Building 21st Century Skills through Development Engineering

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Abstract

At the University of California at Berkeley, the vision of a 2020 Engineer with the skills to solve the global challenges of today is being realized through an emergent program focused on design for social impact. A minor for Ph.D. students, Development Engineering (DevEng) is a degree program and accompanying ecosystem that aims "...to create technology interventions in accordance with the needs and wants of individuals living within complex, low-resource settings." This paper explores how the competencies conveyed through the DevEng program overlap with and go beyond the criteria laid out for the Engineer of 2020. Today's engineering student engages with a wide variety of global problems, only some of which are addressed by solely technological solutions. Academic programs across the country, including DevEng, have recognized that a unique skillset is needed to address these complex challenges. As a result, there is a growing collection of academic programs (e.g., DevEng, Design for Social Impact, Humanitarian Engineering) that train technologically adept engineers to work in multifunctional teams while attempting to have a positive social impact on the world. In this paper, the authors examine the skill development activities that students in the DevEng Program are exposed to and whether they meet or exceed the goals and principles of the 2020 Engineer. The paper further describes the DevEng learning objectives and accompanying ecosystem opportunities to determine whether the program is on track in providing students with a multidisciplinary set of skills and diverse experiences that effectively train the Engineer of 2020.

Keywords

2020 engineer; development engineering; 21st century skills; education ecosystem analysis, skills analysis

1. Introduction

In 2004, stakeholders representing the National Academy of Engineering (NAE), academic institutions, government agencies, ABET, and industry developed an influential framework outlining competencies needed by engineers in 2020. The two volumes of the Engineer 2020 reports [1, 2] recognized that challenges and opportunities faced by the next generation would require new skillsets and that training students to address such multifaceted issues required change from academic institutions. By drafting scenarios of possible technological, societal, global and professional challenges of the future, they developed a new archetype: the engineer of 2020.

Since the Engineer 2020 reports were published, academic programs have aspired to answer this call. Many academic offerings aim to equip the 2020 Engineer, including programs focused on engineering leadership, engineering entrepreneurship, humanitarian engineering, social entrepreneurship, and engineering design. Each employs a different approach but have in common a commitment to ensuring that the engineers of tomorrow are equipped with the skills necessary to address real-world challenges holistically. Problem contexts within global development mirror the working environments outlined in Engineer 2020. Global development encompasses societal problems such as food insecurity, water access, and affordable healthcare, all of which are entrenched within complex social, political, and technical ecosystems. Solutions to address development and poverty-related challenges require practitioners with diverse skillsets to work together as well as collectively possess a deep understanding of the local context.

Although the names of the programs and centers vary (e.g., the Humanitarian Engineering and Social Entrepreneurship (HESE) Program at Penn State University [3], the Center for Socially Engaged Design at the University of Michigan [4], Rice 360: Center for Global Health at Rice University [5]), design for impact programs provide students with opportunities to apply technical skillsets to globally relevant problems, including those faced by low-resource communities. Development-oriented engineering programs have been shown to be effective at recruiting and retaining women students [6,7] as well as providing a means for students to learn critical communication and leadership skills. In 2010, Amadei and Sandekian reported that benefits offered through the Engineering for Developing Communities program at University of Colorado at Boulder directly aligned with ABET criteria and outcomes from the American Society of Civil Engineers *Body of Knowledge* [8]. They further noted that while such opportunities enrich student learning and professional preparation, they require significant planning and funding to sustain over time. The Humanitarian Engineering and Social Entrepreneurship program at Penn State assessed their model of student engagement to understand how it impacted students with regards to global awareness and engagement, multidisciplinary teamwork, and social entrepreneurship. Mehta et al. [9] found the program deepened student competency in all three areas, with higher effects seen among the most engaged students. The literature around assessing attributes of students enrolled in engineering for development programs is sparse, with no studies comprehensively mapping skillsets developed in such programs to those called for by the Engineer of 2020. Available studies comparing programmatic objectives to Engineer 2020 criteria come from outside of the global development context. For example, Palmer et al. analyzed “contextual competence” specifically, one of the skills identified in the Engineer of 2020 report [10]. They used quantitative and qualitative research methods to understand how educational institutions influence students’ contextual competence. They found that students’ abilities to gain a contextual understanding of how their work connects to the broader world was influenced by their institutions characteristics (on a broad, university-wide scale), curriculum (including the courses offered to students), co-curriculum (“out-of-class” opportunities), professional practice opportunities, and connections to industry. Knight [11], on the other hand, explored the full “suite” of skills that the Engineer of 2020 must possess, focusing on how the necessary competencies of the Engineer of 2020 interact with each other. In his study, engineering students self-reported their competencies in their “fundamental skills”, “design/contextual awareness”, “interdisciplinary competence”, and “professional skills” (all dimensions of the Engineer of 2020). Knight used this survey data to find six clusters of engineering students (marked by their differing achievement in the aforementioned skill dimensions. Only one of these six clusters were found to be high-achieving in all dimensions, therefore making them highly proficient Engineers of 2020. Of the 771 mechanical engineers and 234 chemical engineers surveyed, one hundred mechanical engineers and 29 chemical engineers fell into this cluster of highly proficient Engineers of 2020.

The Development Engineering (DevEng) program at the University of California at Berkeley (UC Berkeley) also aims to train engineering students to work in the global development domain. DevEng was developed as a Ph.D. minor (known as a “designated emphasis” on the UC Berkeley campus), and supports students who “research technology interventions designed to improve human and economic development within complex, low resource settings" [12]. Started in 2014 within the Blum Center for Developing Regions [13], the DevEng minor and associated ecosystem at UC Berkeley afford students resources to supplement their research and education. The program features coursework including the design, evaluation, and scaling of development technologies, funding vehicles to support travel and scaling of potential innovative projects and ideas, mentoring and consultation with entrepreneurs and institutional experts, and research in laboratories which develop and scale technological solutions to meet critical needs of people living in poverty worldwide, including the United States [14].

DevEng at UC Berkeley embraces the inclusion of *all* doctoral students in the training, not just engineers – economics, social sciences, public policy, business, and any other field where the student has a minimum level of technical training (e.g. a college level math or data course series, some quantitative elements in the doctoral research, etc.). The ultimate goal of DevEng is to train students of all disciplines to conduct rigorous research in complex environments and address multidimensional issues of global poverty. In this paper, the authors analyze skills taught in the DevEng program and how they overlap with the criteria outlined by the 2020 Engineer reports. The skills cultivated that go beyond the 2020 Engineer are then examined. Finally, the authors conclude with recommendations for the evolution of the DevEng curriculum and other similar programs.

2. Development Engineering: Introducing the Ecosystem

Beyond any individual program, development engineering is a nascent transdisciplinary field with an extreme range of disciplines: by bridging engineering, business, economics, and social sciences, it intends to develop technology interventions which improve human and economic development within complex, low-resource settings. In short, the field aims to improve the lives of people living in poverty at scale. The DevEng program at UC Berkeley was established to develop the skills necessary for this new field and to augment Ph.D. students' deep knowledge within a particular discipline with a broad set of skills (the "T-shaped" approach). The core of DevEng is design thinking, combined with development-based applications to emphasize the incorporation of development goals, constraints and opportunities, a priori planning for scale, as well as the integration of novel sensors, experiments, and large datasets (e.g., from the Internet, satellites, and mobile phones).

Started in 2014, the program arose out of desire from UC Berkeley students and faculty to engage in international and domestic development work and research, but had few applicable methods that would lead towards meaningful and/or scholarly research outcomes [12]. The program attracted community members from mechanical engineering, applied science and technology, civil and environmental engineering, environmental health sciences, sociology, agricultural resource economics, and energy and resources. During its development, the program has offered funding, coursework, research opportunities, and entrepreneurial mentoring, within the ecosystem of the Blum Center for Developing Regions [13].

The program intends to "equip practitioners to work on social problems wherever they exist" [14], by broadening the possible issues engineers are equipped to address. It does so by training engineers and other doctoral students to gather knowledge that is not solely technical, so that the students become a community well versed in translation between disciplines when addressing challenging development problems. The program also aims to align three stakeholder needs of effective education: (1) balancing academic incentives with real-world impact, (2) fitting community-driven work into institution-driven programs, and (3) blending techno-centric and human-centric approaches [14]. The goal is to counter the critique articulated by Thomas Fisher [15], who is concerned about the potential for a lack of focus upon the building of capacity of targeted communities. By assuming the solution is an intervention of their own making, engineers might fail to consider the power, dignity, and rights of the community engaging in the design process for themselves, with resources to do and make their own intervention.

As part of the Blum Center for Developing Economies [13], the DevEng program on UC Berkeley's campus provides space, resources, and foundational learning – including skill development – so that engineers and non-engineers alike – can apply their technological expertise towards low-resource settings and the social challenges that arise therein. The DevEng ecosystem is shown in Figure 1 and its components are described in the remainder of this section.

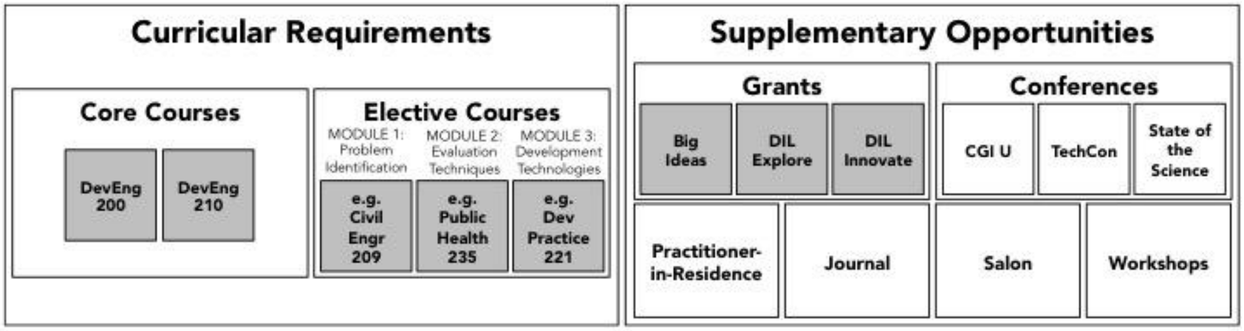

Figure 1. Development Engineering Ecosystem. A variety of components comprise the DevEng DE and the supportive ecosystem, including courses, extracurricular activities, and research funding opportunities.

2.1 Curricular Components

Per the program guidelines [16], the DevEng doctoral minor requires five courses (two core courses plus three electives). The course requirements are in addition to, but might also overlap with, the Ph.D. course requirements of a student's home department. There are no formal prerequisites required for the DevEng doctoral minor, however, a certain level of experience with quantitative analysis is necessary to succeed in the core course (roughly equivalent to an upper division statistics course).

The DevEng pedagogy adopts a Design Thinking framework that is tailored to low-resource settings. Included in the approach are considerations of scale from project inception, as well as sociological, political, and cultural frames of thought. At the core of all activities is the application of data and technology to measure and understand outcomes and impact [12].

For this study, the authors focus on ecosystem components that develop skills for the majority of DevEng students. Thus, the courses and activities evaluated had to be readily accessible to all DevEng students with sufficient documentation for content evaluation. Those components are listed below.

2.1.1 Core Courses

Two core courses, both required for the DevEng DE, are described below.

DevEng200: Design, Evaluate, and Scale Development Technologies (3 units). DevEng200 is a project-based interdisciplinary class co-taught by one technologist and one social scientist. The course is cross-listed through the Development Engineering program, Mechanical Engineering, and the Haas School of Business MBA program. It is organized around analysis and application of case studies by multidisciplinary student teams according to the modules of (i) Understanding the Problem Context, and Needs; (ii) Prototyping Solutions; and (iii) Taking It to the Field. The initial offering of the course in 2014 had high interest - over fifty people vied for thirty initial slots in the course. The subsequent years have all been filled to capacity and comprised of students roughly equally represented from engineering fields, business, and social sciences. The class regularly engages external speakers as well, including researchers, successful development entrepreneurs, company representatives, and many others. Guest speakers either join the regular lectures or in some offerings of the course, there was a special lecture devoted each week to the outside speaker [13].

DevEng210: DevEng Research and Practice Seminar (2 units). DevEng 210 is a seminar course that gives the students a space to communicate, refine, and develop their research projects. Students are required to present research in progress, and receive peer and faculty feedback. Presentations are made by professors, students, and postdoctoral scholars within the DevEng ecosystem as well as industry professionals in the field of development or have special expertise relevant to the practice of development.

2.1.2 Elective Courses:

In addition to the two core courses, DevEng students must take three electives from at least two of the three thematic modules within the DevEng program. The three modules are Project Design; Evaluation Techniques and Methods for Measuring Social Impact; and Technology Development. Of the three electives, only one can be from the student's home department. A full list of eligible courses can be found on the deveng.berkeley.edu website.

- Module 1 – Problem Identification and Project Design: This module includes topics such as human-centered design, participant feedback, project management, needs and usability testing. To represent this module the syllabus of "Design for Sustainable Communities" (Civil and Environmental Engineering 209) is analyzed. CE209 is a broader development themed classes which give students "conceptual and hands-on experience developing sustainable and scalable solutions to alleviate poverty and address basic human needs" [17].
- Module 2 – Evaluation Techniques and Methods for Measuring Social Impact: This module includes classes spanning topics such as large data analytics, statistical analysis for impact assessment, and design of field experiments. It also includes coursework on sustainability and scaling of projects, and on the broader impact on people and communities. Here the syllabus of "Impact Evaluation for Health Professionals," (Public Health 235) is analyzed. PH235 develops direct skills for impact evaluations focused on health interventions of wide varieties.
- Module 3 – Development Technologies: This module spans work on prototyping and technology R&D, as well as the use of novel technologies to evaluate interventions, under topic areas including but not limited to context-specific technology interventions, sensors, data collection, data mining, and analysis. The syllabus of "Climate, Energy, and Development" (Energy and Resources / Development Practice 221) is analyzed for this module. DEVP 221 provides an overview of the science and economics of climate change and their implications for developing countries.

2.1.3 Additional Ecosystem Opportunities

DevEng provides several opportunities to gain skills relevant to successful implementation of development technologies. Many of these are offered through the Blum Center for Developing Economies [13], which serves as the administrative home for the DevEng program, as well as an implementer of the USAID-funded Development Impact Lab (DIL), the Big Ideas @ Berkeley social innovation contest, and other programs. The opportunities are also available to non-DevEng students and provide a means of facilitating multi-disciplinary student engagement (complete descriptions of the ecosystem opportunities can be found at www.bit.ly/ucb-deveng).

Development Impact Lab opportunities: DIL provides various avenues of support, chief of which is research and implementation travel funding ("Innovate" and "Explore" grants) [18].

Big Ideas: Big Ideas is a contest spanning the Academic Year which provides funding, support, and encouragement to teams of students who have big ideas to improve the world [19]. Big Ideas develops events (e.g., workshops on proposal development, team formation, etc.), in-person advising available throughout the academic year, classes (such as the Social Innovator OnRamp, which helps social innovators launch their ideas), mentor-matching for finalist teams, and many other resources intent upon supporting fledgling innovators. Although it is not required and is by design an extracurricular activity, DevEng students regularly compete in Big Ideas and tend to place well, due in part to their strong grasp of developing country context, a well-defined social challenge, and on-the-ground field experience.

The following ecosystem opportunities were not included in our analysis as they were not uniformly taken advantage of by the majority of DevEng students, but are listed for completeness below.

Practitioners in Residence: The Blum Center's Practitioners in Residence Program provides one-on-one consultations with a wide range of experts from Industry, non-profits, government, and social enterprises who are actively working on poverty challenges.

Development Engineering Journal: Development Engineering (Elsevier) is an open access, interdisciplinary journal applying engineering and economic research to the problems of poverty.

Development Impact Lab Salons: Salons are informal small group conversations led by leaders across the technology and development fields. Salons provide a space for students to request candid feedback from peers and external experts.

Development Impact Lab Workshops: Technical workshops designed to help support innovators on campus. Workshops include topics such applying for Institutional Review Board approval, international travel logistics, “Making Sense of Sensors”, “Mobile Data Collection Tools”, and others.

3. DevEng Skill Analysis

In order to assess alignment between DevEng and 2020 Engineer skill development, the authors analyzed aspects of the DevEng ecosystem through four designated levels of exposure, on a scale from zero to four according to the following rubric:

- Zero: the skill was never introduced.
- One: the skill was mentioned at a surface-level; for instance, it was never covered as a major topic, or it was a topic of reading that was never discussed.
- Two: the skill was covered in some depth above simple exposure; for instance, it was covered in a course offering for two or more classes, or it was a critical topic mentioned during another ecosystem component.
- Three: the skill was actively practiced by the students as a part of the program.
- Four: the skill was evaluated; to become successful in different forms of the program, the student was shown to have appreciable capacity or knowledge in the skill to be deemed successful in the act (such as, obtaining a grade for a course, or being considered for a grant).

DenEng200 and 210 are the only courses that DevEng students are required to take. As such, the core courses need to cover the breadth of topics and methods at some level for all of the Engineer 2020 skills. However, if certain skill development activities are not covered in depth in the core courses, they should be covered in supplementary ecosystem components and/or the chosen elective courses. Table 1 shows the results of our analysis, covering where and how skill development takes place within the DevEng Program.

The DevEng core courses both require from the students a deep competency in communication. Students must give intermediate and final presentations of their work and activities to fellow students, clients of the course, and related course professors. Students must also submit written assignments, including blog posts, intermediate and final reports, and homework assignments, which represent their understanding, analysis, and/or application of course topics and projects for evaluation.

Moreover, a teaching team-led course, DevEng200 is designed to facilitate teamwork, by assigning students across disciplines and practical experiences to work together on the course project. In the core DenEng200 course, students practice problem framing through their semester-long course project. Examples of past projects include determining a business model and distribution strategy for urine-derived fertilizer, development of a web-application for electronic medical records, and deployment of a low-cost sensor to track black carbon levels. The projects are inherently “messy”, creating the necessity for students to wade through layers of research and stakeholder objectives to determine where opportunity for innovation exists. Each project and team require at the least foundational understanding of the technologies in their respective project areas, and practical understanding of the technological capacity of all types of projects in the course. The course evaluates the ability to speak about technology, the ability to apply mathematics, science, and engineering, the ability to use modern engineering practice tools, and knowledge of the basic engineering process. Across all projects, students methodically examine how they can leverage the resources and information available to them to first understand and then develop potential solutions to the problem at hand.

The DevEng200 course requires the students to develop an in-depth understanding of their chosen problem space from a systems perspective. In order to develop a feasible and successful (in prototype form) project, students must understand the constraints of the context as well as identify novel opportunities for change within the system. The course also focuses on implementing solutions in emerging regions with contextualized business model development, scaling and impact, and evaluation and measurement. To implement designs, students must recognize economic and social constraints, and possess the ability to create engineering solutions to address these issues. Although systems of stakeholders, supply chains, social networks, impact analyses, etc. are covered in methods and examples, systems tools are briefly covered and systems modeling methods are not practiced in the course.

DenEng200 takes students through laboratory and research skills including sensor usage, data collection, and data analysis. For instance, each student is required to engage in a certain collection of interviews per week to collect enough data for their respective projects. Students also have the opportunity to engage in site visits to collect cultural and/or spatial data. Moreover, students gain experience in data collection, visualization, and analysis in course assignments. Although other existing courses are meant to engage with these topics in depth, DenEng200 introduces the breadth of these methods to the students. Moreover, the purpose of DevEng 210 (the seminar course) is to give students the space to present, critique, and plan future research projects. Ensuring research questions' applicability, rigor of methods, and validity of assumptions are critical in a research process, and required of this course.

Because the DevEng program is focused on design, students in the core courses go through multiple iterations of the design cycle. To this end, human-centered design skills, and practicality are all heavily integrated to ensure the development of a prototypical innovation. Design requires inculcating many qualities which require a changing environment: dynamism, flexibility, adaptability, and above all else, revision. Moreover, the course projects in DevEng200 are intent upon developing upon existing success and failures; whether they are found before the course, or realized during the semester.

There are certain 2020 Engineer skill categories where the DevEng core course coverage is lean; however, in those instances, the supplementary ecosystem components and chosen elective courses serve as complements. Although the students do go through an assignment and more than one lecture on teamwork and leadership using tools from Berkeley's Haas School of Business, the DevEng ecosystem provides many more opportunities to learn leadership, such as with the Big IDEAS contest. In Big IDEAS, students must actively lead a team and defend how their idea can foster an impactful project.

There is also concern around whether core courses focus adopt systems perspectives. One student on the team may be intimately familiar with the context and its relevant dynamics but that is not guaranteed. This gives students practice in evaluating systems (i.e., the health care system, the agricultural sector) to assess how their proposed solution fits in with what is already available as well as how the solution may be implemented and sustained over time. However, the language of systems and instruction on tools to understand how system components interact could be more explicitly taught. Additionally, for certain chosen projects, a locality concern exists; certain students and client stakeholders are chosen for their referential expertise with the local community, but the resources and extended capacity to ensure that the teams during the course interact with the community do not yet exist. However, the is the opportunity for students to learn both about the systems and the local contexts, by applying for the supplementary ecosystem components, such as DIL Explore, DIL Innovate, or Big IDEAS grant.

As survey courses, the core courses lack a depth of focus upon topics aligned with global poverty issues. For instance, there is less focus upon how environmental sustainability intersects with the chosen topics of the course, and how development methods can be used to influence public policy in local settings and globally. Though the class is widely applied, the projects and presented methods of intervention tend to be technological in form, and based on the needs of people in impoverished settings; though sustainability, economy, and public policy issues are related, they are not addressed in depth. However, this opportunity is present in the elective courses: PH235's entire method sets are based upon the practicality of the experiments and are most widely utilized for public policy issues, CE209 has direct resources which can be used to further project once developed outside of academia, and DEVP221 focuses specifically upon poverty and sustainability with public policy being main levers for change.

Although social impact and social justice concepts pervade the DevEng ecosystem, formal models of ethics are not covered. Ethical considerations are covered in practical activities, such as learning how to develop human subjects' protocols where an online ethics course is required. The Big Ideas contest makes grantees discuss ethics as a critical part of the evaluation process of successful grants. Many students decide to study the topics of development engineering specifically because they aim to address the complex issues of our society, and if successful, help better the lives of the severely marginalized; this shows interest in aligning their ethics with their professional work. The transdisciplinary nature of the core courses also provides an introductory foundation for life-long learning in new fields, however, it is difficult to compel every student to practice - or be evaluated upon - the practice of learning and curiosity after the class has been completed. Imaging further opportunities to extend learning – and curiosity – past the ecosystem is a problem yet to be solved.

2020 Engineer Skills	DenEng200	DevEng210	DIL Explore	DIL Innovate	Big IDEAS	CE209	PH235	DEVP221
Leadership	1	0	0	0	4	3	1	3
High ethical standards and professionalism	1	0	2	2	4	1	1	0
Move student from a state of knowledge to professional preparation	2	1	2	2	0	2	2	0
communication	4	4	4	4	4	4	4	4
Teamwork	3	0	0	4	4	4	4	3
Increasing diversity	2	0	0	0	0	2	1	2
Interdisciplinary (e.g., social science, business)	3	2	4	4	4	3	4	2
Integrate humanities, social science and economics	3	2	4	4	4	3	4	2
Engage with stakeholders to set agreed-upon goals	3	0	1	3	0	4	1	2
Understanding systems perspectives	1	0	4	4	1	2	3	2
Understand economic, political, ethical and social constraints	3	2	4	4	4	2	3	4
Creative, inventive, practical ingenuity	3	2	4	4	4	3	1	2
Ability to engage in life-long learning	1	1	2	2	2	2	0	0
Ability to build on past successes and failures	4	2	4	4	4	4	2	4
Be able to revise goals and objectives as technological advances and other changes occur - agility;	3	0	1	2	3	4	2	2
Dynamism, agility, resilience and flexibility	3	0	1	2	3	4	2	2
Customization	2	0	2	2	3	4	4	2
Understand and work in the global economy	1	2	2	2	1	3	1	4
Engineering sustainability	1	0	0	0	1	1	0	4
Understand global development in emerging regions	4	2	4	4	1	3	2	4
Formulate public policy	4	0	0	1	1	1	2	3
Know tools of the engineer and other technical professionals	2	0	4	4	0	3	2	1
Grounded in fundamentals	1	0	3	3	0	2	4	1
Applications of the Engineering process to define and solve problems using scientific, technical and professional knowledge bases	4	0	4	4	1	4	0	1

Table 1. 2020 Engineer Skills in DevEng at UC Berkeley. The numbers refer to the depth of each skill (ranging from zero to four) covered in each component of the DevEng program.

4. Expanding the 2020 Engineer: 21st Century Skills

Though the 2020 engineering criteria reflect a vision of critical values of the future engineer, there can always be improvement with knowledge of global challenges. This paper posits additional skills that the engineers of the future should add to their toolbox. To create this list, the authors look beyond the competencies listed in the original Engineer of 2020 reports [1,2] to consider skills listed in the ABET Student Outcomes criteria [20], skills mentioned in a participant poll associated with a global development conference work session [21, 22] at a conference gathering of engineering and development practitioners (the Higher Education Solution Network's "TechCon" of 2016) [23], and finally, skills mentioned in Development Engineering documentation [13, 24] . The skills were grouped together to find common themes, which are labeled here as 21st century skills. The names, general definitions, and the respective sources of the subcategories of the larger skills sets are available in Table 2 below.

The DevEng Program further trains students in skills beyond those called for by the Engineer of 2020. Such new skillsets including fieldwork, business model development, impact evaluation, human-centered design, data analysis and cross-cultural understanding, among others, collectively constitute what the authors refer to as 21st Century skills. The 21st Century skills are critical for students to learn in order to start addressing global challenges. The skills are cultivated through the same main vehicles: (1) coursework and (2) ecosystem opportunities. Skills learned are not exclusive to either one of these, however, in this section the framing is used to provide examples of how the program brings such skills to fruition for students.

The required and elective courses in the DevEng program aim to push engineers beyond their comfort zone of well-defined problems and into the realm of problems with complex constraints and dimensions. Human-centered design is a key tenet used in order to help students begin to understand how they can get their arms around a part of messy challenge like food insecurity, as well as how they can ensure benefit for those whom the problem is affecting. In DevEng core classes, students are also introduced to and assessed on qualitative and quantitative research skills. An example benefit of this is that an engineer may deepen their ability to conduct ethnographic interviews and be more equipped to understand future political implications of infrastructure construction. On the flip side, a policy study studying human rights violations in factories may learn about sensor deployment and prototype how technology could be used to monitor worker conditions. The emphasis on mixed-methods through courses better equips students to conduct actionable research and design more holistic solutions. Coursework also introduces students to tools such as business model development and impact evaluation, to encourage that solutions designed for impact are sustainable over time.

Engagement in the DevEng ecosystem through opportunities on-the-ground research, business plan competitions, and connection with industry experts, to name a few, allows students to deepen their abilities and relevant skills. Fieldwork opportunities in low-resource settings, provides students hands-on experience conducting research, understanding problem constraints, and foster cross-cultural understanding. The program's emphasis on co-design and stakeholder engagement helps to ensure that students are working with communities directly striving to create beneficial value. Furthermore, ecosystem engagement provides students with insight into the many fields which address similar issues. For example, access to sanitation could be made more available through an innovative toilet design, a new business model for existing infrastructure, a policy initiative, an advocacy campaign, or other alternative means. DevEng brings together practitioners and students from across campus that are sometimes working on similar projects with vastly different approaches. This multi-disciplinary engagement helps students to look beyond technology, to understand that often solution success is inhibited by a socio-political or socio-economic factor, and also to look for holistic solutions. Exposure to different methods of problem solving can further encourage iteration and evolution of ideas and solutions. Finally, as an additional course as PhD students, the program aligns its focus not just on the development of projects which better the lives of the marginalized, but towards ensuring students can conduct rigorous, impactful research in their respective fields using state-of-the-art methods in their chosen context.

21st Century Skill	Definition	Skills From Documentation & Source
Leadership	Able to lead diverse teams; able to integrate knowledge and content across sectors to make decisions; able to communicate decisions and expected impacts	Develop 21st century professional skills (teamwork, communication, leadership, and ethics) [25 DevEng NSF NRT], p. 12 Facilitate knowledge integration and develop communication, mentoring and leadership skills. [25 DevEng NSF NRT], p. 6 Leadership [1 Visions], p. 50 Thoughtful [22 TechCon poll] Fearless [22 TechCon poll] Passionate [22 TechCon poll] Empathetic [23 Agogino TechCon slide] Cross-cultural [23 Agogino TechCon slide] Humble [23 Agogino TechCon slide]
Make ethical decisions	Able to navigate ethically challenging professional situations, drawing on knowledge of ethical standards	Develop 21st century professional skills (teamwork, communication, leadership, and ethics) [25 DevEng NSF NRT], p. 12 High ethical standards and professionalism [1 Visions], p. 56 Move student from a state of knowledge to professional preparation [2 Educating], p. 18 Professional, ethical preparation [21 ABET]
Communicate effectively	Able to translate concepts across disciplines	Communicate effectively [21 ABET, 23 Agogino TechCon slide, 1 Visions, p. 43, 55] Develop 21st century professional skills (teamwork, communication, leadership, and ethics) [25 DevEng NSF NRT], p. 12
Work in cross-disciplinary teams	Able to work in cross-disciplinary teams; possess knowledge of conflict resolution and facilitation tactics; able to appreciate insights from practitioners in any field; understand and promote diversity in the workplace through conscientious decisions and initiatives	Develop skills in interdisciplinary team research [25 DevEng NSF NRT], p. 12 Ability to function on multidisciplinary teams [21 ABET, 1 Visions], p. 43] Increase diversity [2 Educating], p. 43; [1 Visions], p. 27, 50 Interdisciplinary (e.g., social science, business) [1 Visions, p. 50, [22 TechCon poll] Integrate humanities, social science and economics [1 Visions], p. 49, 55 Kind [22 TechCon poll] Ability to look beyond tech [23 Agogino TechCon slide]
Frame a problem within a system	Able to discern problem space and identify critical aspects of the problem; able to engage with diverse stakeholders to assess competing goals or interests;	Engage with stakeholders to set agreed-upon goals [2 Educating], p. 18 An ability to identify, formulate, and solve engineering problems [21 ABET] Problem identification [25 DevEng NSF NRT], p. 8 Systems thinking [1 Visions p. 34, 23 Agogino TechCon slide]
Understand contextual constraints	Able to understand the systemic and specific constraints of a design problem; able to work within or around those constraints to find a workable solution	Integration of goals, constraints, and opportunities [25 DevEng NSF NRT], p. 12 Understand economic, political, ethical and social constraints [2 Educating], p. 18; [1 Visions], p. 27 Local [23 Agogino TechCon slide] Understand societal constraints [21 ABET] An ability to identify, formulate, and solve engineering problems [21 ABET] Systems thinking [1 Visions p. 34, 23; Agogino TechCon slide]
Design practical and high leverage solutions	Able to discern the effective intervention points within a system; build novel yet usable designs that satisfy an important need	Design a system [21 ABET] Develop community/ human-centered design skills [25 DevEng NSF NRT], p. 12 Creative, inventive, practical ingenuity [1 Visions p. 50, 45; 22 TechCon poll] Practical [22 TechCon poll] An ability to identify, formulate, and solve engineering problems [21 ABET] Systems thinking [1 Visions p. 34, 23 Agogino TechCon slide]

Iterate and evolve ideas and solutions	desire to continuously iterate and evolve ideas and/or solutions as new information becomes available	Learn diverse laboratory and research skills, including prototype design, build, and testing [25 DevEng NSF NRT], p. 12 Learn diverse laboratory and research skills, including prototype design, build, and testing [25 DevEng NSF NRT], p. 12
Pursue curiosity	Retain intellectual curiosity throughout life-time; be open-minded to new solution approaches and seek inspiration from previously encountered problems; be willing and able to learn	Ability to engage in life-long learning [2 Educating, p. 45; 1 Visions, p. 57; 21 ABET] Curious [22 TechCon poll] Open-minded [22 TechCon poll]
Adapt to changing environments	Able to understand and integrate into practice changing information and contexts	Ability to build on past successes and failures [1 Visions], p. 38 Be able to revise goals and objectives as technological advances and other changes occur - agility [2 Educating], p. 18, 44 Dynamism, agility, resilience and flexibility [1 Visions, p. 56; 23 Agogino TechCon slide; 22 TechCon poll] Customization [1 Visions], p. 36 Knowledge of contemporary issues [21 ABET] Fieldwork Skills [25 DevEng NSF NRT], p. 6
Conduct actionable research	Able to identify important and relevant research topics; able to carry out data collection and interpret results to answer research questions	An ability to design and conduct experiments, as well as to analyze and interpret data [21 ABET] Develop skills in both qualitative quantitative research tools [25 DevEng NSF NRT], p. 12
Implement solutions that stick	Able to execute well-conceived solutions in the real world; able to translate from the creation process to an effective implementation; able to understand what makes a solution impactful	Understand and work in the global economy [1 Visions], p. 33 Engineering sustainability [1 Visions], p. 50 Global development in emerging regions [1 Visions], p. 51 Formulate public policy [1 Visions], p. 37, 43 Business model development [13 Levine], p. 5 Develop skills in business plans, scaling, and impact [25 DevEng NSF NRT], p. 12 Evaluation and measurement [25 DevEng NSF NRT], p. 6 Continuous impact analysis [13 Levine], p. 5 The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context [21 ABET]
Fluent in technology	Able to understand fundamental technical principles; able to acknowledge the benefits and the limitations of technological solutions	Know tools of the engineer and other technical professionals [2 Educating], p. 18 Grounded in fundamentals [1 Visions], p. 49 Applications of the Engineering process to define and solve problems using scientific, technical and professional knowledge bases [2 Educating], p. 17 An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice [21 ABET] An ability to apply knowledge of mathematics, science, and engineering [21 ABET] Technology fluency [25 DevEng NSF NRT], p. 6

Table 2. 21st Century Skills, as developed by authors. Sources cited include original Engineer of 2020 reports, ABET Student Outcomes criteria, skills mentioned in a participant poll and a conference work session at the TechCon 2016 Conference, and finally, skills mentioned in Development Engineering documentation.

5. Limitations

The authors note several limitations to the work herein. First, this study utilizes a document content analysis to investigate the presence, practice, and evaluation of skills being taught to doctoral students. This includes mainly calls for proposal, grant request applications, and auxiliary papers about the Development Engineering program. However, the content, skills, and fields covered in the DevEng courses are not direct reflections of the course implementation; skills might be introduced but not mentioned in the syllabus, and some topics in the syllabus might be covered only superficially. Moreover, what is taught is highly dependent on the professor who teaches the course, and the evaluators who read proposals and disburse the grants. For the purposes of this study the authors have assumed that there is relative alignment between the topics in the syllabus and the topics in the actual class.

Second, there is high variance between the syllabi concerning how much information about the class they hold. For instance, the syllabus for DEVP221 has much less information about the expectations for the course than CE209; the latter includes anecdotes about the course, advice for the students about excelling, highly detailed day-by-day activities and homework assignments, readings and literature during and after the course, and its explanations for its depth and breadth. The less content a syllabus has, the more likely certain skills the class might teach won't be marked for the analysis. Another related limitation is only using one syllabus per module is a limitation as well, Other classes in each module might cover elements more than the chosen courses.

Third, the authors used written documents from the ecosystem components that are widely accessible to DevEng students. This excludes the opportunities from other critical and diverse ecosystem components, such as the skills demonstrated during the doctoral qualifying exam (terminal exam), the inclusion of chapters of development-centric research dissertations, or papers submitted to the Development Engineering Journal. These omissions are largely due to dearth of publicly available information (exams are closed, Journal submissions are not public, etc.) and the young program has not produced enough dissertations for public review. However, the authors feel the pedagogical and auxiliary elements discussed herein represent a large majority of the training DevEng students receive.

Fourth, there is inherent potential mismatch between what is presented in the classroom, and what the student actually learns and practices. This is an issue of any academic setting; however, this is why the program aims to give students multiple opportunities to learn outside of the classroom. The additional ecosystem components, including mentorship meetings, grants, conferences, journals, and workshops, give students multiple opportunities to learn about professional, research-centric, and applied experiences. Ultimately, however, the students have the final say over their mastery of the 21st century skills they decide to learn, practice, and implement.

6. Conclusions and future research

As expressed before, the DevEng ecosystem serves as a unique experience to learn the skills and values of the 2020 engineer. In this search, the authors found evidence of student skill development in deep communication, creativity and adaptability through design thinking, the integration of multiple disciplines and backgrounds through teamwork and broad introduction of related development fields such as economics and social constraints, the ability to be dynamic in contexts, to build upon past successes and failures, and revise goals and customize outputs to address the goals, towards understanding global development in developing regions. There are skill topics which can be better institutionalized into the program, such as marshaling students towards increasing diversity, towards better understanding environmental sustainability, a more foundational background in ethics topics and application, creative ways to influence life-long learning opportunities, and the influence of political structures and the influence of public policy. Moreover, though the topics in DevEng have an ethical focus and are instigated by ethically-minded engineers, formal ethical frameworks are not institutionalized into the program. Ensuring ethics conversation which make students investigate personal values, understand philosophical ethical frameworks, and grapple with ethical conundrums of poverty, is a potential starting point for future improvements.

However, the DevEng ecosystem also makes critical contributions towards inculcating what our research community is calling 21st Century skills. These skills include the ability to look beyond technology, to use human-centered design to address the complex problems of development, the capacity of learning diverse laboratory and research skills, including prototyping, building and testing, the ability to design and conduct experiments, and develop both quantitative and qualitative research skills towards conducting actionable research, the ability to develop and scale business plans, and a focus on evaluation and measuring the outcomes of proposed change-oriented activities.

This study of the content of the DevEng courses and learning ecosystem provides the baseline for future research that will cover the outcomes assessment of the program in the future. A recently awarded NSF grant supporting DevEng ("InFEWS") [25] will build on the existing framework, create a new focus on the intersection of food, energy, and water systems for low resource areas, and importantly, set up an evaluation framework. In addition to formative assessment (student performance measures) conducted by faculty within the program, the DevEng program will work with an external evaluator to develop a summative assessment focusing on (1) program infrastructure, (2) faculty collaboration and productivity, and (3) student expectations and experiences. Content analysis of theses and dissertations will inform the degree to which students apply DevEng in their graduate research. Finally, the assessment will establish an exit survey (delivered upon graduation) and further surveys 5 years, and then 10 years, after graduation to track student employment post-graduation in order to survey what topics and experiences they found most useful. The authors anticipate this research to provide critical data for the improvement of interdisciplinary programs akin to DevEng.

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9. Biography

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