology, few studies lie at the intersection of engineering, sustainability, and phenomenography (see Table 1). Our study addresses that gap, resulting in both empirical and practice-oriented contributions to the field of engineering education research. Specifically, the findings can be used as parts of a tool for scaffolding students' learning experiences: by using our quotes as mirrors for students' own ideas about sustainability; by developing an assessment tool based on the categories of description or by highlighting critical aspects of sustainability through structured variation around the three dimensions of variation identified. However, we also urge caution in interpreting our findings, based as they are on undergraduate student conceptions, excluding more complex understandings of sustainability held by practitioners or scholars. Hence, if the aim is to push students' understanding far beyond current dominant constructs, for examples those concerning economic growth [1], we would need an expanded range of categories.

II. Literature Review: Explorations of Students' Conceptions of Sustainability

A literature review was conducted to explore intersections among sustainability, engineering, and phenomenography. In March 2020, we performed several literature searches using Scopus and employing different combinations of relevant key terms (see Table I). For the combinations deemed most relevant for this study—Phenomenography + Sustainability respective Engineering + Sustainability + Conceptions + Students—we conducted additional complimentary searches using Web of Science and IEEE Explore as well as in the Papers on Engineering Education Repository for combinations involving all three main key terms (see Table I for details). For each key term, several variations were used; for example, *sustainability* was supplemented by *sustainable W/4 development* and *sustainable W/4 design*. Field codes and search operators were adapted according to the specific database standards. The abstracts from the most specific and relevant searches were assessed for eligibility. After removing duplicates, 202 abstracts were screened (by author 1) for inclusion or exclusion using Rayyan [2]. Relevant papers were then reviewed in detail.

TABLE I. Results from literature searches using different combinations of relevant key terms

Engineering and/or Phenomenography	**Sustainability**		
	(only)	***+ Conceptions***	***+ Conceptions + Students***
Neither	363 099[a]	13 412[a]	683[a]
Engineering	37 987[a]	1 193[a]	165[b]
Phenomenography	33[b]	11[b]	7[b]
Both	12[c]	1[c]	1[c]

[a.] Result of search in Scopus on 9th March 2020.

[b.] Same as a. + Web of Science + IEEE Xplore. Abstracts screened for inclusion.

[c.] Same as b. + Papers on Engineering Education Repository. Abstracts screened for inclusion.

This is an Accepted Manuscript of an article published by IEEE in **IEEE *Xplore*** on 4 December 2020, available at: https://doi.org/10.1109/FIE44824.2020.9274122.

Our first observation from the literature review is that few studies of sustainability in the context of engineering employ a phenomenographic approach. Experiences of sustainable design among practicing engineers [3], engineering students' approaches to wicked sustainability problems [4], sustainability literacy among engineering lecturers [5], and engineering students' experiences of the learning of sustainability literacy skills [6] have all been studied, but our search found no phenomenographic study of engineering students' conceptions of sustainability. (Note that the one indicated in Table 1 actually focuses on student science teachers [7]). Phenomenography has been used to explore how sustainability is understood by both teachers and students in other fields of higher education, such as sociology [8] and business management [9], but not engineering.

Our second observation from the literature review is that, while 165 papers resulted from the search aimed at finding other methodological explorations of engineering students' conceptual understanding of sustainability, only about 10% of those appear to have an explicit focus on qualitative explorations of students' conceptions of sustainability. Such an approach is important if we, for example, want to know not just the content students absorb but how different conceptions differ from and relate to one another. The next section explores how a qualitative, and specifically a phenomenographic research approach, can so contribute.

III. Methodology: Phenomenography

Phenomenography is a qualitative research methodology that investigates the ways people experience and understand their world. Note that phenomeno*graphy* is distinct from phenomeno*logy,* another qualitative research methodology. Phenomenography assumes a non-dualistic relationship between the world and human knowledge of it, where experience of a phenomenon in the world is located neither solely inside the subject nor solely in the world apart from the subject but between the two. Thus, descriptions of experiences say nothing of a phenomenon's "true nature" but how it is experienced by humans as knowers and acting subjects.

Phenomenography assumes there is neither a single, complete description nor an unlimited number of distinct descriptions of any phenomenon. This is tied to the nature of awareness. According to Marton and Booth [10] awareness has two important qualities. The first is that it is not possible to be aware of everything at the same time in the same way. If this were possible, then there would be no variation in experiences. The other quality is that people are aware of everything at the same time although not in the same way. Thus, "the different ways of experiencing a phenomenon reflect different combinations of the aspects that we are focally aware of at a particular time" [10, p. 126]. If people experienced a phenomenon in an infinite number of ways, then they would live in different worlds, being unable to communicate with each other. Since this is not the case, the number of ways of experiencing a phenomenon must be finite [10].

Based on their experiences of a phenomenon, humans make meaning of it, and from this meaning understanding arises. While meaning is derived partly from an individual's (unique) experience, it is not infinitely variable for each individual subject. Because humans communicate, meaning making is an act of negotiation or co-creation. Hence, according to Marton and Booth, "The basic principle of phenomenography is that whatever phenomenon we encounter, it is experienced in a limited number of qualitatively different ways" [10, p. 122].

As a result of this assumption, phenomenography focuses attention on *collective*—rather than individual—experience. A researcher applying a phenomenographic framework takes a *second-order* perspective by investigating other people's experiences and understandings of a given phenomenon. The aim is to find the limited number of variations in understanding of a phenomenon existing within a given group, situated as it is within a given context. According to Marton and Booth, "The description we reach [using phenomenography] is a description of variation, a description on the collective level, and in that sense individual voices are not heard" [10, p. 114].

In navigating the space between singularized understanding and infinite variation, phenomenographic research seeks to identify *critical variation* in the ways members of a group experience a particular phenomenon and then construct an *outcome space* of "categories of description" of the phenomenon. This allows us to focus on the "differences that make a difference." Marton and Booth provide the following definition: "The outcome space is the complex of categories of description comprising distinct groupings of aspects of the phenomenon and the relationship between them" [10, p. 124]. As a rule of thumb, categories of description are distinct from, and stand in a logical relation to, one another. This relation is frequently hierarchical—organized according to relative complexity—but not always so [11]. Higher-level (more complex) conceptions do not simply replace lower level ones, but usually fully encompass them. In other words, higher-level conceptions constitute a more holistic understanding of a phenomenon; lower-level conceptions are not "less correct" but may be less comprehensive. Still in a learning situation the goal is often to help students move toward higher-level conceptions. Another rule of thumb is to employ as few categories as possible for capturing the critical variation represented within the data.

A classic example of phenomenographic inquiry is the seminal study by Marton and Säljö [12, 13], which explored how students approached their learning (i.e., via deep and surface approaches). More contemporary examples of phenomenographic research in the context of engineering education are explorations of the experiences of first-year engineering students working on ill-structured problems in teams [14], engineering students' experiences studying entrepreneurship [15], and engineering students' experiences of human-centered design [16]. Key to all phenomenographic studies is the focus on differences or variation—rather than similarities—among different ways of experiencing or understanding a phenomenon in the world.

The object of study in phenomenography is not to characterize individual subjects' experiences of a given phenomenon but instead *the collective experience* by a select group. Hence, variations in understanding are not determined across individuals, but *across the data set as a whole* treating the research data as a *pool of meaning* [10]. This approach accommodates particular individuals articulating distinct understandings of the concept or phenomenon in question at different times. In fact, during phenomenographic data collection, the aim is to maximize the variation both in terms of both the individuals data are drawn from and the range of articulations from each individual. Thus, it is usual practice to

select a theoretical sample of subjects to cover the group according to a predetermined plan and have a well-prepared guide for semi-structured interviews, a common method of data collection in phenomenography. Marton and Booth explain how interview transcripts (or other written texts) are analyzed within phenomenography:

> The researcher has to establish a perspective with boundaries within which she is maximally open to variation… The analysis starts by searching for extracts from the data that might be pertinent to the perspective, and inspecting them against […] two contexts: […] [1] in the context of other extracts drawn from all interviews that touch upon the same and related themes; [2] in the context of the individual interview. […] This process repeated will lead to vaguely [discerned] structure through and across the data that our researcher/learner can develop, sharpen, and return to again and again from first one perspective and then another until there is clarity [in the form of a system of categories of description] [10, p. 133].

When using a phenomenographic approach, researchers try to bracket their own conceptions of the phenomenon of study to minimize bias. However, since phenomenography is an interpretive research method, it is impossible to completely remove researcher perspectives and choices, especially in creating the necessarily interpretive set of categories of description. One way of reducing bias is to work in iterations, ideally with multiple colleagues constructing the categories together. Even when a researcher is doing the analysis alone, iteration is key to turning emerging themes into a robust outcome space. Working this way helps to give trustworthiness to the findings.

IV. Methods: Student Interviews & Observation

A. The Research Context

The research was carried out in the context of an undergraduate course titled, Sustainable Design Politics and Culture (SDPC), offered at a Northeastern US university. SDPC was offered as an advanced social science elective course and aimed at helping students identify and assess opportunities for and limitations of various solution approaches in moving toward a sustainable future. In particular, the course was designed to provide students with conceptual tools to understand how *social and economic power* operates in technological arenas, including political, and institutional forces impacting sustainability initiatives.

While SDPC was designed with engineering and architecture students in mind, the course was open to all majors at the university. The student composition was: ten engineering and information technology majors, five architecture and design majors, and one science major. The class had an equal number of women and men. The majority of the students were in their final year while two engineering students were in their second year. Fifteen out of the sixteen students successfully completed the course. The class met for two-hour sessions twice a week over 14 weeks.

The course was broken down into three units: 1) an orientation to sustainable design in theory and practice; 2) investigation of specific contexts and cases of sustainable design practice; and 3) identification of strategic pathways to achieving a more sustainable future. The aim of the orientation unit was to give the students the conceptual tools needed to carry out individual research into existing sustainability case studies. This unit centered on three lenses to sustainability: changing individual behaviors (e.g., consumerist approaches), technological innovation, and institutional innovation (e.g., organizational or policy change). Each lens was explored through a mix of common and individually-selected readings. Unit 2 centered on students' individual research into a range of sustainability initiatives, usually on topics connected directly to their majors. Looking to the future, Unit 3 had students individually identify pathways to sustainability, connecting back to the three lenses on sustainability from Unit 1: individual behavior, technology, and institutions.

The main mode of learning within the classroom was guided discussion—of readings, of the student research findings and writing process, and of student experiences. Here, the instructor took the role of facilitator, framing the discussion but allowing the students to drive it according to their interests and interpretations of what was most relevant, with occasional redirection by the instructor asking targeted follow-up questions. In addition to the two major student-research submissions, students were required to write ten research updates based on the readings and their in-process research throughout the semester. Final grades were based on the research projects, the research updates, and participation in discussion. Because of the degree and amount of independent research, the class required a high level of student initiative and self-direction.

B. Data Collection

Author 1 conducted systematic research into student learning in SDPC and attended the course once a week as a participant-observer for most of the term (weeks 3 to 13). In addition to classroom participant-observation, data were collected via student interviews and a review of select student assignment submissions. Student participation in the research (apart from general classroom observation) was voluntary, and the instructor played no role questioning students or interpreting results of interviews until they were de-identified. To gain as broad a pool of meaning as possible for the project, the observing author asked some students if they would be willing to participate in a greater capacity. In total 10 students agreed to interviews during the term, with interviews typically lasting between 60 and 90 minutes.

The interviews were semi-structured to allow important themes to be elaborated. Interviewees were asked questions such as: What is the course about? Based on the course title, what did you expect the course would be about? Has the course had any impact on how you think about your future profession and career, and, if so, how? What do you understand by sustainability? What do you understand by social justice? What connections do you see between sustainability and social justice? (Interviews were conducted during a broader project on social justice.) The interviews were audiotaped, transcribed verbatim, and de-identified.

C. Data Analysis

Guided by our phenomenographic framework, the steps of our analysis were: 1) identifying qualitatively different ways SDPC students understood sustainability by identifying relevant excerpts in the transcripts; 2) clustering excerpts around emergent categories of description, while retaining critical variations in understanding; 3) identifying the key dimensions of variation contained in the entire pool of meaning, and 4) arranging the emerging categories of description in order of perceived complexity. By working

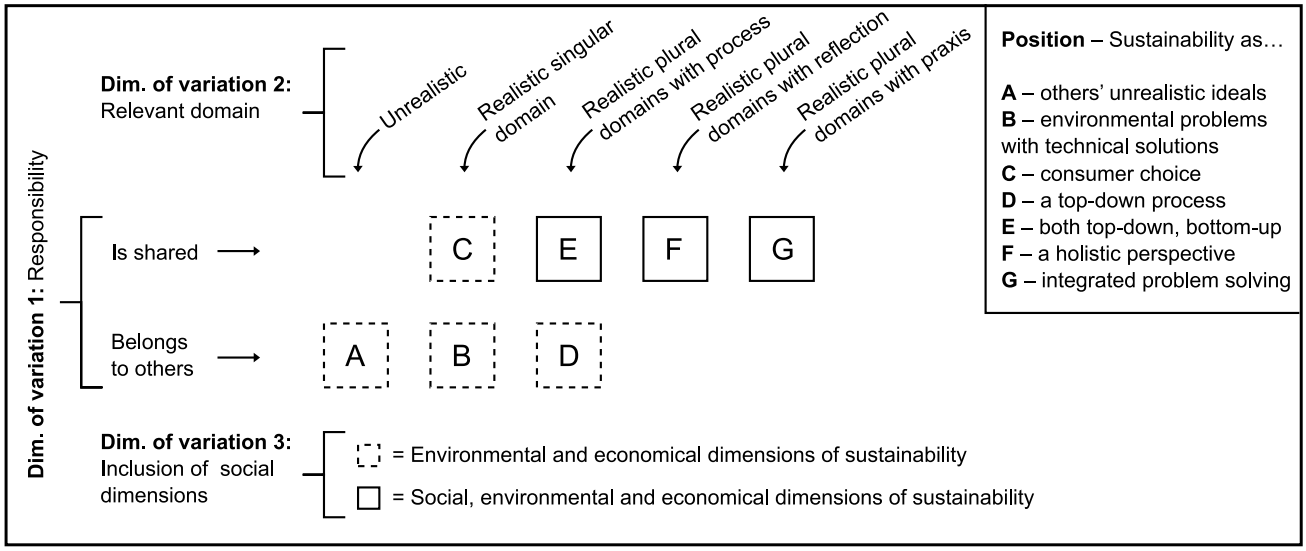

Fig. 1. The outcome space for technical students' conceptions of sustainability with seven categories of description and three dimensions of variation

with, contemplating, and discussing the emerging themes in a series of iterations, several categories of description corresponding to qualitatively different ways of understanding sustainability came into focus. In parallel, three dimensions of variation common to the emerging set of categories were identified. The categories of description and dimensions of variation emerged together and helped to define and refine one another and, ultimately, the entire outcome space.

V. Findings: An Outcome Space for Technical Students' Conceptions of Sustainability

Based on how the students articulated their understandings of sustainability in the context of the course, we identified and then ordered seven categories of description (see Fig. 1). Before describing the categories, however, it is helpful to elaborate our ordering process. We ordered the categories of description according to increased complexity as reflected by variation in three critical aspects: *responsibility* (from "belongs to others" to "is shared"); *relevant domain* (from "unrealistic" to "praxis") and *inclusion of social dimensions* of sustainability (from "none" to "integrative"). These dimensions were themselves emergent from the data.

A. Dimensions of Variation

Three dimensions of variation structured the outcome space.

1) Responsibility

A first important dimension of variation (*DoV 1*) revolved around conceptions of *responsibility* for contributing to sustainability initiatives. Some students (sometimes) articulated an understanding of sustainability as mainly associated with other people; as a set of rules, regulations, and policies that should be created by others or simply as categories of technologies whose implementation is determined by others. Common across these cases is the absence of distributed responsibility for contributing to sustainability, either of the individual student or of any generic citizen more broadly. In contrast, some students (sometimes) articulated understandings of sustainability that included the importance of individuals taking direct responsibility for contributing to sustainability, both concerning one's own decision making and for participating in structural reform as a citizen. Here, students expressed that responsibility for sustainability is shared and includes the individual.

Thus, the "responsibility" dimension of variation in the emerging outcome space has two states: responsibility *belongs to others* and responsibility is *shared* among multiple stakeholders and overlaps across domains. Understandings of sustainability that involved shared, overlapping responsibilities included but extended beyond recognition that certain stakeholders have particular types of responsibilities. Hence, this understanding represented a more nuanced and complex conception of responsibility and thus is categorized higher in the outcome space.

2) Relevant Domain

A second important dimension of variation (*DoV 2*) revolved around what students took to be the *relevant domain of sustainability*, especially by employing concepts central to the course. Some students talked primarily about technical solutions to sustainability problems or barriers to proposed technical solutions. Such articulations identified a single domain of sustainability (as treated in the course) and, hence, were categorized as "singular". At other times, students described sustainability in terms of the "triple bottom line" or as taking a "holistic perspective" to problem solving, which were categorized as "plural domains". Still other articulations of the domain of sustainability included: unrealistic ideals; a process orientation (mainly articulated as "bottom-up" versus "top-down" decision making) or conceptual change, and how sustainability leads to new ways of thinking (e.g., sustainability as a lens to guide one's practice) and new ways of acting (e.g., working to improve society).

The "domain" dimension of variation in the outcome space has five states: 1) unrealistic, 2) realistic singular domain, 3) realistic plural domains emphasizing process, 4) realistic plural domains with attention to reflection, and 5) realistic plural domains oriented to praxis (action informed by systematic reflection). These states of variation are ordered according to three levels of complexification: from unrealistic to realistic, from singular to integrated/plural, and from reflection alone to praxis (reflection-informed practice).

3) Inclusion of social dimensions

A third dimension of variation (*DoV 3*) is an extension of the prior dimension, particularly its framing around sustainability's "triple bottom line". This dimension is given special attention because it represented a distinct conceptual challenge concerning the role played by non-economic social forces. Some students (sometimes) discussed sustainability in terms of economic and ecological facets only without bringing up other social/cultural/institutional considerations, whereas other students (sometimes) integrated social considerations into their conceptions of sustainability. Importantly, those students who included the roles played by various "social" forces never discussed sustainability solely in social terms, but always added social dimensions to economic and/or ecological dimensions. Thus, the *presence of social dimensions* of sustainability in an integrated way was considered to represent a more complex conception of sustainability and is categorized higher in the outcome space.

B. The Outcome Space: Seven Categories of Description

This section elaborates the seven categories of description representing different conceptualizations of sustainability, organized according to increased complexity. Each category is illustrated with representative quotations from student interviews, which have been lightly edited to improve readability (i.e., by removing utterances that do not add meaning, such as filler words). For each category, shifts in the dimensions of variation (DoV) are elaborated to highlight the relations among categories and to map the outcome space.

1) Category A – Sustainability as other people's unrealistic ideals

Here students described sustainability as unrealistic, associated with idealists far removed from the students' own "common sense" understanding of the world.

Student 1: When I think of people that advocate sustainability right now, I do kind of consider them flakes because they're very isolated within their studies. This is what they're passionate about, but they don't really have exposure to how to integrate it into the real world, …where the people move and they give up everything and they're like a commune. I mean, that's a great way to advocate … sustainability, but is it really feasible within the way the world works? I don't really think so [given] the way that the nation is built and companies make money and people can merge into the middle class.

Here a substantive conception of sustainability is not articulated (DoV 2). Economic considerations are evident, but they seem to be understood as immutable barriers that exist apart from what sustainability entails (DoV 3). While there is an implied orientation toward pragmatism, the subject remains disengaged and without responsibility to act, offering only criticism of others' efforts (DoV 1).

2) Category B – Sustainability as environmental problems with technical solutions

Typical for this category is the focus on a single dimension of sustainability, such as a particular environmental concern or a specific technological solution.

Interviewer: So, if we don't prioritize sustainability, what do you believe would happen?

Student 4: I mean, pretty soon into the future, I think we're going to be facing more and more problems with global warming, with hurricanes and droughts, and loss of species…. Some of them may be less important than others, but it just… They all work into the system that is kind of slowly falling apart, and we're a part of it.

Here, the focus is exclusively on environmental problems. While multiple dimensions of ecological plight are identified, sustainability is understood singularly as responding to environmental problems.

Student 8: There's a machine that can sequester one ton of CO_2 a day. I mean, even if all the cars were taken off the road right now, CO_2 levels would still be going up. If we're really serious…, we're going to need to actually start sequestering CO_2. In terms of global warming, that's one answer. It's not a cheap answer but it's … the best thing on the table right now.

Here, the focus is on a specific technological solution to one particular environmental problem. The problem and solution are put into play with one another, and there is acknowledgement of the partiality of the suggested solution, but the starting point is technology-as-solution to a given environmental problem. Other dimensions of "getting serious" in environmental problem solving are left unidentified. The singular focus (*DoV 2 shifted in comparison to A*) and general passive subjectivity (*DoV 1 unchanged in comparison to A*) marks this as a relatively non-complex category of description.

3) Category C – Sustainability as consumer choice

Similar to the previous category, this one focuses on a single domain of sustainability, namely responsible consumer choice. Different from the previous category, this one is connected to the student's own actions in the world (*DoV 1 shifted in comparison with A and B*). In other words, in this conception, the student accepts individual responsibility to contribute to the solution to sustainability problems, even if in a simplified way.

Student 5: [A text we read] said the most important thing is what you wear and what you eat; those are the most important products to pay attention to.… It's definitely compelling me to think about … what I buy—yeah—that is making an impact. I think I really will try, once I have some more time, to go to the farmers' market here in [the city] and buy stuff there instead of buying the produce in the store.

Student 2: I try to practice all the stuff [we talk about] myself, personally: you know, the use of plastic bags, the use of bottles…. [The instructor] asked us, "How do you contribute personally to sustainable design?", and my contribution was "I bike to and from campus". So I think I'd like to adopt as many ideas as possible or as many changes. So I know I said the lifestyles thing is most important. The stuff is part of lifestyles, like, … How do you shop from now on by using not plastic bags, but by using a reusable bag?

In this category, the focus is still quite singular (*DoV 2 unchanged in comparison to B*) and does not address the system of interactions that structure both market offerings and consumer choices (*DoV 3 unchanged*). This marks this as another relatively non-complex category of description.

4) Category D – Sustainability as a top-down process

This category marks a shift from individual, localized actions to systemic change. For this category specifically, sustainability is understood as a set of high-level policies for institutional reform.

Student 8: Well, for global warming, I mean, you had the CAFE [Corporate Average Fuel Economy] standards.… It's basically the fuel efficiency standards for vehicles, and that's mandated by the federal government and that hasn't gone up for a while, and now it's starting to go back up. Those [policy changes] would certainly help [address] those types of constraints, where you give a company [an order]: You need to do this. And then they work within that [requirement], because everybody's on the same level playing field; there's no competitive advantage.

Student 1: Sustainability itself, I think, is an important topic. I think it has to stem from the top-down because people in corporations are fundamentally self-centered…. I think maybe government should regulate the industry, like I said earlier in class about having constraints for people … and businesses to operate in.… They're still operating within certain constraints right now, and they still manage to make money. So I think if there were sustainability constraints put on corporations and people's lives, we would adapt and function and everything would still work.

This category highlights a shift from individual decisions to policy and institutional structures, with emphasis on change beyond what could be achieved by any individual acting alone (*DoV 2 shifted in comparison with B and C*). However, in comparison to category C, individual responsibility disappears, and the people subject to policy changes are seen as relatively passive subjects, responding to others' initiative (*DoV 1 unchanged in comparison to B*). Additionally, sustainability is still mainly described in environmental and economic terms (*DoV 3 still unchanged*). This is an example of a category of description with intermediate complexity.

5) Category E – Sustainability as both top-down, bottom-up

This category follows on from C and D with subjects collectively responsible for bringing about systemic change (*DoV 1 shifted in comparison to D, but unchanged in comparison to C*). Government/policy plays an important role, but the responsibility of individual subjects and communities is also clearly evident.

Student 10: Right now, what we're looking at is the pathways to sustainability. Most of them I found are about community-based participation. A lot of it is all about collaboration, grassroots movements, I mean people being active in the government to get the government to promote green or sustainable policies. So, I assume it's … a lot of sustainability is social… I think before the course, I wasn't so much aware of the social aspect of it.

Student 9: Yeah, the case study I chose to do was on grassroots movements in California directly related to electronic waste, so the release of chemicals in the manufacturing process—of semi-conductors and hardware, computer hardware in particular—and how a lot of these localized groups saw this getting leaked into their water supplies and harmfully affecting them and the workers at the factory and things of that nature, and working with government groups like the Environmental Protection Agency ... and how they, from the bottom-up, have affected markets to actually change. Things like that.

This category captures the interplay between bottom-up political pressure and top-down structural/policy change; the two are seen as working together (*DoV 2 unchanged in relation to D but shifted in relation to C*). Here, we see explicit articulation of a "social" dimension of sustainability, which is added to the environmental and economic dimensions (*DoV 3 shifted in comparison to A-D*), which helps distinguish this as an example of a more advanced category of description.

6) Category F – Sustainability as a holistic perspective

Here, students understand sustainability as a way of perceiving the world in an integrated manner. The subject has an active responsibility to act, but in a reflective, analytic way.

Student 7: I think it's probably helped me to look at a bigger picture instead of focusing more narrowly on one thing. It's because sustainability is not about this one thing; it's on this one thing and everything else and all the impacts and how everything kind of meshes together. So I've never really had to look at that really huge picture before. So I guess that's been helpful.

Student 10: [W]hen you have a situation, it's pretty easy to identify who's involved. But then, [with] critical thinking, you're thinking about, "Okay, so you have who's involved. What else are they involved in? And how does that contribute back to what is going on in the particular situation?" … One of the key things through the course was really taking the issues and finding the connections and relationships between them, so that you have an understanding of what's really going on. It's easy to look at one part of it without looking at the whole system, but it's just not what sustainability is about.

Key here is the importance of seeing how things fit together, understanding the systems of interactions underlying sustainability problems. We see a shift toward reflection (*DoV 2 shifted in relation to E, DoV 1 and DoV 3 are unchanged*) that marks this as an example of more advanced category of description than Category E.

7) Category G – Sustainability as integrated problem solving

This category includes emphasis on understanding the complexities of sustainability problems but moves on to include the importance of acting on that knowledge to improve outcomes. In other words, the focus is on integrated sustainability problem solving.

Student 10: I found that whenever you learn about sustainability, some of the problems like consumerism and just the way we live our daily lives, it's kind of hard to ignore them once you know them. It makes you think more about the solutions and what changes you can make, and that's really how our society is going to have to make progress.

This same student later articulated the need for analysis of complex interactions in order to eliminate "root causes" of sustainability problems.

Student 10: Whenever you look at design, the new trend in design or some of the new trends, I don't know exactly how old it is, what I've learned is you really have to… When you're approaching a problem, you look at all the different elements that come into the problem. Otherwise, you're not going to really get to find a solution. It could alleviate some of the symptoms, but it won't actually be a solution, which is kind of what sustainability is all about: getting to the root of environmental, social, economic—what's wrong with the system, not necessarily this particular part of it.… You're trying to address the systemic issues.

Another student understood sustainability as problem solving with a long view. This articulation explicitly connects social and environmental concerns with economic ones:

Student 8: I mean, what comes to mind immediately is third world countries, where people don't have the food to live or the water to drink and the chance to give their kids a future…. There's another student in class that, I mean, he made the point that he doesn't see how social justice affects sustainability at all.… It's like, "Well, they're two completely different things." I mean you have the ecology of the system and then you have the social justice aspect…. Like I said, I try and take a longer view and … you have a set of people that are consistently not allowed to express themselves or not allowed to be a part of a larger society. There's going to be a point where you just can't do that anymore, and I think that's part of sustainability…. You have to work towards that point where what you're doing now, if you were to keep doing it, would be okay. You always strive for something better.

This category of description is integrative and oriented around praxis—systematically reflecting on the conditions leading to a certain outcome and then acting on that knowledge to create better outcomes (*DoV 2 shifted in comparison to F*). Attention to social dimensions of sustainability is evident, but not to the exclusion of environmental or economic considerations (*DoV 3 is unchanged*). The subject has responsibility to think and act to achieve sustainable outcomes (*DoV 1 is unchanged*). Taken together, this represents the most advanced category of description of the outcome space.

VI. Discussion: Limits of the Outcome Space

One strength of phenomenography is that it can capture a range of articulated understandings of a phenomenon, such as sustainability, in a limited number of distinct conceptions without getting lost in the finer details. This has been convincingly demonstrated with the current study. Nevertheless, the findings of any phenomenographic study are contextually dependent—who one asks, what and how one asks, where and when one asks all matter. Hence, while our findings capture a wide range of understanding operating within this institution's undergraduate student population, they do not capture a wider range of possible conceptions, excluding both simpler conceptions (sustainability equals consumer recycling) or more advanced conceptions likely to held by sustainability scholars, practitioners, or other experts.

In our eyes, a course with the explicit aim of expanding students' understanding of the concept, such as the one we have studied here, is a good starting point for such exploration. But it also invites us to consider the potential role to be played by inclusion of higher-order conceptualizations or potential incommensurabilities, say those held by experts in sustainability and adjacent fields. None of our interviewees, for example, brought up the tension between sustainability and dominant models of economic growth or corporatized technology development. So the question becomes whether and how higher-order conceptualizations ought also to be accounted for when deploying our outcome space in the design of educational interventions.

Such an expansion could be achieved in different ways. For example, we could expand our pool of meaning by collecting data from another strategically chosen context or group, such as interviewing select sustainability professionals or scholars. This would likely result in additional higher-order categories of description. Another approach would be to do a theoretical extension of our outcome space by drawing upon relevant literature, such as the work on degrowth [1] or other critical approaches to sustainability. In this way, a hypothetical Category H could be represented by a shift in the domain dimension of variation (*DoV 2*) beyond a focus on praxis to a more systemic critique that might include incommensurability between sustainability and growth.

In addition to hypothetical higher-order categories, we could sketch out an additional potential lower-order category based on possible states of our identified dimensions of variation (*DoV 1*: Is shared and *DoV* 2: Unrealistic), which would be something along the lines of "Sustainability as one's own naïve ideals". Here the importance of sustainability and personal responsibility would be stressed but the responses would remain vague. We can speculate that this category might have appeared if we had also collected data, for example, from young children. The absence of this potential category from our collected data is likely a consequence of the context of the course with its focus on concrete aspects of sustainability in the context of technology design.

Another important limitation of the current study is that we only focus on conceptual understandings of sustainability: what it is; how it is defined. We acknowledge that there are also normative and affective aspects that are also important to consider when teaching and learning about sustainability.

VII. Implications: Teaching Sustainability within Engineering Education

When discussing phenomenography as a tool for improving learning, Micari, Light, Calkins, and Streitwieser, draw on Marton and Booth [10, p. 155] to state: "Change in conception can be thought of as 'learning that enables the learner to experience a phenomenon in a way she has not been able to experience it previously'" [17, p. 463]. A common goal in sustainability education is to help students move toward more multifaceted and multiperspective understandings. We believe the findings of this study can be used to create scaffolding for students' learning experiences toward that end.

In this section, we outline three different possible scaffolds based on our findings. As previously pointed out, our range of identified categories would need to be expanded with additional higher-order categories, for example by drawing on more and broader data, to be useful for challenging dominant conceptualizations surrounding sustainability held by students, such as the immutability of the economic growth paradigm. Additionally, when developing a framework for teaching sustainability within engineering education, it would be important to consider other kinds of scaffolding as well [18].

A. Scaffold 1: Quotes as mirrors for students' own ideas about sustainability

One scaffolding technique would be to use the student quotes from this study as a mirror for other students to reflect on and learn about their own conceptions of sustainability. A similar approach was used in another course that was part of the broader study, *Engineering and Social Justice*, summarized in [19]. Here, students were given a set of quotes about social justice from interviews with the previous year's students, and they were then asked to read, discuss, and construct an outcome space by grouping quotes as they saw fit and pointing out any relations among the groupings. The idea of the exercise was to expose the students to variation in how social justice is understood by others in a similar context as

themselves, thereby helping them to identify critical differences, which in turn would help them develop a more complex understanding of the concept of social justice. The student quotes describing sustainability presented in this paper could be used in a similar fashion: pooled together without the outcome space mapped. Students could then create their own maps and explore for themselves the key dimensions of difference represented by the sample quotes. This could give students an educational experience around sustainability similar to the one captured in the following quote from a student in the social justice course:

I really enjoyed the quote exercise. I could see a lot of myself in some of the quotes, and at the same time a lot of views that I definitely do not share. One thing I found is that they helped to clarify some of my views on social justice as I had the opportunity to evaluate whether or not I agreed with the statements being made [19, p. 146].

B. *Scaffold 2: Assessment tool based on the categories of description*

Data from a study such as this can be used to develop a combined assessment-and-evaluation tool. Such a tool would be especially useful when taking a view of education as transformation or of passing through learning thresholds. Meyer and Land [20] initiated work on "threshold concepts" when they noticed that students in a variety of subjects passed through a series of critically important thresholds, which were transformative of the students' ability to understand key concepts. By passing through these thresholds, students were opened up to new ways of thinking that were previously inaccessible. Passing the threshold entailed a learning journey through a passageway that Meyer and Land call "liminal space". Studying the conceptions of students along this passageway can be helpful in locating the critical blocks and, possibly, the learning needed to progress through them.

Data from a study such as this—where the outcome is a dimension of variation from less to more complex understandings—can help educators clarify high-level course and program learning outcomes and develop tools to monitor student progress along the way. The data can be used to map a liminal pathway—such as was created by [21]—identifying pathways from simpler to more complex conceptions. Having students submit incremental reflective work, such as with a weekly learning journal, would provide opportunities for instructors to regularly assess student progress along the liminal pathway [22].

C. *Scaffold 3: Structured variation around the dimensions of variation*

The *variation theory of learning* [23] provides an opportunity for another scaffolding technique. In this framework, people come to understand what something *is* by contrast with that which it *is not*. Variation and invariance are the key points here. For example, drawing on Booth [24, p. 14], the concept of red is brought into an individual's focal awareness by exposure to deliberate *variations* in size, in shape, and in type of object in relation to objects of other colors, while the property of redness is maintained *invariant*. Similarly, the three dimensions of variation in our findings (i.e., *responsibility*, *relevant domain,* and *inclusion of social dimensions* of sustainability) provide a relational structure for the seven categories of description of the outcome space for sustainability presented in this paper.

Certainly, sustainability is a more complex and multidimensional phenomenon than the color red, but the same principles of learning through variation still apply. The idea is not that more variation is better, but rather that variation is *structured* around certain critical conceptual dimensions. Based on two of the three dimensions of variation for sustainability identified in this study—*responsibility* and *relevant domain*—an instructor could design a series of scenarios or examples of sustainability in which one dimension is kept invariant while the other is allowed to vary. The third dimensions of variation—*inclusion of social dimensions*—represents a significant shift in the outcome space but is too intertwined with the other two dimensions to say anything meaningful if they were to be kept invariant. So, the instructor would also need to prepare scenarios or examples where multiple dimensions vary simultaneously. If the *domain* dimension was kept invariant, we would get two meaningful scenarios where either Categories B and C or Categories D and E can be compared and contrasted in terms of responsibility. If the *responsibility* dimension was kept invariant, we would get two meaningful scenarios where either Categories A, B, and D or Categories C, E, F, and G can be compared and contrasted in progressions of increasing complexity. For example, the second scenario highlights steps in which individuals develop a broader, more multifaceted, more active perspective on sustainability.

This systematic approach to variation and invariance would not only help students to comprehend the multidimensional nature of sustainability but also provide mechanisms for students to navigate the conceptual thresholds separating naïve and nuanced approaches to sustainability. For an integrated understanding of the whole and how different critical aspects interact, there need to be simultaneous variation in all dimensions of variation at some point, but it is preferable for students to first be able to discern each of the critical aspects separately [25]. The important thing here is not just to vary the experience for students but to enable them to *experience the variation* around these critical aspects.

VIII. Conclusions

When teaching complex and contested concepts such as sustainability, it is important to consider the diversity of ways in which the concept is likely to be understood by students and to confront and navigate those differences in a deliberate way. While much scholarship on sustainability exists, little appears to qualitatively explore engineering students' understanding of the concept. By employing phenomenography, with its strong tradition of exploring and improving student learning, we contribute to this somewhat underdeveloped area. This study provides a well-developed and structured outcome space with a comprehensible, if somewhat limited, range of conceptions of sustainability identified among a group of technical undergraduate students in the US. We also provide three concrete ideas about how the findings can be used to scaffold student learning experiences in other contexts. Extending this work with additional higher-order conceptions might be useful for challenging to go beyond dominant conceptualizations.

Acknowledgment

Jens thanks colleague Yommine Hjalmarsson for her essential help with the literature searches. Jens also thanks colleagues in the EER division who read and commented on an advanced draft of the manuscript.

REFERENCES

[1] M. Sandberg, K. Klockars, and K. Wilén, "Green growth or degrowth? Assessing the normative justifications for environmental sustainability and economic growth through critical social theory," *Journal of Cleaner Production,* vol. 206, pp. 133-141, Jan. 2019, doi: https://doi.org/10.1016/j.jclepro.2018.09.175.

[2] M. Ouzzani, H. Hammady, Z. Fedorowicz, and A. Elmagarmid, "Rayyan-a web and mobile app for systematic reviews," *Systematic Reviews,* Article vol. 5, no. 1, Dec. 2016, Art no. 210, doi: 10.1186/s13643-016-0384-4.

[3] L. Mann, D. Radcliffe, and G. Dall'Alba, "Experiences of sustainable design among practicing engineers? Implications for engineering education," in *Conference Proceedings of ASEE 2007 Annual Conference and Exposition*, Honolulu, HI, USA, June 2007, pp. 12.716.1-12.716.26. [Online]. Available: https://peer.asee.org/1981.

[4] J. Lönngren, Å. Ingerman, and M. Svanström, "Avoid, Control, Succumb, or Balance: Engineering Students' Approaches to a Wicked Sustainability Problem," *Res. Sci. Educ.,* Article vol. 47, no. 4, pp. 805-831, Aug. 2017, doi: 10.1007/s11165-016-9529-7.

[5] N. Kokkarinen and A. J. Cotgrave, "Are university lecturers literate in sustainability?," in *Handbook of Research on Pedagogical Innovations for Sustainable Development*, K. D. Thomas and H. E. Muga Eds., IGI Global, 2014, pp. 606-618.

[6] N. Kokkarinen and A. J. Cotgrave, "Sustainability literacy in action: Student experiences," *Struct. Surv.,* Article vol. 31, no. 1, pp. 56-66, Mar. 2013, doi: 10.1108/02630801311304422.

[7] A. Kilinc and A. Aydin, "Turkish Student Science Teachers' Conceptions of Sustainable Development: A phenomenography," *Int. J. Sci. Educ.,* Article vol. 35, no. 5, pp. 731-752, Mar 2013, doi: 10.1080/09500693.2011.574822.

[8] P. Baughan, "Variation in sociologists' perspectives about sustainability in higher education: Outcomes from a phenomenographic study," in *Sustainable Development Research at Universities in the United Kingdom* (World Sustainability Series), W. Leal Filho Ed., Springer International Publishing, 2017, pp. 313-325.

[9] L. C. Farias, A. L. A. L. Coelho, and C. Coelho, "Sustainable Development Goals and education for sustainability: analysis of the sustainability concepts of Administration students in a public higher education institution," *Administracao,* Article vol. 20, no. 3, pp. 747-785, Sep-Oct 2019, doi: 10.13058/raep.2019.v20n3.1494.

[10] F. Marton and S. Booth, *Learning and awareness*. Mahwah, N.J.: L. Erlbaum Associates, 1997.

[11] P. Green, "A rigorous journey into phenomenography: from a naturalistic inquirer standpoint," in *Doing developmental phenomenography*, J. A. Bowden and P. Green Eds., RMIT University, 2005, ch. 3, pp. 32-46.

[12] F. Marton and R. Säljö, "On qualitative differences in learning: I—outcome and process*," *British Journal of Educational Psychology,* vol. 46, no. 1, pp. 4-11, Feb. 1976, doi: 10.1111/j.2044-8279.1976.tb02980.x.

[13] F. Marton and R. Säljö, "On qualitative differences in learning—ii outcome as a function of the learner's conception of the task," *British Journal of Educational Psychology,* vol. 46, no. 2, pp. 115-127, Jun. 1976, doi: 10.1111/j.2044-8279.1976.tb02304.x.

[14] E. Dringenberg and Ş. Purzer, "Experiences of First-Year Engineering Students Working on Ill-Structured Problems in Teams," *J. Eng. Educ.,* Article vol. 107, no. 3, pp. 442-467, Jul. 2018, doi: 10.1002/jee.20220.

[15] M. Täks, P. Tynjälä, M. Toding, H. Kukemelk, and U. Venesaar, "Engineering students' experiences in studying entrepreneurship," *J. Eng. Educ.,* Article vol. 103, no. 4, pp. 573-598, Oct. 2014, doi: 10.1002/jee.20056.

[16] C. B. Zoltowski, W. C. Oakes, and A. E. Cardella, "Students' ways of experiencing human-centered design," *J. Eng. Educ.,* Article vol. 101, no. 1, pp. 28-59, Jan. 2012, doi: 10.1002/j.2168-9830.2012.tb00040.x.

[17] M. Micari, G. Light, S. Calkins, and B. Streitwieser, "Assessment beyond performance: Phenomenography in educational evaluation," *American Journal of Evaluation,* Article vol. 28, no. 4, pp. 458-476, Dec. 2007, doi: 10.1177/109821400730802.

[18] J. Lönngren, T. Adawi, and M. Svanström, "Scaffolding strategies in a rubric-based intervention to promote engineering students' ability to address wicked problems," *European Journal of Engineering Education,* Article vol. 44, no. 1-2, pp. 196-221, Mar. 2019, doi: 10.1080/03043797.2017.1404010.

[19] J. Kabo, R. Day, and C. Baillie, "Engineering and Social Justice: How to help students cross the threshold," *Practice and Evidence of Scholarship of Teaching and Learning in Higher Education,* vol. 4, no. 2, pp. 126-146, Oct. 2009.

[20] J. H. F. Meyer and R. Land, "Threshold concepts and troublesome knowledge (2): Epistemological considerations and a conceptual framework for teaching and learning," *Higher Education,* Article vol. 49, no. 3, pp. 373-388, Apr. 2005, doi: 10.1007/s10734-004-6779-5.

[21] J. Kabo and C. Baillie, "Seeing through the lens of social justice: A threshold for engineering," *European Journal of Engineering Education,* Article vol. 34, no. 4, pp. 317-325, Aug. 2009, doi: 10.1080/03043790902987410.

[22] C. Baillie and S. A. Male, "Assisting engineering students along a liminal pathway and assessing their progress," *Australasian Journal of Engineering Education,* Article vol. 24, no. 1, pp. 25-34, Jan. 2019, doi: 10.1080/22054952.2018.1562320.

[23] F. Marton and A. B. M. Tsui, *Classroom discourse and the space of learning*. Mahwah, N.J.: L. Erlbaum Associates, 2004.

[24] S. Booth, "Engineering education and the pedagogy of awareness," in *Effective Learning and Teaching in engineering*, C. Baillie and I. Moore Eds. London: Kogan Page, 2004.

[25] G. Akerlind, J. McKenzie, and M. Lupton, *A threshold concepts focus to curriculum design: supporting student learning through application of variation theory*. Australia, NSW, Sydney: Australian Learning and Teaching Council, 2011.