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Undergraduate Students Becoming Engineers: The Affordances of University-Based Makerspaces

Jana Bouwma-Gearhart [1,*], Yoon Ha Choi [1], Cindy A. Lenhart [1], Idalis Villanueva [2], Louis S. Nadelson [3] and Estefany Soto [3]

[1] College of Education, Oregon State University, Corvallis, OR 97331, USA; choiyoon@oregonstate.edu (Y.H.C.); lenhartc@oregonstate.edu (C.A.L.)

[2] Department of Engineering Education, University of Florida, Gainesville, FL 32611, USA; i.villanueva@ufl.edu

[3] College of Education, University of Central Arkansas, Conway, AR 72035, USA; lnadelson1@uca.edu (L.S.N.); esoto1@cub.uca.edu (E.S.)

* Correspondence: jana.bouwma-gearhart@oregonstate.edu

Abstract: In the last decade, postsecondary institutions have seen a notable increase in makerspaces on their campuses and the integration of these spaces into engineering programs. Yet research into the efficacy of university-based makerspaces is sparse. We contribute to this nascent body of research in reporting on findings from a phenomenological study on the perceptions of faculty, staff, and students concerning six university-based makerspaces in the United States. We discuss the findings using a framework of *heterogeneous engineering* (integration of the social and technical aspects of engineering practice). Various physical, climate, and programmatic features of makerspaces were read as affordances for students' development of engineering practices and their continued participation and persistence in engineering. We discuss the potential of makerspaces in helping students develop knowledge, skills, and proclivities that may support their attending to especially wicked societal problems, such as issues of sustainability. We offer implications for makerspace administrators, engineering program leaders, faculty, and staff, as well as those developing and delivering professional development for faculty and staff, to better incorporate makerspaces into the university engineering curriculum.

Keywords: makerspaces; postsecondary education; engineering education; heterogeneous engineering; affordances

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Citation: Bouwma-Gearhart, J.; Choi, Y.H.; Lenhart, C.A.; Villanueva, I.; Nadelson, L.S.; Soto, E. Undergraduate Students Becoming Engineers: The Affordances of University-Based Makerspaces. *Sustainability* **2021**, *13*, 1670. https://doi.org/10.3390/su13041670

Academic Editor: Siva Chandrasekaran

Received: 9 January 2021
Accepted: 31 January 2021
Published: 4 February 2021

1. Introduction

1.1. Makerspaces in (STEM) Education Environments

Makerspaces were originally founded as places where members of a community could access tools, resources, and support to work on design problems of personal interest (e.g., fixing a bike gear, creating an automated plant-watering garden structure) [1,2]. These spaces are commonly equipped with both "lower-tech" tools (e.g., sewing equipment, wrenches) and those more "cutting-edge" (e.g., 3D printers, laser cutters) [3]. In formal education environments, including in K-12 schools and colleges and universities, makerspaces are more recent structures [4]. In the last two decades, postsecondary institutions have seen a notable increase in makerspaces on their campuses, as well as the integration of these spaces into university engineering programs [5–9]. Although differing in exact focus, staffing, and accessibility, a university-based makerspace, generally speaking, can "serve as a meeting place for a university's maker community, and provides resources to design, fabricate, and evaluate engineered systems" [9] (p. 2). Certain other characteristics are typical of many university-based makerspaces that, overall, foster users' innovation. These include allowing for unstructured activities and intermingling of individuals and their ideas [8].

Similar to community spaces, university-based makerspaces may provide a greater array of students' access to equipment and space for projects, in comparison to other campus spaces (e.g, laboratories and machine shops) that are typically utilized by programs in the STEM (science, technology, engineering, and mathematics) disciplines. Makerspace proponents have argued that these spaces are more welcoming and democratizing spaces for underrepresented students in the STEM fields [2,10–12]. Women students may find makerspaces a place to engage in work that resonates with their design interests, including around innovations of potential societal benefit [13]. University-based makerspaces may inspire engineering faculty to teach innovations that can attend to a diversity of student interests and experiences [5]. These collective research findings motivate postsecondary education's expansion of investment in makerspaces [14].

Yet, there is conflicting evidence concerning equity and access to and within makerspaces and concerning engineering activities within them specifically. Of notable concern is the potential of makerspaces to strengthen the status quo around engineering activities, privileging participation of white, male, and affluent individuals. Makerspaces have been criticized for potentially replicating this inequitable involvement, across STEM [15], via the promotion of a "maker culture" unwelcoming to women and racially/ethnically minoritized groups [16]. Yet this research, as with most research concerning makerspaces in formal education settings, is limited and tends to focus on K-12 environments [17].

Overall, research into the efficacy of makerspaces in higher education environments (hereafter *university-based makerspaces*) is sparse, with few phenomena explored to inform their efficacious use by students, faculty, and programs [10,18]. While a few recent studies have elicited engineering students' perspectives regarding university-based makerspaces [19–21], these studies have focused on student experiences in a specific course or project they completed. These studies may not capture the multi-functional nature of university-based makerspaces that can encompass formal coursework, student club activities, and personal or non-coursework-related projects that constitute students' engagement with makerspaces [3].

Additionally, while a plethora of research exists concerning the role of professional engineering programs, broadly speaking, on the development of undergraduate students as engineers (e.g., [22–24]), research is just now emerging on the role of makerspaces in this development [25]. Limited evidence indicates that makerspace activities help students develop dispositions and practices relevant to engineering, such as confidence and motivation related to designing [26,27], creativity related to the graphical representation of ideas [28], and collaboration abilities [3,6]. Others argue that university-based makerspaces may encourage student engagement in real-world problem-solving [14,27,29]. This includes around some of society's most pressing problems [12], such as sustainability, *wicked* in its complexity [30], requiring collaboration and integration of diverse knowledge bases and skills across disciplines. Yet, some of these claims around makerspaces are without adequate empirical basis.

Given the ultimate goal of university engineering programs to develop engineering professionals, there is a need for future research around makerspaces' potential contribution to the development of students' knowledge, skills, and proclivities around engineering [5,20,31]. This includes the examination of the perspectives of students, as well as educators who can and do lead, create, and implement curriculum and instruction that engage university engineering students in engineering-related makerspace activities. These needs root our study of faculty, staff members', and students' perceptions of university-based makerspaces as affordances for undergraduate students' development as engineers.

1.2. Postsecondary Engineering Programs and the Preparation of Students as Engineers

A main goal, perhaps the main goal, of university engineering programs is preparing students to be engineers, enabling them to perform as professional engineers do, drawing on certain knowledge, and exhibiting the skills necessary to participate in professional practices [32]. Beyond practice, engineering programs, like other professional preparation programs, must also support students' development of *professional identity*, or "the attributes, skills, knowledge, beliefs, practices, and principles, which are representative of professionals as they work within and evolve with their profession" [24]. Various scholars have argued that to achieve the "internalization" of requisite professional understandings and proclivities [33] (p. 4), university-based engineering programs must provide students with more experiences aligned with the work of contemporary engineer practitioners, or *authentic* practices [20,34–36]. Through these activities, students can also develop more accurate understandings of the work and field of professional engineers [33].

Many undergraduate engineering preparation programs have evolved to better align curriculum and instruction with professional engineering practices [37], including via incorporation of makerspace-associated activities [20,21,28,38]. Yet there is still reason for concern that engineering programs, including those involving student makerspace activities, may not adequately prepare students to be 21st-century engineers, prepared to address complex societal issues [12]. In the last two decades, researchers have documented that misalignments still exist between students and professional engineers, including around communication styles and project execution [34,39,40]. Students' misperceptions of the work of engineers are obviously influenced by experiences in their university engineering programs. For instance, the problem-solving required of university students, in comparison to practicing engineers, is typically more structured and organized and with more obvious solutions [31,41]. Engineering students spend less time and energy gathering relevant information and generating alternatives when confronted with solving design problems [39], adopt less of a social orientation [24,40], and have difficulty reflecting professional identities in professional communications and design presentations [34].

Some researchers have raised concerns for students' inaccurate notions of the work of professional engineers. For instance, Stevens et al. [31,42] have noted that undergraduate engineering students often do not recognize aspects of engineering work beyond the technical. While, admittedly, the work of engineers evolves with forces such as globalization and new technologies [31,43], there are still certain aspects/practices that largely root complex, collaborative, and creative engineering work over time [35,37,43]. Not surprisingly, these aspects are reflected in ABET's (Accreditation Board for Engineering and Technology) accreditation criteria [32] for baccalaureate and integrated baccalaureate-master's level engineering programs. These are conceptualized as seven student learning outcomes around solving complex problems, via application of appropriate knowledge and analytical processes; creating meaningful and ethical solutions; and effective communication and teamwork. Engineering education programs with ABET accreditation must document their efficacy in helping students achieve these outcomes.

1.3. The Heterogeneous Perspective of Engineering

The complex work of engineering professionals is what Stevens et al. [31] (building from Law [44]) conceptualize as the *heterogeneous perspective* of engineering. This perspective includes practices often perceived as social (e.g., collaborating and organizing across individuals and organizations, using disciplinary representations to communicate ideas and persuade others) alongside those perceived as more technical (e.g., use of technology, applying algorithms, interpreting data). The integration of the social and technical is key, with the heterogeneous perspective of engineering in contrast to seeing engineering work as a dichotomy of technically oriented *versus* socially oriented work (and predominantly still technical [12,31,45]). A more accurate notion of engineering, in fact, may help to retain students who may otherwise turn away from the field due to not understanding its attention to social problems [41].

Stevens et al. [31] argue for a reconceptualization of engineering work, to better acknowledge the heterogeneous perspective. This includes a reorientation of postsecondary engineering programs towards students' development, and accurate understanding of the skills, knowledge, and proclivities of practicing engineers. Reflected in Learning Outcomes

#2 and #4 of ABET [32], researchers continue to call for university engineering programs to do a better job at helping students recognize the political and values-driven dimensions of engineering [12,46–49]. Proponents of university-based makerspaces have pointed towards their role in developing students as activist engineers, who can "develop holistic, systemic solutions to complex social and environmental problems through collaborative making that centers around the collective good" [12] (p. 128). Yet this potential is not well confirmed with empirical research.

1.4. Paper Focus

Herein we present findings from a phenomenological research study concerning the perceptions of faculty, staff, and students of the affordances of six university-based makerspaces on students' development as engineers. We discuss our findings using a framework of heterogeneous engineering [31,44], which also illuminates what faculty, staff, and students perceive as key programmatic outcomes for students' development as engineers, as well as the nature of being an engineer. We consider implications for makerspace administrators, faculty, and staff, as well as those developing and delivering professional development for them.

2. Materials and Methods

2.1. Research Focus

Our research question was: What do faculty, staff, and students perceive university-based makerspaces to afford for undergraduate students' development as engineers?

2.2. Assumptions: Individuals' Perceptions of Affordances of Education Innovations

Our investigation relied on the theoretical concept of *affordances.* Modern affordance theory stems from the work of ecologist James Gibson [50] who described affordances as the dialectic between properties of animals and features of their environment, allowing for actions on the part of animals (e.g., bark on a tree *affording* animals with claws to climb). Chemero [51] argued that affordances are better conceptualized as relationships involving the traits of individuals and features of the environment at specific points in time concerning an individual's needs, interests, and capabilities.

STEM education researchers have employed theories of affordances to examine the way individuals make sense and use of features available in their learning environments. Affordance theory has been used to examine postsecondary STEM educators' instructional decision-making [52], their sensemaking around education improvement initiatives [53], and their adoption of instructional innovations [54]. Researchers have also used affordance theories to frame investigations of instructional innovations on learning, such as the influence of new technologies to support student learning in STEM [55–57] and shifts in motivation to pursue science careers [58].

We assume the premises of Chemero's [51] *actor-environment relationship model* of affordance theory. We used the theory to focus our attention on the intersection of the *features* within individuals' contexts, including education innovations (i.e., the university-based makerspace and its components) that individuals (i.e., faculty, staff, students) perceived as allowing actions or outcomes (i.e., the development of students as engineers) in relation to the perceptions, needs, and abilities of individuals (i.e., the students engineering programs are meant to impact). As is the case of all educational innovations, not all features are perceived by individuals as promoting actions or outcomes; some features may be perceived as a hindrance to actors' outcomes, regardless of designer intentions. Importantly, individuals read features as "affordances in terms of prior knowledge, experiences, and desires" [59] (p. 18). We utilize Halverson and Halverson's [59] *artifact analysis model* to explore the connection between makerspace *features*, potentially perceived by individuals as *affordances*, allowing (or not) certain *outcomes*. Our analysis treats university-based makerspaces as the *artifact* (what others would call an *innovation*) of focus. Operating from the main outcome of students' development as engineers, we focused specifically on stakeholders' perceived affordances of makerspace features (e.g., the physical equipment within them) for that outcome. As well, in light of previously documented notions of engineering, we gave enhanced attention to one factor potentially impacting these perceptions, that being varied notions of students' development as engineers and related notions of engineering as a profession (see Figure 1).

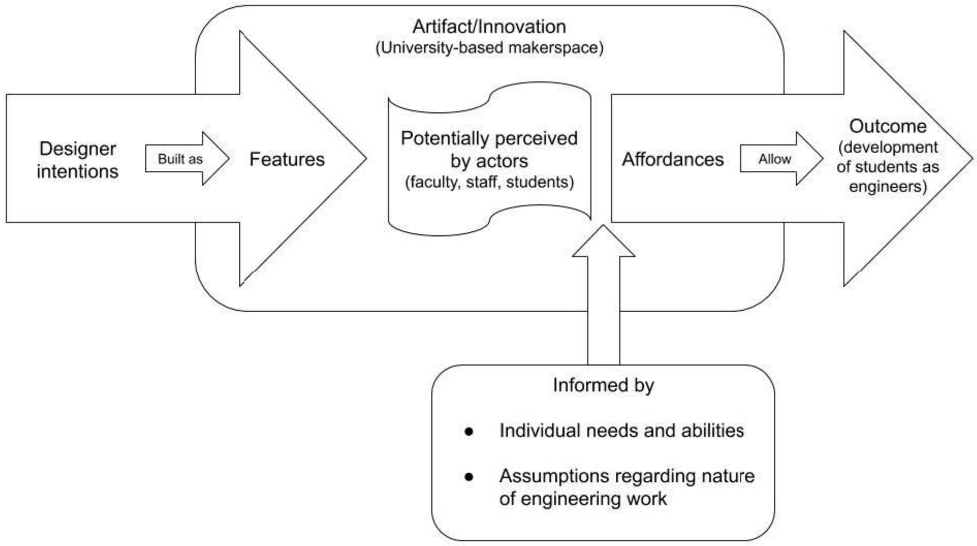

Figure 1. Adapting the artifact analysis model from Halverson and Halverson [59] and Bouwma-Gearhart et al.'s [53] modified use of the original model, our conceptualization of university-based makerspaces as artifacts, comprised of features, per designer intentions, potentially perceived by actors as affordances for outcomes.

2.3. Setting

Our exploratory study was part of a larger National Science Foundation-funded project that is focused on documenting the experiences of faculty, staff, and students at university-based makerspaces. We focused on the professional development of undergraduate students as engineers within the context of makerspaces integrated with undergraduate engineering preparation programs. Our larger project was informed by and aims to build upon research that drew connections between undergraduate student access, success, and persistence in the STEM fields with concepts such as a sense of belonging [60,61], motivation [62,63], and professional identity [23,24,33]. The larger project entailed the collection of survey, interview, and observation data from six university-based makerspaces across the United States. The findings of this paper are largely based on data from interviews with faculty, staff, and students.

All six makerspaces in our study functioned as open spaces for drop-in use by students and as teaching facilities in which formal courses or course-related components took place (e.g., labs, group projects). They all also served as meeting spaces for student organizations, as student study areas, and as casual places for students to hang out and socialize. We chose among U.S. university-based makerspaces affiliated with a college of engineering or engineering department at their respective institution. Attempting to limit some confounding factors in our findings, we also chose makerspaces at institutions with other similarities, utilizing only those designated as *Doctoral Universities: Very High Research Activity* within the Carnegie Classification of Institutions of Higher Education [64]. Five of the institutions were public universities and one was a private, not-for-profit university. All were located in the United States, with three of these located in the West, two located in the Southwest and one located in the Midwest. Given the potential differences in makerspace use based on time in existence, we chose six sites that had been in existence for varying lengths of time, ranging from less than 1 year to 10 years (see Table 1); however, no relevant differences were found and noted in the data per this characteristic.

Table 1. Characteristics of six university-based makerspaces included in the study.

	Affiliated Institution Type	Geographical Location	Affiliation to Engineering Department	Area	Number of Years in Existence (at Time of Site Visit)
Site 1	Doctoral Universities: Very High Research Activity; Public	Western U.S.	Y	750 m^2	Less than 1 year
Site 2	Doctoral Universities: Very High Research Activity; Public	Midwestern U.S.	Y	1100 m^2	1 year
Site 3	Doctoral Universities: Very High Research Activity; Public	Western U.S.	Y	2050 m^2	3 years
Site 4	Doctoral Universities: Very High Research Activity; Public	Western U.S.	Y	2250 m^2	3 years
Site 5	Doctoral Universities: Very High Research Activity; Public	Southwestern U.S.	Y	2150 m^2	4 years
Site 6	Doctoral Universities: Very High Research Activity; Private, Not-For-Profit	Southwestern U.S.	Y	1850 m^2	10 years

2.4. Data Collection

We utilized a phenomenological approach [65,66] to gain an understanding of the essence of individuals' lived experiences (i.e., engaging with and perceptions of a university-based makerspace). We conducted semi-structured in-person interviews with 45 faculty, 29 staff, and 148 students at the six university-based makerspaces, over two visits to each makerspace between 2017 and 2019. Each visit and data collection were conducted by a 2–3-member research team (a faculty member and research assistant(s)) from three institutions; each makerspace was visited by the same research team over time. Faculty members we interviewed affiliated with their campus makerspace primarily as instructors who taught a course(s) or an associated component of a course in the makerspace. Some faculty interviewees also held administrative or advisory roles in the makerspace. The staff members we interviewed held various roles associated with their campus makerspace ranging from administrative, instructional, student support, and technical support roles. Due to the overlap of faculty and staff functions within the makerspace in many cases (as administrators or instructors, for instance), and due to the similarities in the themes we identified across interview data from these two groups, we have grouped faculty and staff in the reporting of our findings. Although a small subset of the students we interviewed also held part-time student staff positions in their campus makerspace, we did not include these individuals in our definition of "staff." Given their similar general use of the makerspaces and overlapping "student perspective" that emerged we, instead, considered their interview data alongside the interview data from other students in our study.

We established an initial contact person at each makerspace before visiting, whom we identified either via a review of the makerspace website or via in-person contact at professional convenings for makerspace personnel. Through the help of the contact person and/or via our review of makerspace websites, faculty and staff interviews were arranged before we arrived at the study sites. In few cases, we conducted impromptu interviews of faculty and staff we encountered during our site visits. Faculty/staff interview questions were designed to elicit how they supported students' engagement with makerspaces, what they wanted their students to learn through their use of makerspaces, and to what extent they felt makerspaces promoted the skills and practices essential to engineering. All student interviews were conducted as we encountered them in the makerspaces, without prior arrangement to our site visits. Student interview questions were designed to elicit how the students engaged with makerspaces and what they learned per their use of makerspaces.

We audio-recorded and had the interviews transcribed verbatim. See Appendices A and B for the interview protocols. Due to interviews often taking place in fairly public places, and wanting them to be unobtrusive, unintimidating, and as comfortable as possible for interviewees, we did not ask interviewees to disclose their social identities, such as gender and race/ethnicity. Thus, these are not reported.

2.5. Data Analysis

We followed the recommendations of Auerbach and Silverstein [67] concerning coding and analysis. For each of the six sites, the research team that collected the data performed initial coding. Initial coding was done in two phases, an inductive followed by a deductive phase. The inductive phase consisted of reading the verbatim transcripts, drawing perspectives from participants' own words to determine emerging concepts and themes around makerspaces' impact on undergraduate students. Afterward, we worked across the three research teams and used the emerging themes to create a template around which to compile site summaries. Site summaries served as each research team's deductive phase of coding. The summaries informed subsequent analysis around this paper's focus, led by the first and second authors. Utilizing these summaries, the second author identified relevant interview segments and open-coded instances in which faculty, staff, and students mentioned their perceptions of makerspaces following the notion of features and affordances in general and concerning the objective/goal of developing students as engineers [51,59]. At each stage of analysis, we analyzed to the point of data saturation [68], until discovering no new patterns and feeling the patterns were based on adequate data richness concerning detail and nuance [69]. Themes were considered salient only when at least two participants mentioned the topic. All authors provided periodic checks of each other's work and, together, we came to a consensus concerning discrepancies. Towards informing the state of affairs regarding makerspaces and engineering education at U.S. universities writ large, we only report in this paper on features and affordances noted for at least two university sites by multiple interviewees. Our research process is summarized in Figure 2.

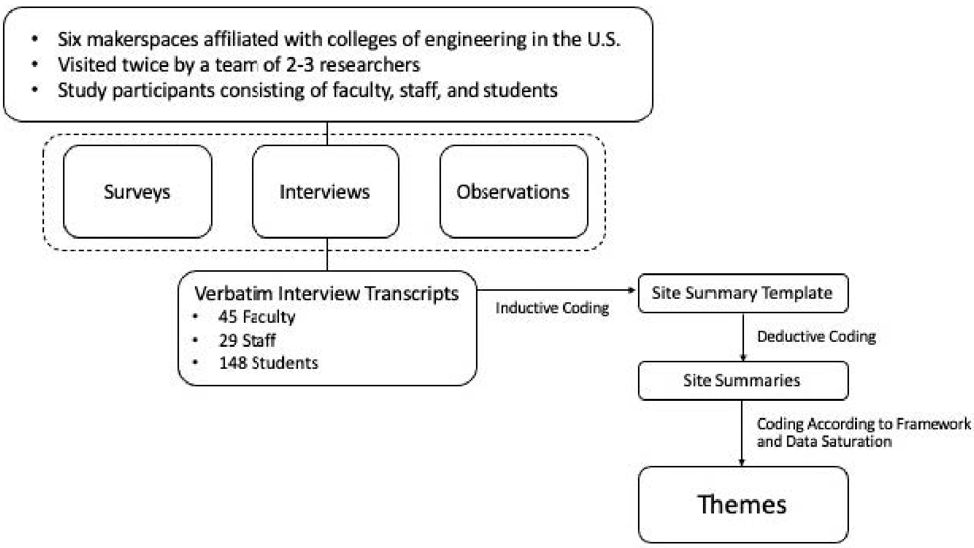

Figure 2. Schematic of the research process.

3. Results

3.1. Features of Makerspaces

Interviewees across the six sites discussed numerous features of their campus makerspace that they perceived as affordances for students' development as engineers. We grouped these features into three categories: physical features, climate features, and programmatic features (Table 2). Physical features included tools and equipment available at the makerspace; layout of the makerspace; physical capacity of the makerspace; and lowered barriers to entry (e.g., controlled cost, liberal eligibility requirements for access, hours of operation/access considerate of student schedules, a convenient location on campus). Climate features included a space for students' (sometimes first) exposure to making; a generally welcoming and supportive environment (including for non-engineering majors), consisting of diverse staff and users in terms of gender and race/ethnicity; availability of knowledgeable staff and other users that could help to navigate the space or technologies; feelings of allowability to experiment and fail in the space and using the space for personal projects and "hanging out;" and minimal monitoring of student users by faculty and staff. Programmatic features included courses or workshops offered in the makerspace; industry or community partnerships (in the form of financial backing and/or mentorship for student projects); and student part-time employment opportunities as makerspace staff. The above features were mentioned as makerspace aspects which interviewees appreciated, particularly with regards to students' participation in and development of engineering practice.

Table 2. Features of university-based makerspaces as identified by faculty, staff, and students.

Feature	Identified by	Illustrative Quote
Physical Features		
Tools/equipment	Faculty/staff and students	[B]eing able to come in here, 3D print things to test if they fit, to laser cut things to make sure the shape of everything's right, and then waterjet or whatever it happens to be that you want for your part is really convenient to have on campus and gives you a lot of flexibility. (Student.)
Layout of makerspace	Faculty/staff and students	[W]hat's really nice about this space, I feel because of the open layout, there's no closed rooms per se. I feel like it's a little bit more inviting than some of the other spaces here on campus. So I do appreciate things in that respect. So if I had a project, this would be the place I would come to. (student) [T]hey do not close the [maker]space for the classes. I wasn't sure how to make that work. And our first quarter doing it [holding a class in the makerspace], it didn't work very well because it was so loud and noisy that trying to give instruction did not work very well. (Faculty.)
Physical capacity of makerspace	Faculty/staff and students	The old model of engineering programming was not sustainable–a group of students working in one faculty member's research lab and with that person's equipment. This would not work in the cohort model or with lots of students. In [campus makerspace], in the winter and spring [quarters], we run the intro to engineering design classes and we can't use faculty research labs for this. (Faculty.) [I]n the initial weeks of the semester there's no priority [for accessing the makerspace] at all. You just, first come, first serve. This semester we started to, well at the end of last semester we started to hit capacity so we had to institute some kind of prioritization, so we stopped taking sign-ups [for access to the makerspace] in mid-February for this semester and then the priorities afterwards were students enrolled in a course in this building who need the makerspace to fulfill their course requirements. (Faculty.)
Lowered barriers to entry and use (e.g., cost, eligibility requirements, hours of operation, location)	Faculty/staff and students	[O]ne of the nice things is that it [campus makerspace] is very open to anyone. The only requirements we have are that you're a student and that you've gone through [the training]. Then you can use the space whenever you want . . . We're open from early morning until midnight, right? So, a lot of people really enjoy that. Come in here, start to print, come back later in the day and pick it up and stuff. (Student.)

Table 2. *Cont.*

Feature	Identified by	Illustrative Quote
Barriers to entry and use (e.g., cost, eligibility requirements, hours of operation, location)	Students only	[Y]ou can waive the cost [of accessing the makerspace] if you're in some research group. Which was my case. But if I wasn't able to waive the costs, I would have probably looked more into which free spaces they [the institution] had and which type of services you could do there . . . I think it doesn't make sense. Like we're already paying a lot . . . We should have free access to [campus makerspace]. (Student.)
Climate Features		
Exposure to making	Faculty/staff only	I've seen a lot of very, very interesting 3-dimensional structures that are being produced in the machines in the [campus makerspace] that I never thought of doing myself . . . it's just not the one on one either, the individual student and machine producing what the student wants, it's the opportunity to actually participate in a community to be exposed to an environment to see what other people are doing, what other ideas are being generated, what other types of structures or products are being produced. (Faculty.)
General welcoming and supportive environment	Faculty/staff and students	I think as a general consensus, everybody here [campus makerspace] is just a really big community. So no one is kind of left out . . . Everyone here just wants to like make something cool and see what their friends make and help them through the process and learn something along the way. (Student.)
Welcoming environment towards non-engineering majors	Faculty/staff and students	[Campus makerspace] is open to everyone, not just engineers . . . I would say 70% of people in here are either engineers or architecture students. A lot of architecture students do prototyping here. But I like that it's available for people who aren't that. I have one of my friends who I strongly recommended she try this out . . . and she's really enjoying it also, and she's not STEM at all. (Student.)
Diverse staff and user base (e.g., gender, race/ethnicity)	Faculty/staff and students	[Campus makerspace] hosts a lot of events, which I think does actually help reach more students, students of color, female students . . . it has made itself accessible or usable to as many student groups as possible. (Staff.)
Availability of knowledgeable staff and other users	Faculty/staff and students	[T]he staff is really great, and I think they do a lot of great support for teaching students how to use things. And if you have a question about like, "I don't know what to do for my project," they'll say, "You should use a printer. You should use a laser cutter." Whatever your application is. And they have a lot of great experience with that. (Student.)
Allowability to experiment and fail	Faculty/staff and students	[T]he project was just kind of a personal thing, so there wasn't really anything at stake . . . I didn't feel like there was anything lost and I feel like the experience enough, was kind of fun. (student) We encourage them to fail dramatically in this class, because it is a safe place to try things and it does not matter whether it fails. (Faculty.)
Allowability of personal projects and "hanging out" in makerspace	Faculty/staff and students	I thought it was engineering. You had to come in with a project, you had to, you know, be working on something super professional. But now people come in here [campus makerspace] and they don't even use the machines. They just study and that's totally normal. (Student.) [Students] can come in for something that's basic sticker making or like a glass fusing workshop, something that they might be using a machine indirectly, but it's not like the primary focus . . . our hope is that by bringing them into study, or play games or hang out or whatever, that they see that and are interested in it and are able to participate in that way. (Staff.)

Table 2. *Cont.*

Feature	Identified by	Illustrative Quote
Minimal monitoring of student users by faculty/staff	Faculty/staff and students	[Student work in the makerspace] doesn't require a lot of supervision. The students are pretty much in what I consider to be a fairly safe environment where they really can't do a lot of damage . . . by and large, it does not require a lot of supervision from me. (Faculty.)
Programmatic Features		
Courses, trainings and/or workshops offered at the makerspace	Faculty/staff and students	[B]y hosting workshops and a variety of different events we do, we make sure that we always have introductory classes as well as kind of more high level so that we're engaging all levels of makers in the space. (Staff) [Making use of the campus makerspace] has been a learning experience. Luckily there is a lot of training opportunities they are offering so they will teach you what you need to know. (Student.)
Industry or community partnerships (e.g., financial backing, mentorship of student projects)	Faculty/staff and students	[F]or the third project in the past few semesters, we give them a little prototyping budget so they can order something from [online retailer] whether that's an RC [remote controlled] car kit, or a drone, or something like that. That's available because [company] sponsored our class, so we have a little bit of a budget to work with. (Faculty.)
Student part-time employment opportunities at makerspace	Faculty/staff and students	I am so happy that this is my first job because my boss and just everyone else here [campus makerspace] has been very welcoming . . . I've just been surrounded by so much like support and collaboration and especially at [campus makerspace]. (Student.)

However, there were a few features that interviewees noted as unhelpful to students' development as engineers; and some claimed these features even hindered students' participation in the makerspace and in associated activities. For instance, some of the makerspaces we visited either lacked a dedicated teaching space, with an open floor plan and open-access policy. While this allowed makerspace users to freely move about and use the space and it equipment (whether or not they were affiliated with a formal course session taking place), some instructors who taught classes in these spaces noted that these features led to distractions, largely noise, that hindered their teaching. Additionally, the makerspaces we examined varied with respect to student access fees, ranging from completely free for all students registered at a university to one-hundred dollars (USD) per per student per semester. Some of the students whose campus makerspaces required higher usage fees noted claimed this as prohibitive of makerspace use and felt it unjustified (although, at one makerspace, there were ways to avoid this fee if affiliated with a research project or course necessitating makerspace use).

3.2. Affordances of Makerspaces

Faculty, staff, and students identified various affordances of their campus makerspace, which they perceived as contributing to students' development as engineers. We grouped these affordances into two broad categories: (a) affordances relevant for students' exposure to and learning of professional engineering practices, and (b) affordances relevant for students' participation and persistence in the field of engineering. A list of these affordances and corresponding illustrative quotes can be found in Table 3.

Table 3. Affordances of university-based makerspaces as identified by faculty, staff, and students.

Affordance	Identified by	Illustrative Quote
Relevant for Engineering Practice		
Hands-on experience	Faculty/staff and students	So the classes I teach are very hands-on, practical classes that involve the use of cell fabrication machines. They involve using electronics and soldering stations ... they couldn't exist if they didn't happen in a Makerspace setting. And so the students have to learn and use the machines from day one. And in order to do their work for the classes, they need to be there, they can't work from home. (Faculty) [Campus makerspace] gets me the kind of hands-on experience that I think all these other schools without this kind of accessible space [do not] really give you. Because something that people keep telling me and something that I've also been noticing is ... as we start meeting people from those schools who are kind of coming to the same workplace as we are, they don't have nearly the same kind of handling experience that we do ... A big part of that actually is because we know how to use all this equipment ... and actually work with different things. (Student.)
Knowledge of specific skill or how to use a specific equipment	Faculty/staff and students	[In a class taking place in the makerspace] [w]e're just learning about manufacturing processes ... we also talked a little bit about milling, and CNC [computer numerical control], and kind of what you need to think about when you're designing for those cases. (Student.)
Designing	Faculty/staff and students	[O]ne of the things we're really working on with this [engineering course taking place in the makerspace] is that some engineering disciplines don't feel ... like they are going through the design process in the same way that mechanical engineering is. And what we're trying to do is find ways to make sure that we're emphasizing to people who want to go into bioengineering or want to go into civil engineering, that you still go through the process of having an idea, sketching it out, making rough sketches, and then somehow testing it. (Staff.)
Creating a physical product	Faculty/staff and students	[T]hese printers are actually shifting the way that class is designed. Like before it used to be everything on Revit [modeling software] on the computer and doing a lot more of the same things we did in the introductory classes, but now they've taken it a step further and produce an actual, physical deliverable, which we like better I feel. (Student.)
Prototyping	Faculty/staff and students	So, I've only offered that course twice and every time I kind of learned how much I can push the students with this [maker]space because this kind of thing did not exist when I was a student, so I have no idea how much I can push them. So, last year I just told them you have to redesign it. You can CADD [computer aided design and drafting] it, it doesn't have to be printed or tested. Most teams did that. Some teams actually redesigned it, printed it, prototyped it, tested it, and then did another iteration. So, now I'm going to add that for all students in the next year. (Faculty.)
Testing	Faculty/staff and students	I mean everybody goes through the lecture, and then we go through a bunch of theoretical presentations, which students kind of assume are going to be true. But, there's no real way of being able to tell if it is actually true or not. I think that being able to build models, let's them do simple things like stress tests and breakage tests and things like that are a real good way to reinforce the learning that happens in a traditional classroom. (Faculty.)

Table 3. *Cont.*

Affordance	Identified by	Illustrative Quote
Iterating	Faculty/staff and students	That's what's great about three printers. The ones we have here are pretty quick and cheap. People are constantly refining whatever projects they're working on. We did the same thing, went through 10 different versions of the hand pieces for what we're doing . . . If you're an engineer, the fun is the iterative process. You can feel yourself getting closer and making progress. That's what I enjoy. (Student.)
Building	Faculty/staff and students	[T]hese are the things you need to know if you are going to be building something . . . you need to know what sequence and why do you put the sequence the way you do. Why do you put this here and here? And so when you [students] go into a job interview and can say that they have learned some of these things [at campus makerspace], that is what they [employers] are looking for. (Faculty.)
Interactions with others with similar interests	Faculty/staff and students	You get to meet people of the same interests I guess, or the same major or just in the same class that have to do the same thing that you do and if you come here for studying, you can always find a community or a group that's studying the same thing. (Student.)
Interactions with others with interests or expertise other than one's own	Faculty/staff and students	I would say it's [being in campus makerspace is] valuable in the sense of interacting and working with different disciplines. Because especially like in a full-time job, you know, you aren't just working with other engineers, it's a lot of different people from different backgrounds. (Student.)
Teamwork/Collaboration	Faculty/staff and students	[Campus makerspace] is really inviting. I would say that [it] feels open and the word I would use to describe is, it's a collaborative space. For me it's almost less just design but is like teamwork. This is where people come to talk about ideas and collaborate on whatever it is. (student) [What I want students to get out of by being in the campus makerspace] is the spirit of collaboration that we try and foster in our courses . . . I'm a big believer in that sort of learning style, not you get lectured and you go into your dorm room and do the homework assignment, or go to the lab and work by yourself. I think a lot of the more traditional engineering programs still have that model, and that's why those spaces were designed that way. Because you'd do a lecture and then you go off to the lab and you do your work. But in our department, we believe that's not the dominant or really great way to have people learn. So it's a lot more collaborative . . . And that's why we like running these courses in these makerspaces, because well you see, they sit around the tables there, and they work in small groups even though they might have individual assignments. (Faculty.)
Ownership over one's work	Faculty/staff and students	We're trying to get them to build something and to sort of feel some ownership over okay, what is the problem and identifying their own problem which I think is maybe the hardest part for freshmen, so we're really working hard on trying to get that right. And then, having them work through that process and work with a team and build something that works and have that ready by the end. I'm hoping that all the teams have something that they're proud of at the end. (Faculty.)

Table 3. *Cont.*

Affordance	Identified by	Illustrative Quote
Projects with "real" consequences	Faculty/staff and students	Yeah, there were real consequences to my decisions either failures or successes, so I really could feel what I was doing. And when I did succeed, it was much more than 'oh yeah, I did well,' it was more like, 'yes! I did that.' (student) When we have the tools to make things, that's really when engineering comes alive and that's when we get to demonstrate our skills and we get to make an impact in the world. So, having those resources [in the campus makerspace], I think is so great to actually make ideas come to life. (Student.)
Entrepreneurial activities	Faculty/staff and students	So, I have a, air quotes, start up. I mean, we're just trying to build a product and then launch it to market . . . it's [campus makerspace is] a team space where we can come and we can build together . . . I don't have a lab anywhere else . . . but the makerspace is—I almost feel like I'm coming on to a tech campus. (Student.)
Communicating ideas	Faculty/staff only	I feel the uses of . . . makerspaces are to aid you with pitching your idea and creating something and having an idea and having a representation of it, and presenting it to someone. Because you can always talk about it all day and have a 3-D model that you click around on your screen. But to have something that someone can physically hold and you can talk about and see if they're on board with you, that's a skill that necessarily we don't teach in the engineering department. (Faculty.)
Creativity/innovation	Faculty/staff only	I've seen a lot of very, very interesting 3-dimensional structures that are being produced in the machines in the [campus makerspace] that I never thought of doing myself. It's, aha, that's actually a really kind of interesting way of building a structure . . . And that, I think, really helps the creative side. It helps a person become a more creative person, just by seeing what has been done out there and what is possible with certain types of machines. (Faculty.)
Integration of multiple disciplines	Faculty/staff only	I think if they're [students are] in the machine shop, it's very engineering-focused and they can easily get sucked into 'I have to make this project one way because this is what's offered here.' In a makerspace, they're open to more different kinds of making and they're seeing other students engage with a sewing machine, for example, to incorporate engineering and arts in a different way . . . So, inspiration and creativity are huge. (Staff.)
Inaccurate/incomplete notion of engineering	Faculty/staff only	I think that students get lulled into the perception that they can 3D print just about anything without realizing that the tolerances that are involved, the volumes that are involved, and even the strength of the material that's involved is not catered to many types of products . . . Just as long as the student understands the placement of these types of machines in the overall design environment, and especially where it belongs in the production environment. It actually serves to improve a student's function as an engineer, but if misused, it can actually have a detrimental effect. (Faculty.)
Relevant for Participation and Persistence in Engineering		
Student sense of comfort and belonging in makerspace	Faculty/staff and students	[B]eing able to have this readily available [makerspace] environment where you can just hang out and do your own thing while still being open to like interacting with other people, is really valuable. Kind of like, I guess for me, analog would be like your living room. Um, yeah, it's like [a] home base sort of thing. (Student.)

Table 3. *Cont.*

Affordance	Identified by	Illustrative Quote
Ability to ask questions at makerspace without fear	Faculty/staff and students	[T]he workers here are super nice and they are not intimidating at all; you can ask them anything and you don't have to worry about feeling stupid or pushy or embarrassed. (Student.)
Job or job prospects	Faculty/staff only	[Having experience in the campus makerspace] just builds a resume, so like I said, really makes them [students] stand out. Job fairs come here and see that they work in [campus makerspace] and they get selected. (Faculty.)
Creation of new course previously not possible without makerspace	Faculty/staff only	[T]he best examples of how a facility influenced academics—so this course did not exist without [campus makerspace]. It was created because of these tools. (Faculty.)
Appeals to users of various skill levels	Faculty/staff only	I think it's [campus makerspace is] really helpful for the students who have no background because there are people here to help them. [And] there are people who have their own printers or work on cars or whatever and feel very comfortable in that kind of thing. And the makerspace gives a very safe place for everybody to try something. (Faculty.)
Makerspace activities as fun/engaging	Students only	[We] went through 10 different versions of the hand pieces for what we're doing . . . There's certainly frustration. Most of the frustration is just the fact that we're so close and we have to wait again for printouts, but that's part of the fun. If you're an engineer, the fun is the iterative process. You can feel yourself getting closer and making progress. That's what I enjoy. (Student.)

3.2.1. Affordances Relevant for Engineering Practices

Affordances under this first category are those that interviewees claimed prepare students to develop as engineers by exposing students to and aiding in their learning of engineering practices. One of the most frequently mentioned affordances under this category was students acquiring "hands-on" experience, which was made possible due to available physical features in the spaces, the various tools and equipment. Interviewees stated that the availability of these physical features allowed students to develop specific skills (e.g., soldering) or knowledge on how to use a specific piece of equipment (e.g., laser cutter). Another frequently mentioned affordance, across all interviewee groups, was students' engagement in the process of design. For many interviewees, makerspace-afforded design was a a larger process encompassing other engineering practices that made use of the makerspace's physical features, such as creating a physical product, prototyping, testing, iterating, and building. In and of themselves, all interviewee groups discussed these practices as affordances that the makerspaces provide for students.

Interviewees claimed other makerspace affordances as attributable to the social and programmatic features of the makerspaces. All interviewee groups spoke of makerspaces affording students' interaction with others with similar interests, as well as those with different interests or expertise. This point was sometimes made by interviewees while discussing how the makerspaces afforded teamwork and collaboration, and at other times while discussing how the spaces allowed students to take ownership of their work. All interviewee groups mentioned that makerspaces afforded students' engagement in projects with "real" consequences, sometimes with entrepreneurial/marketing potential. Additionally, faculty and staff spoke of affordances for students to communicate ideas, be creative and innovative, and to integrate multiple disciplines' knowledge and skills in their work.

While all of the above affordances were perceived as generally helpful for students' development of engineering practices, some faculty and staff voiced concerns that the physical features in makerspaces may lead students to develop an inaccurate or incomplete understanding of engineering. They expressed concern that some students may become overly dependent on fancy equipment without critically thinking about whether the equipment is necessary to the overall process of design and production. For instance, one staff member stated, "We used to joke that people shouldn't cut rectangles on the 'lazy cutter' . . . like don't use the laser cutter as a 'lazy' cutter." Faculty expressed the need for students to understand that producing rapid prototypes is only part of design and product development and, by extension, working as an engineer.

3.2.2. Affordances Relevant for Participation and Persistence in Engineering

Interviewees also reported various makerspace affordances for students' further participation and persistence in engineering. These affordances seemed predominantly related to the climate and programmatic features of the makerspaces. One of these most frequently mentioned affordances was students' sense of comfort and belonging fostered in the makerspaces. In many cases, the makerspaces in our study functioned not only as spaces where "professional" or "school-work" engineering-related activities took place, but also as spaces of social gathering, for students to work on personal projects or "hanging out," including for students not in engineering programs/majors. Overall, interviewees insisted that students generally felt unencumbered in their activities in the space. Reflecting on students who were working on more professional or school-work related projects, many interviewees noted that makerspaces afforded these students viewing the engineering field as more appealing and accessible. All interviewee groups detailed students' ability to ask questions in the makerspaces without fear or embarrassment. While interviewees largely discussed engineering majors feeling these impacts, a few interviewees also felt that non-majors' engagement in these spaces had them feeling similarly.

Faculty and staff also claimed jobs or job prospects resulted from engineering students' participation in the makerspace. Faculty and staff claimed the makerspace allowed students' involvement with courses (both in engineering programs and in other programs) not possible without the makerspace, including courses appealing to students of various skill levels, ranging from those with "no background" with equipment in the spaces to those who have their "own (3D) printers," as noted by one faculty interviewee. Additionally students, engineering majors and non-majors alike, identified activities within the makerspace as being fun and engaging, that motivated their participation in engineering activities. As articulated by one student, "there is the fun side of engineering and I get that here [in the makerspace]; not so much in my classes." For those students enrolled in engineering programs/majors, interviewees claimed that students' enjoyment of engaging in activities in the makerspaces afforded students persistence in their engineering programs and into the professional field.

4. Discussion

Using framing from affordance theory [51] and an analysis model for education innovations (or *artifacts*, from Halverson and Halverson [59]), we identified features and affordances of university-based makerspaces that foster students' development as engineers. As perceived by faculty, staff, and students, affordances included physical features (e.g., equipment), and well as features related to creating a welcoming and supportive climate for participation. Interviewees also detailed makerspace features related to engineering programs and their norms and requirements (e.g., courses and workshops) that would otherwise not have been offered on their campus. Interviewees spoke of affordances concerning two aspects of "becoming an engineer." The first aspect concerned students' development regarding engineering practices, such as via "hands-on" experience with the physical features of makerspace (tools and technologies). These also included the practices of design and teamwork, fostered by makerspace features both technical (e.g., open spaces and equipment) and those more social (e.g., enhanced interactions with diverse others, a sense of ownership over one's own creations). These findings help to confirm the work of other researchers who have detailed university makerspaces as places where students can gain design and fabrication knowledge and skills through the availability of tools and equipment, as well as collaborators [3,19,70].

Our findings are corroborated by a recent study by Jalal and Anis [20], who found that engineering students in makerspace-based courses reported being exposed to design problems and processes that closely mirror the complexity and ambiguity of professional engineers' projects. As did these researchers, we found students' work in university-based makerspaces fostered their ability to approach novel engineering problems somewhat authentically, utilizing the practices of engineers, such as working collaboratively on real-life design problems that required applying various knowledge and skills (some of which were only acquired in the makerspace), planning and organizing tasks, creating prototypes, and considering and responding to user needs.

We find especially promising the potential role of makerspaces in helping users develop knowledge, skills, and proclivities that may support their attending to social problems that are notably complex, even *wicked* per the incomplete knowledge needed to solve them, the need for diverse stakeholder involvement, and the interconnectedness of the problems with others [71]. Many science problems, such as those pertaining to sustainability, are wicked [72], requiring attention to theories, data, and practices of inter-related disciplines, often across STEM [73] and others outside of STEM. Design problems are wicked as well as [73,74], ill-defined or unstructured. Design/innovation around sustainability may, thus, be especially wicked. "Sustainable innovation means innovation that balances the long-term influences of the process and the output with the needs of people, societies, the economy, and the environment. In addition, sustainable innovation democratizes innovation as it aims at including all people" [75],(p. 87, 2016). With their potential to afford design processes utilizing cutting-edge technologies, alongside social interactions that can bring those with differing perspectives and strengths, makerspaces seem promising in affording experiences authentic to those coming together to solve the wicked problems of society.

In fact, how to best prepare students to engage with complex problems, and the creation of potential solutions, is itself a wicked problem, alongside most questions of teaching and learning in higher education as complex human phenomena [76]. Our research here points to makerspaces as one tool that university educators and their students may have at their disposal to engage with complex problems, all the while learning about and ing engineering. Specifically, our data points to the potential of makerspaces in helping to develop students' system perspectives and thinking that are of critical importance to understanding and solving complex problems (e.g., [77–79]). Makerspace-situated design activities, requiring various knowledge and skills, planning and organizing tasks, creating prototypes, and considering and responding to user needs, may afford innovation around complex real-life problems.

Our second category of affordances for students' development as engineers concerned those relevant for students' participation and persistence in engineering, largely associated with the welcoming social climate of makerspaces. Makerspace advocates often point to their potential to be democratizing spaces that can broaden participation and persistence in the engineering field. Limited research seems to confirm this, to a certain degree, for women (e.g., [13]) as well as racial/ethnic minorities in engineering [80]. Admittedly, our data does not speak directly to whether university-based makerspaces increase (or have the potential to increase) the participation and persistence of certain demographic groups around social identities such as gender, race/ethnicity, or socioeconomic status. Yet the consensus among our interviewee groups was that the university makerspaces we studied were making efforts to, and succeeding in, attracting and retaining users, including current and potential engineering majors, that otherwise may have felt intimidated by engineering or design or making. This welcoming climate was partially fostered by the availability of knowledgeable and diverse staff and other users (including student peers employed there part-time), and (with some overlap with Jalal and Anis' [20] findings) a feeling of allowability to experiment and fail in these spaces. Adding to other limited research, including recommendations to encourage makerspaces use by those with physical limitations [81], these findings may support makerspace design to ensure a greater diversity of users.

This potential may be especially promising. A scientifically and technologically literate citizenry is essential to meet the U.N. Sustainable Development Goals [82], as well as ensure that the U.S. remains economically competitive in an increasingly resource-constrained global marketplace [83]. However, a limited STEM workforce is not sufficient to address such problems, including wicked ones such as sustainability, now widely recognized in both business and academic circles as needing greater attention [84]. Addressing problems such as water scarcity, growing energy demand, and global climate change requires reshaping the way we educate a larger group of university students, who can think critically about and have roles at the intersection of technology and civic life.

We note that the two categories of affordances that we identified (each of which are important in their own right) may, per their intersection and co-occurrence for students engaged in these spaces, be collectively more impactful for students. A space fostering engineering skills, knowledge-acquisition, and comfort with engineering-based activities can help students visualize and situate themselves in the profession. This is especially important for minoritized groups in engineering, that research has shown have a tendency to make decisions regarding engagement in engineering based on personal, rather than accurate, notions of the "norms and expectations" of engineering [33] (p. 8). University-based makerspaces may be uniquely situated to allow a diversity of students to develop practices relevant to the engineering profession while simultaneously providing an environment that encourages and supports their participation and persistence in the field.

Our study identified university-based makerspace affordances for both engineering and non-majors alike. Additionally, while others have noted makerspaces as potential "entry points to the technology" for students [20] (p. 1260), our interviewees provided nuance concerning issues of access and accessibility in these spaces. They specifically highlighted both potential barriers to entry into university makerspaces, such as cost and eligibility requirements (that were sometimes constraining at the sites we studied), and features affording more access, such as expanded hours of operation and centralized locations on campus. Entry points into making (including for non-engineering majors) was afforded by the makerspaces, as well as activities and understanding related to the broader concept of design, such as creating a physical product, prototyping, testing, iterating, and building [85].

While we do not know the actual extent to which the makerspaces of our study actually impacted students (matriculation and graduation, assuming and advancing in a professional engineering position), it seems that the novelty of physical and social/climate-related features likely allowed for value-added impact, and especially in conjunction with more typical engineering programming. In some cases, makerspaces provided such novel features that faculty went so far as to say that some programming (e.g., certain classes, activities) would not have otherwise been possible. The makerspaces, and their features, were relatively easy-to-utilize, potentially buying faculty meaningful revisions to their teaching without adding significantly to their workloads [86], that we know may be especially important for faculty who may not be as experienced with incorporating education innovations that can improve student learning and development [87]. The makerspaces that we studied, utilized by faculty for formal coursework and programming and also allowing other uses, were conducive to a diversity of student users and their diverse desires around engineering-related activities. For engineering majors, most notably, the makerspace climate seemed to make the engineering field more enticing of their participation, a field well-known for student attrition and, specifically, for certain groups. Interviewees described makerspaces as generally welcoming and supportive places, even for students without prior experiences in making and makerspaces, including for non-engineering majors who appreciated engaging in enjoyable engineering-based personal projects in the space. In many cases, the makerspaces we examined functioned as both spaces where "professional" or "school-work related" engineering took place as well as social space to study or simply "hang out." These findings add fodder to others' insistence that makerspaces can function as spaces for informal socialization, including assertions based on anecdotal evidence [3] and on investigations around makerspaces used less by formal programs [70].

While our interviewees largely spoke positively of makerspaces' impact on students' development as engineers, interviewees occasionally discussed specific features that could be viewed as hindering students' participation and development in engineering, both directly and indirectly. While the open floor plans of these spaces were generally thought of as desirable, faculty noted that distractions and noise could impede students' learning. While makerspaces were generally considered to be open access across all six campuses, especially in relation to other campus spaces where engineering practices could happen (e.g., machine shops), student interviewees also indicated that makerspaces requiring usage fees, and those used heavily for coursework, were not be as accessible as they would like. Additionally, faculty and staff indicated a concern that some features within makerspaces may lead students to develop an inaccurate or incomplete understanding of engineering. Some faculty and staff voiced concern that some students may become overly dependent on fancy equipment without understanding of the place of technologies and rapid prototyping in design, potentially adding to concerns others have noted about undergraduate engineering education fostering an overly technical notion of engineering in contrast to the realities of much authentic engineering work [28].

Still interviewees at our sites, and especially faculty and staff, discussed even the most technical features as affording practices, such as system-oriented thinking, at the technical-social intersection of engineering. For example, during our site visits, we frequently heard about (and witnessed) students discussing their 3D printing outputs with other students, faculty, and staff to troubleshoot or refine their design, before attempting another iteration of their output. In some cases, these projects were tied to meeting the specifications of a problem posed by industry or community partners. Thus, even though learning to use a 3D printer or prototyping may appear to be "technical" affordances of makerspaces, such activities often accompanied more "social" affordances, such as collaboration and meeting client needs. Additionally, faculty, staff, and students alike frequently mentioned teamwork or collaboration as one of the affordances they perceived as being available in makerspaces and contributing to students' development as engineers, occurring in the context of working on more "technical" tasks, such as creating physical products or testing their products.

Specifically, the makerspaces we studied were described as spaces that allowed engineering students to interact with those of different interests or expertise and multiple disciplines' knowledge and practices. This reality may help students round out their notion of engineering practice, seeing connections and overlap with other disciplines and ways of knowing that may also inform, for instance, the processes of design work and its ultimate goals, including goals with political and ethical implications. At least for these six sites, university-based makerspaces, and those working within them, might be well equipped to more directly address this crucial aspect of students' development as engineers. Professional engineers must feel a sense of ownership and responsibility to solve "wicked" problems. The typically understood practices of engineers (e.g., technology use, collaboration on complex projects) must be achieved via awareness and attention to political, ethical, and human welfare implications often inherent in these practices. A related understanding regarding the work of professional engineers, so far having received limited coverage by educators and researchers, is engineering as *praxis* [47], or practitioners critically reflecting and acting upon the world in order to transform it for social good [86]. Although ABET criteria [32] imply this notion, university engineering programs and faculty may not understand or be committed to students' understanding of engineering as praxis to the point of emphasizing it with the same intensity as they do other aspects of engineering practice.

Karwat et al. [47] advocate for engineering education programs to help round out students' notions of engineering, to include engineering as praxis, and to explore with students what this means for their development and engagement as engineers. Such may require helping students replace a typical understanding of engineering practice as (solely or predominantly) being technical with a more heterogeneous perspective of engineering, framed within a focus on fostering metacognitive awareness and attention to the political, ethical, and human welfare implications of engineering (see Figure 3). Beyond not helping students to develop accurate and authentic notions of practice [20], not stressing these realities may mean students who are looking for future careers that allow for this may be turned away from engineering [41], alienating those who may be able to bring a much-needed diversified perspective into the field of engineering. Notably, understanding and discussion of engineering as praxis was not evident in our data; we did not find any obvious mention of affordances of university-based makerspaces that interviewees perceived would support students' metacognition around the inherently political nature of engaging in engineering practices [47]. Yet university-based makerspaces may be functioning in ways that help students get closer to these realizations and commitments.

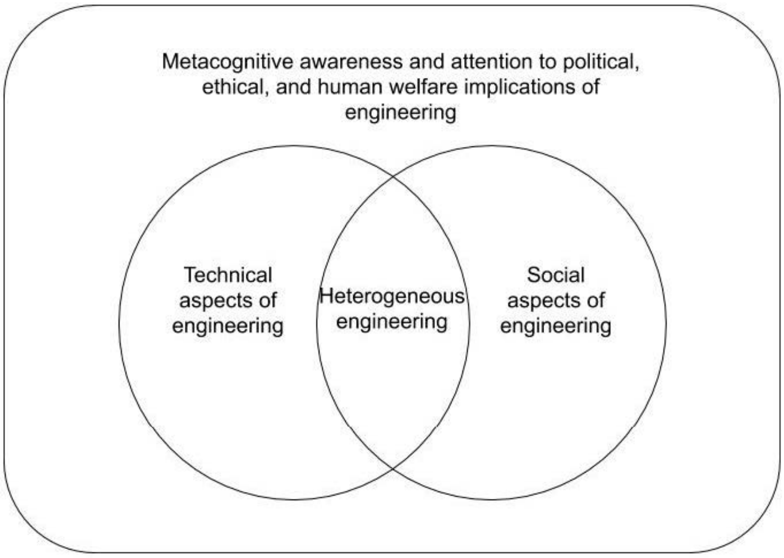

Figure 3. Informed by Karwat et al.'s [47] notion of engineering as praxis, our conceptualization of engineering as praxis, incorporating Stevens et al.'s [31] notion of heterogeneous engineering.

Limitations

We recognize the limited generalizability of our findings. Our six sites do not represent all university-based makerspaces across the globe, let alone the United States. Although efforts were made to discover and interview all engineering faculty teaching in these spaces, and every staff member we encountered working in them, we also did not secure a representative sample of faculty, staff, and students engaging with university-based makerspaces at these universities. However, across our sizable sample of individuals, we noticed a considerable overlap in stakeholders' (as individuals and as stakeholder groups) perceptions across the six study sites, feeling we achieved data thickness [69], or data from enough sources. The overlap reflects some level of data consistency, particularly given the diversity in makerspace geographic location, size, and years of operation. Thus, our finding may illuminate the nascent field of research on university-based makerspaces, and those broadly interested in attempting to design and offer makerspaces as innovations to assist students' development as engineers, and the programs and faculty who are working towards this goal.

5. Conclusions and Implications

The body of research on the topic of makerspaces' impact on students' development regarding knowledge and skills is just now emerging, for the STEM disciplines overall, and across the K-20 formal schooling spectrum. This paper adds to the limited body of empirically based literature that is beginning to explore the affordances of university-based makerspaces on postsecondary students' development, specifically their development as engineers. In this paper, we presented the perceptions of faculty, staff, and students of the affordances of six university-based makerspaces for the development of students as engineers. University-based makerspaces are easily read as spaces filled with physical features promoting technical affordances for students. We have found that a collection of features found in these spaces can afford non-technical aspects of developing engineering practice, as well as practices arguably at the intersection of the technical and social aspects of engineering. We found, when looking across interviewee groups and sites, that university-based makerspaces are places that may afford what various stakeholders are calling for from postsecondary engineering programs, namely the preparation of students within the *heterogeneous perspective* of engineering [31,32,44] requiring complex, collaborative, and creative work attending to both physical–technical and human–social components within and across systems.

Our interviewees further described makerspaces as generally welcoming and supportive spaces that encouraged the participation and persistence of a diverse group of students in engineering activities, including those who may have been previously intimidated or uninterested. Nonmajors and those pursuing degrees in engineering, alike, enjoyed being in the space, pursuing formal course requirements and projects of personal interest, strengthening their interests in engineering-related pursuits. Ultimately, the crux of what university-based makerspaces may offer in the development of students as engineers is greater access to an array of modern techno-social affordances relevant to the practice of engineering, co-existing with affordances that aid in students' participation and persistence in activities at this intersection.

These include activities attending to complex problems requiring systems thinking. Alongside creating activities that utilize makerspaces to foster students' systems perspectives, faculty and staff can encourage students to be metacognitive about this perspective in the field of engineering, utilizing cutting-edge technologies as teams effective at capitalizing on and merging the diverse knowledge, skills, and perspectives needed, planning and organizing tasks, and considering and responding to society's needs. Through these activities, the faculty can help students understand the political and values-driven nature of engineering activities, especially when tackling solutions for the most wicked problems in contemporary society. We recommend that, as makerspaces continue to become an integral part of engineering education, that concerted efforts in training and hands-on experiences amongst faculty and staff are synergistically incorporated into the four-year curriculum to further motivate students to develop into engineers while using makerspaces as "safe spaces" for their formation. Of course, professional development may be needed to prepare educators to do this, as planning for students' meaningful engagement in makerspaces, and what it means to their development as engineers and notions of engineering, is potentially already new-enough territory [5].

Additionally, as evidenced by the affordances of these spaces for engineering majors and non-majors alike, and the concern for student fees/access and capacity concerns associated with makerspaces, we recommend additional attention from higher education administrators to help make these spaces accessible and sustainable for use by more students. Those designing these spaces, and those providing funding for them may be particularly influential in making sure certain "high impact" affordances are provided [88], that may attract and support diverse users of these spaces (e.g., trained staff and other support personnel; open access areas for personal projects; places to "just hang out"). ABET leaders might also consider the evolving role that makerspaces are playing in engineering education, encourage such spaces, and assessment of them along more climate-focused criteria around elements that support the more holistic development of engineering students.

As for researchers interested in university-based makerspaces, and especially in the development of students for STEM professions, we see a need for more investigation of direct links of makerspace features to the intended outcomes of designers, administrators, and faculty. Such research will allow designers of such spaces, as well as educators, to utilize elements most predictive of student learning and development, and for faculty professional developers to help faculty effectively utilize these. Additionally, investigations of the longer-term effects of engagement in makerspaces (including through graduation and into professional practice) would be beneficial for numerous stakeholders. Lastly, investigations into the degree to which makerspaces, and their elements, live up to their promise of diversifying traditionally exclusionary fields (such as engineering) are needed, specifically about systemic forms of marginalization along lines of race, gender, class, ability, and others that may bear out in makerspace policies, rhetoric, and practices.

Author Contributions: Conceptualization, J.B.-G. and Y.H.C.; data curation, Y.H.C., L.S.N., I.V., E.S. and C.A.L.; formal analysis, Y.H.C., L.S.N., I.V. and E.S.; funding acquisition, J.B.-G., L.S.N. and I.V.; investigation, J.B.-G., Y.H.C., L.S.N., I.V., E.S. and C.A.L.; methodology, J.B.-G., L.S.N. and I.V.; project administration, J.B.-G., L.S.N. and I.V.; resources, J.B.-G., L.S.N. and I.V.; supervision, J.B.-G., L.S.N. and I.V.; validation, J.B.-G., L.S.N. and I.V., visualization, Y.H.C.; writing—original draft preparation, J.B.-G. and Y.H.C.; writing—review and editing, J.B.-G., Y.H.C., L.S.N., I.V., E.S. and C.A.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science Foundation, grant numbers EEC 1664271, 1664272, 1664274, and 2113755.

Institutional Review Board Statement: Ethical review and approval for this study was provided by the Institutional Review Boards of University of Central Arkansas (protocol code 18-138 approved on 23 August 2018), Oregon State University (protocol code 2019-0052 approved on 16 April 2019), and University of Florida (protocol 202003240 approved on 6 January 2021).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to confidentiality concerns for participants.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

Faculty and Staff Interview Protocol

1. I'd like to hear about the history of the makerspace at your institution
    a. Who motivated/supported the development of the makerspace?
    b. How have engineering programs and colleges interacted with the makerspace historically? Is this interaction similar to other programs' interactions (other than engineering)?
    c. How are decisions made with respect to programs or course use of the space or other priorities for its use?
2. How are you/others supporting student participation in makerspaces?
3. What motivates you or others to incorporate the use of a makerspace in coursework?
4. Please share an example of an assignment that you or others give students that requires them to engage in a makerspace.
5. What does a successful student look like in your program? How do you think a makerspace supports this?
6. To what extent do you think that participation in a makerspace may help students develop with respect to their engineering program and trajectory in the field?

7. Are there other things you are hoping students gain from their participation in makerspaces?
8. If applicable, what ABET outcomes are you or others expecting students to accomplish through participation in makerspaces? Are there additional outcomes you or others are expecting?
9. How much autonomy do students have regarding their activity in the space? How much are they allowed to determine their use of equipment/tools in the space (i.e., 'play')?
10. How do you interact with the makerspace and the students when they are using the space? What does this look like?
11. To what extent do you think makerspace assignments promote skills and practices that are essential to engineering? Can you provide examples?
12. To what extent are students encouraged to use the space beyond their required school projects or tasks? (Are students using the area to 'hang out' or 'socialize', are voluntary events hosted there, etc. Are they allowed to be?).
13. How have makerspace assignments/activities influenced students' learning? Please share any evidence of this influence, school-related and otherwise.
14. To what extent do you feel makerspaces may help struggling students?
15. Are there students you see struggling in the makerspaces or during specific activities within the makerspace? If so, what are some of the challenges you notice them dealing with?
16. What changes would you make regarding makerspace layout, use, promotion, integration with academic programs?
17. Is there anything else you'd like to share or clarify?

Appendix B

Student Interview Protocol

1. Tell me about your experiences working in makerspaces. [Probe for formal education (course affiliated) experiences AND any informal (participant-initiated) experiences]
2. What's the value of being in a makerspace?
3. What do you think your instructor(s) want you to gain from being in the makerspace?
4. How are the makerspace assignments helping you learn about what engineers do?
5. Through participation in makerspace activities, what practices are you learning that you think are essential to engineering and how valuable do you think the skills are?
6. Do you feel you belong in a makerspace, why or why not? What does belonging look like to you?
7. How do you form and work in teams in the makerspace as compared to classroom or study groups?
8. Do you feel there are norms or unwritten rules for participating in the makerspace? If so, what are they?
9. Are there people you feel you relate better to in the makerspace? If so, how, and if not, why?
10. Share a time when you got stuck when working on a makerspace project. What did you do? Is this the same approach with other engineering assignments?
11. [If applicable, any questions that occur to interviewer per what witnessed during observed makerspace activity]

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