*International Journal of Engineering Education* Vol. 37, No. 1, pp. 195–203, 2021
Printed in Great Britain

0949-149X/91 $3.00+0.00


# Enhancing Senior Engineering Student Projects by Incorporating Needs Assessment, Manufacturing Engineering, and Pilot Testing*

GREGORY THEYEL
Biomedical Manufacturing Network, 66 Maryland Avenue, Berkeley, California, 94707 USA and California State University, 25800 Carlos Bee Boulevard, Hayward, California 94542 USA. E-mail: gregory.theyel@biomedmfg.org

ALLAN BAEZ MORALES
Frugal Innovation Hub, Santa Clara University, 500 El Camino Real, Santa Clara, California 95053 USA.
E-mail: abaezmorales@scu.edu

EVANGELIA BOUZOS
Frugal Innovation Hub and BioInnovation and Design Lab, Santa Clara University, 500 El Camino Real, Santa Clara, California 95053 USA. E-mail: ebouzos@scu.edu

PRASHANTH ASURI
BioInnovation and Design Lab and Department of Bioengineering, Santa Clara University, 500 El Camino Real, Santa Clara, California 95053 USA. E-mail: asurip@scu.edu

How can the senior engineering student project experience be enhanced so students gain a more complete understanding and appreciation of the entire technology development process, develop more skills needed in their first jobs, and become more capable of developing projects that meet their client's expectations? Interview data from managing engineers about the skill needs of newly hired engineers and interview data from students who completed their senior engineering project reveal gaps – such as customer needs assessment, manufacturing engineering, and pilot testing – between the skill needs of new hires and their senior engineering project experience. Workshops were implemented to address these gaps and a second round of student interviews reveals the gaps were bridged.

**Keywords:** senior engineering student projects; technology development; workshops; needs assessment; manufacturing engineering; pilot studies

## 1. Introduction

Senior engineering student projects can play an important role in enhancing the talent pipeline, and engineering departments at numerous universities have implemented project-based learning [1]. The goal of project-based learning is to help students enhance their preparedness for their careers. Prior research on the outcomes of senior engineering student projects has shown strengths and shortcomings. Strengths include developing knowledge and transferable skills [2, 3], learning across contexts [4], and solving industry problems [5–8]. Common critiques of student projects include a lack of engagement with target customers and stakeholders more generally, few projects actually being deployed, and a lack of pilot testing [9–12]. This current research seeks to build upon the recognized strengths and address some of the important weaknesses by answering the research question: how can senior engineering projects help students develop more transferable skills and become more capable of developing projects that meet their client's expectations?

This research presents interview data from managing engineers who hire newly degreed engineers and interview data from senior engineering students at Santa Clara University (SCU), which we use as a case study. The interviews with managing engineers and students reveal that graduating engineers could benefit more from their projects and, in particular, from a more complete understanding and appreciation of the entire technology development process. These findings offer valuable insight and have motivated our workshop approach for enhancing the senior engineering project experience to improve the teaching of engineering by presenting more aspects of technology development. These aspects include customer needs assessment, engineering drawings, prototyping, cost of goods, and pilot testing. Incorporating a more complete understanding of technology development better prepares engineering graduates for employment and professional success. Our approach is a work in progress and there is ample room for the workshop design to evolve and mature. We offer a look at an emergent design intended to prepare future engi-

* Accepted 3 August 2020.

neers to pursue meaningful opportunities by contributing more complete, professional solutions as part of their senior engineering student projects.

The paper is organized as follows. We begin with how this research builds upon existing research on project-based education in engineering. This is followed by our interview data from managing engineers about the skill needs of newly hired engineers and interview data from students who completed their senior engineering projects in May 2018. We focus on the gaps between the findings of these two sets of interviews. Next, we present the technology development process – from concept through designing, prototyping, production, and deployment – as a philosophy for gaining more useful outcomes from the senior engineering project process. We then introduce a workshop approach we developed to help students build their technical skills, enhance teamwork and project management abilities, improve capabilities for working with customers, and gain a more complete understanding and appreciation of the entire technology development process. Next, we share the results of a second round of student interviews conducted in May 2019 that act as a test of the effectiveness of the workshops. We conclude with a summary of our findings, analysis, and plans for future research.

## 2. Engineering Skill Needs and Senior Engineering Projects

The needs of organizations that hire engineering students must be better understood in order to build a stronger engineering talent pipeline [11]. Therefore, industry engagement with curriculum development, senior engineering student projects, and input on the skill needs of entry-level engineers are critical [11, 13]. Prior research [12–15] has focused on the need for incorporating design thinking, customer perspectives, and deployment into senior engineering student projects. Project-based learning in the form of a capstone or senior engineering student project has been offered as a solution for better preparing engineering students for their careers [1]. The development of transferable knowledge and skills [2, 3], learning across contexts [4], and solving industry problems [5–8] have been offered as guidance on how to design the student project experience. There have also been calls for more engagement with target customers and stakeholders, increased emphasis on design for manufacturability, and the use of pilot testing in order to enhance the project design [9–12]. This current research seeks to contribute to prior research by offering an approach for students to develop more transferable skills and become more capable of completing projects that meet their client's expectations. Specifically, we use the technology development process as a framework and develop specific workshops to instruct and engage students in skill development.

We interviewed more than 100 engineering hiring managers inquiring about the skills they look for in new hires for entry-level engineering positions. Hiring managers responded to questions about the importance of the skills of entry level engineers along a Likert scale of 1 (not important), 2 (slightly important), 3 (somewhat important), 4 (very important), and 5 (extremely important). The managers (as well as all of the student teams) volunteered to participate in the research and understood the purpose of the research and its risks. Fig. 1 summarizes the findings showing the average scores for 12 engineering skill areas. Consistent with many recent studies on the skills needed of graduates, the first three highest ranked skills can be described as soft skills [16–18]. Problem-solving, communication and documentation, and teamwork are skills in high demand from entry-level engineers. The next two ranked engineering skills, pilot testing and customer needs assessment, combine soft and analytical skills as engineers develop prototypes and locate and communicate with likely customers in order to conduct pilot testing and understand

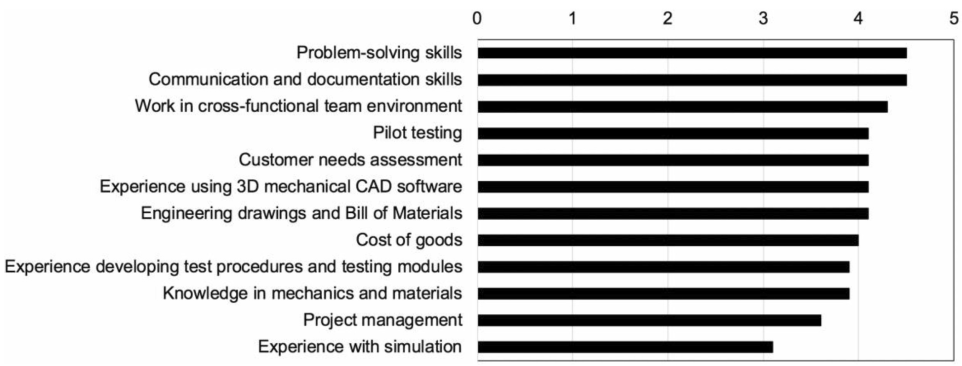


**Fig. 1.** Engineering Skills Needs. Average Likert scores (1 = not important to 5 = very important) for twelve engineering skill areas, informed from interviews with hiring engineering managers.

and prioritize customer needs. The next highest ranked skills, CAD use, engineering drawings, bill of materials, and cost of goods are analytical (sometimes referred to as hard) skills. These top skills all average 4.0 (very important) or higher and should be the focus of engineering curriculum in order to better prepare students for future employment.

Next, we interviewed SCU students who completed their senior engineering student projects in May 2018. The SCU project experience spans the entire academic year, while many students are still completing a full course load. Students complete planning, analysis, design, and evaluation of an engineering project, which is an integrated, complex, and realistic project that involves many aspects of the engineering profession. The main objective of the SCU senior engineering project is for students to develop the skills needed to identify, solve, and address real-world problems while converting a need into an engineering solution. The students are expected to apply knowledge from their previous courses to accomplish project formulation, conceptual and detailed designs, technical evaluations and assessment, and communications.

Senior engineering student projects involve students completing a project where they take an idea from concept to design to prototype. As described above, the learning objectives include design engineering, project management, and integration of resources and previous course work. Data on the successful deployment of senior engineering projects is extremely limited with only anecdotal evidence of occasional projects reaching customers. Very few projects advance beyond a prototype and seldom entail customer needs assessment, engineering drawings, pilot testing, cost of goods, and design for manufacturability. This is not to say that the design and project management education students gain from their senior project experience is not valuable, but there is an unmet opportunity to include additional requirements for the senior project experience that would foster a more complete experience, resulting in better career preparation and increased likelihood of deploying the technologies/products. By program design, most projects are capped at the development of a prototype. This limits learning, as students do not consider advancing from a prototype to production and deployment, a consideration that is insightful and relevant for employment after graduation.

In order to assess the current context of senior engineering projects, we questioned students about their experience and perspective on senior engineering projects. We interviewed five Santa Clara University undergraduate biomedical and mechanical engineering teams (more than 20 students) at the end of their senior project experience in May 2018. We chose these teams by using a due diligence process for assessing the readiness for deployment of each of the 47 undergraduate projects from the Class of 2018 [19]. This process entailed assessing technology (advancement potential), market (size and potential competition), investment (ease of fundraising), and team (skill availability). Each project received a score from one (low) to five (high) for the four due diligence elements and a total score by adding the four element scores together. We completed interviews with the five teams with the highest scores. We chose this purposeful sampling approach, based on the four criteria, because we wanted to conduct in-depth interviews with the teams that were likely to have the most advanced projects. Purposeful sampling involves identifying participants using preselected criteria based on the research question. As stated above, our research question is: how can senior engineering projects help students develop more transferable skills and become more capable of developing projects that meet their client's expectations?

The teams were asked about their assessment of customer needs and how understanding these needs affected project design and features, their use of manufacturing engineering (including engineering drawings, bill of materials, manufacturability, and cost of goods), and their use of pilot studies with customer groups and the effects of piloting on further development of their project. These questions resulted in detailed explanations of how and why, which confirmed our choice of purposeful sampling and qualitative data collection and analysis. Next, we present illustrative insights and quotes from our interviews with the student teams.

Regarding customer needs, interviewees reported collecting very little first-hand needs data from likely customer groups. Their approaches to design were largely based on second-hand information. One team conveyed they ". . . had a difficult time getting access to the likely customers for [their] product, as [the customers] are in developing countries. [They] have just been able to talk with [the] project sponsor" and another team reported they ". . . talked with people who interacted with [the] likely customers . . ." As a result of this paucity of information, several teams confessed they ". . . designed what [they] thought would be the best technical solution to the problem [they] were presented at the beginning of [their] project."

Responses to project aspects related to manufacturing engineering were consistent in the lack of attention. Student responses were summed up by the following: "We have focused on design and consider manufacturing out of the scope of our project. We see manufacturing as another, separate project." These sentiments show the missed project development opportunity of manufacturing engineering, such as review of material choices, design for manufacturability, functionality and quality review, and optimizing cost of goods. Without these considerations, completing projects that are scalable, sustainable, and replicable is highly unlikely.

Pilot studies were rare among the student teams, so feedback from potential customers was lacking. One team offered the following regret saying: "We never got to the point of pilot testing, though we are really curious about how people would use and respond to our technology." Other teams stated they felt pilot testing was beyond their project scope. One team was an exception reporting that they ". . . conducted pilot studies, which gave [them] so much insight on how people would use [their] product." This sole team began to see the benefits of pilots, such as product/service refinement and additional development of relationships with likely customers.

These challenges and gaps in student understanding are not unique to the senior project experience at Santa Clara University. Engineering programs at other universities share these same shortcomings, which was confirmed during conversations with department chairs at other San Francisco Bay Area universities, including a research university and a state university. Recognizing these missed opportunities enables the ability to improve the senior engineering project experience and better prepare students for their careers upon entering the workforce.

## 3. Technology Development Process

An understanding of the technology development process offers insight on how senior engineering student projects could be enhanced. Technologies evolve from observing problems, perceiving needs, and developing a concept into a product or service [20, 21]. The progression from concept to deployment is often referred to as the technology development process [21]. This evolution begins with a concept that may be developed into a product design and then a prototype to be manufactured and deployed. Fig. 2 shows the technology development process.

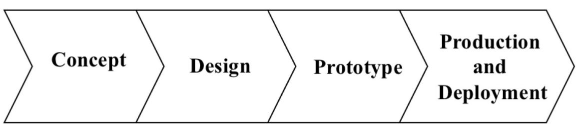


**Fig. 2.** Technology Development Process. Schematic describing the technology development process from concept to design to prototype to production and deployment.

While the development of technology is presented as a seemingly linear process, it is anything but seamless. Evolution from concept to deployment is often hindered by what can be described as gaps in the process. Some technologies never advance from the point of a concept to design for many reasons, such as they are not technically possible, are too expensive to develop, lack commercial application, or are superseded by a competing technology. The conversion of a technology from a concept to a design involves the translation of knowledge into utility and can be hindered by a *translation gap* [22].

If a technology moves to the design phase, it faces the challenge of proof of concept, or showing that the technology can be advanced from a design drawing to a tangible prototype of a product [15, 16]. This part of the technology development process involves translation from possibility to actuality, with a prototype representing possibility and proving actuality. The gap between design and prototype can be vast due to challenges with materials as well as manufacturing processes and can be referred to as a *tangibility gap*.

Moving from prototype to production and deployment involves customer acceptance via value creation and may often involve complementarity with other products and processes. Acceptance of a product or process at this point is influenced by technical, market, and social determinants [15, 16]. The product must meet the technical, economic, and social needs of a particular set of users. A daunting *value gap* may occur between prototyping and production and deployment.

Based on our interviews with engineering hiring managers and student project teams and insights gleaned from the technology development process, we offer three propositions. First, *communication and engagement with prospective customers are essential for product design*. Imperative to understanding customer needs, this entails knowing who likely customer groups will be for the product or service, how to determine what needs information should be gathered from customers in order to uncover the value of the product to the customer, and how needs data should be gathered. It also includes how to translate needs data into product requirements and engineering specifications, how to prioritize product requirements and engineering specifications, and how to determine product/service design changes. For example, the customer may likely be broader than just the end user. In the case of a smart pill bottle meant to improve patient adherence to a prescribed drug regimen, there are multiple customers, including the patient, their family, the payer, and the specialty pharmacist. Therefore, multiple customer groups need to be engaged in the process of product design.

Second, *manufacturing engineering needs to be integrated throughout the entire technology development process*. Manufacturing sets the opportunities and limitations for the production of a product. Therefore, knowing what you can make is essential as a project advances from concept to design to prototype to production and deployment. Manufacturability – including materials, processes, functionality, quality, safety, and cost – needs to be fully integrated throughout the technology development experience.

Third, *pilot testing needs to be integrated into the technology development process*. Piloting involves seeing how well a product or service works, developing relationships with likely customers, considering additional features that should be added to the original product to optimize the solution for the customer, and assessment of cost and value. Therefore, pilot testing not only helps with assessing the performance and outcomes of design decisions, it also can help build a customer group by engaging potential customers in the technology development process.

## 4. Results

As part of this research, we developed a workshop approach for helping students enhance skills needed in their first jobs, offering students a broader understanding and appreciation of the entire technology development process, and helping students develop projects that better meet their clients' expectations. Fig. 3 shows elements of the process and the gaps described above and illustrates how our workshops help bridge these gaps. The following are descriptions of the three workshops, which are also the results of this research.

### *4.1 Workshop #1: Customer Needs Translated into Product Requirements*

New product design must include the translation of customers' needs into technical requirements and design parameters. This workshop (and a follow-up session to review and critique workshop-related homework assignments that include the items below) teaches the following steps to help translate customer needs into product features:

- Identify all of the likely customers, e.g., direct users, those affecting the buying decisions, payers, etc.
- Determine what needs information should be gathered from customers.
- Gather customer needs data (via user observation, surveys, interviews, focus groups, anthropological analysis, brainstorming, etc.).
- Analyze needs data and cluster needs into the following two groups:
  - (i) needs whose satisfaction is taken for granted: the essential condition for the product to meet the target market;
  - (ii) needs that increase customers' satisfaction and product attractiveness: their fulfillment differentiates the product from competitors.
- Translate needs data into technical requirements, which are technical aspects that the product needs to fulfill in terms of performance, reliability, and safety.
- Translate technical requirements into design parameters, which are physical and functional characteristics of the product.

The objective of workshop #1 is to help bridge the *translation gap* by assisting students to better understand customer needs (Table 1 summarizes the issues to be addressed by the workshops and modules for addressing each issue). This will aid with the conversion of a technology from a concept to a design by helping translate knowledge into utility. After participating in a workshop setting where teams identify their customer groups, identify needs information desired, draft data-gathering questions, and practice interviewing, the students complete homework on these tasks. They meet two weeks later to review their assignments and address their challenges and questions. We acknowledge the

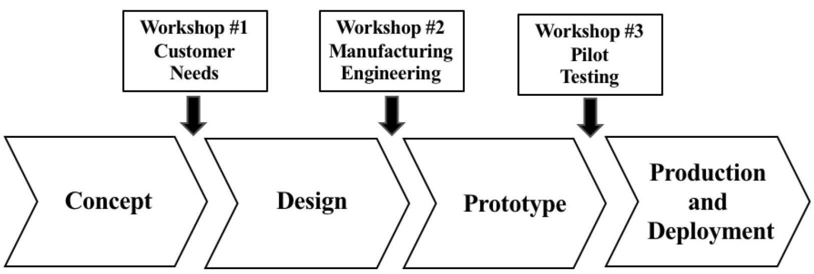


**Fig. 3.** Enhanced Technology Development Process for Senior Engineering Student Projects. Schematic describing the technology development process, common gaps that hinder the process, and proposed student workshops to help bridge these gaps.

**Table 1.** Workshop Contributions. Issues addressed by each workshop and workshop modules for addressing issues.

| Issues to be Addressed | Workshop | Workshop Modules for Addressing Issues |
|---|---|---|
| Bridge Translation Gap | #1 Customer Needs | Identify customers |
| | | Gather customer needs data |
| | | Analyze customer needs data |
| | | Translate needs data into technical requirements and design parameters |
| Bridge Tangibility Gap | #2 Manufacturing Engineering | Review drawings and bill of materials |
| | | Assess manufacturability |
| | | Review functionality and quality |
| | | Assess cost of goods |
| Bridge Value Gap | #3 Pilot Testing | Test product or service |
| | | Develop relationships with customers |
| | | Consider additional features |
| | | Cost and value assessment |

continuing challenges teams face trying to communicate and engage with prospective customers in order to understand their needs. A couple of these challenges are distance, as customers can be located across the world, and new technology, which can lack an obvious audience.

### *4.2 Workshop #2: Manufacturing Engineering*

Teams developing a new product often face a formidable gap between design and their prototype. Above we refer to this as the tangibility gap, and this gap can be bridged by manufacturing engineering. Manufacturing engineering is the development of the tools, processes, machines, and materials to make products. Understanding manufacturing possibilities and limitations is essential at the beginning of and throughout the technology development process.

Workshop #2 (and a follow-up session to review and critique workshop related homework assignments that include the items below) teaches the following steps for helping move a new product from design to prototype:

- Review of Product Engineering Drawings and Bill of Materials. This is the blueprint for making a product and must be thorough, accurate, and easy to follow. This also involves assessing options for material choice, e.g., better, cheaper, locally available, etc., and using off-the-shelf components instead of custom parts whenever possible.
- Manufacturability Review. This is the extent to which a product can be easily manufactured. If the product has a non-standard design or requires complex assembly and/or specialized machinery or training, then it has lower manufacturability.
- Product Functionality and Quality Review Plan. This plan addresses all specific product requirements and helps ensure the product is functional, reliable, and safe. This involves meeting electrical and mechanical engineering requirements for parts and components and establishing any on-going testing the product should undergo to ensure continued quality and performance.
- Manufacturing Cost Review. To have a financially sustainable production process and run a profitable operation, the product production cost must align with the manufacturer's suggested retail price for the end product. If the product cannot meet this goal for production costs once it gets to market, then it is not ready for production.

The objective of workshop #2 is to help bridge the *tangibility gap* by assisting students to understand the development of the tools, processes, machines, and materials to make their product (Table 1). This will help teams with the translation from possibility to actuality, with a prototype representing possibility and proving actuality. In a workshop setting, students review drawings and bills of materials, their products for manufacturability, and cost of goods. They also plan for product functionality and quality and complete homework on these tasks and meet two weeks later to review their assignments and address their challenges and questions.

### *4.3 Workshop #3: Pilot Studies for Enhancing Product Design*

Pilot studies are an essential step for testing and enhancing product design and prototypes and are essential before product production and deployment. Workshop #3 (and a follow-up session to review and critique workshop-related homework assignments that include the items below) instructs teams on the following:

- Test the product or service, often referred to as proof of concept, to see how well it works.
- Develop relationships with likely customers.

- Consider additional features that should be added to or subtracted from the original product or service to optimize the solution for the customer.
- Conduct a cost and value assessment of a particular product or service over the short and long term.

The objective of workshop #3 is to help bridge the *value gap* by assisting students to understand customer acceptance via value creation (Table 1). Moving from prototype to production and deployment involves engaging with customers to understand additional features that should be added to the original product or service; thereby, optimizing the solution for customer acceptance. This workshop helps students refine their prototypes through pilot testing with customers. After participating in a workshop setting where students learn how to test their products, engage with customers, consider additional features, and conduct a cost and value assessment, the students complete homework on these tasks and meet two weeks later to review their assignments and address their challenges and questions.

### *4.4 Workshop Outcomes*

In May 2019, we conducted a second set of interviews with seven senior engineering project teams (more than 20 students) that participated in the three workshops. The teams invited to participate in the workshops were chosen by two faculty members based on the projects' leadership in readiness for deployment. Fig. 4 compares the results of the interviews in 2018 and 2019 showing the likely effects of implementing the skills workshops on the technology development activities. In all cases, the students interviewed in 2019 showed greater use of the workshop skills compared to the students interviewed in 2018. We calculated chi square values in order to determine if there were significant differences between the 2018 and 2019 values. Activities related to the Needs Assessment and Manufacturing Engineering workshops occurred at a statistically significant higher level for the 2019 teams compared to the 2018 teams. While the difference in the level of adoption of pilot studies (content of the third and final workshop) is not statistically significantly higher in 2019 compared to 2018, this may be due to the scheduling of this workshop and follow-up meetings too late in the academic year, leaving student teams with little time to incorporate piloting into their projects. The adoption level of the elements of the Piloting workshop can likely be improved by scheduling this workshop earlier in the academic year.

### *4.5 Research Findings*

Enhancing the preparation of students for engineering careers begins with understanding the needs of the organizations that will hire them. Engineering hiring managers identified the top skill needs, and we sought to incorporate these into the senior engineering student project experience via supplementary workshops. The following skills were successfully incorporated into the student projects: (1) communication and engagement with prospective customers in order to understand their needs and how to translate them into product/service features; (2) manufacturing engineering processes integrated throughout the entire technology development process for better and more realistic choices for materials, manufacturability, quality, performance, and affordability; and (3) pilot testing involving determining how well a product or service works, developing relationships with likely customers, considering additional or fewer features that should be added to the original product to optimize the solution for the customer, and assessment of cost and value.

Appendix A offers a student project example that explains how the workshops helped the team understand the importance of the entire technology development process, develop a product that more closely met their client's expectations, and prepare the students for employment and professional success.


**Fig. 4.** Engineering Student Project Activities. Adoption of technology development activities after skills workshops were implemented in 2019 (black bars) in comparison to 2018 (grey bars). Answers are plotted on a Likert scale from 1 to 5 (1 = not important to 5 = very important).

## 5. Conclusions

The premise of this paper is that incorporating a more complete understanding of technology development better prepares engineering graduates for employment and professional success. Our objectives are to enhance the senior engineering project experience, so students develop more skills needed in their first jobs, gain a more complete understanding and appreciation of the entire technology development process, and become more capable of developing projects that meet their clients' expectations.

We recognize that not all the engineering projects are the same, so our findings vary in their relevance from project to project. Computer engineering projects may entail developing an app, for example, which may be created in four months, tested remotely for the next three months, and deployed for a customer before the end of the nine-month school year. Civil, mechanical, and biomedical engineering projects developed for a client across the world potentially face more time, communications, and resource challenges as teams struggle to engage directly with clients and pilot testing can prove nearly impossible. For these reasons, our findings are not applicable for all projects, but instead should be introduced with the nature of the projects in mind.

Technologies usually evolve from observing problems, perceiving needs, and developing concepts to deploying products or services in a progression, which is often referred to as the technology development process. We endorse this process as the organizing principle for enhancing the senior engineering student project experience by adding instruction and experience in customer needs assessment, manufacturing engineering, and pilot testing. As shown in Fig. 3, these three areas of education can bridge the current gaps between the instructional gains of the senior engineering student project experience and enhanced skills needed by entry-level engineers.

*Acknowledgements* – We thank the engineering hiring managers and senior engineering project students for participating in the interviews and assisting with data collection.

## References

1. J. Chen, A. Kolmos and X. Du Forms of implementation and challenges of PBL in engineering education: a review of literature, *European Journal of Engineering Education*, 2020.
2. D. Gijbels, F. Dochy, P. Van den Bossche and M. Segers, Effects of Problem-Based Learning: A Meta-Analysis from the Angle of Assessment. *Review of Educational Research*, **75**(1), pp. 27–61, 2005.
3. A. Kolmos and F. K. Fink, *The Aalborg PBL Model: Progress, Diversity and Challenges*, Edited by L. Krogh, Aalborg: Aalborg University Press, 2004.
4. I. Calvo, I. Cabanes, J. Quesada and O. Barambones, A Multidisciplinary PBL Approach for Teaching Industrial Informatics and Robotics in Engineering, *IEEE Transactions on Education*, **61**(1), pp. 21–28, 2018.
5. M. J. Terrón-López, M. J. García-García, P. J. Velasco-Quintana, J. Ocampo, M. R. Vigil Montaño and M. C. Gaya-López, Implementation of a Project-Based Engineering School: Increasing Student Motivation and Relevant Learning, *European Journal of Engineering Education*, **42**(6), pp. 618–631, 2017.
6. M. Wallace and A. Webb, In the Midst of a Shift: Undergraduate STEM Education and "PBL" Enactment, *Journal of College Science Teaching*, **46**(2), pp. 47–55, 2017.
7. C. Zhou, Integrating Creativity Training Into Problem and Project-Based Learning Curriculum in Engineering Education, *European Journal of Engineering Education*, **37**(5), pp. 488–499, 2012.
8. C. Y. Chen and K. C. Teng, The Design and Development of a Computerized Tool Support for Conducting Senior Projects in Software Engineering Education, *Computers and Education*, **56**(3), pp. 802–817, 2011.
9. J. Uziak, A project-based learning approach in an engineering curriculum, *Global Journal of Engineering Education*, **18**, pp. 119–126, 2016.
10. J. Froyd, P. Wanket and K. Smith, Five major shifts in 100 years of engineering education, *IEEE*, **100**, pp. 1344–1360, 2012.
11. J. R. Goldberg, V. Cariapa, G. Corliss and K. Kaiser, Benefits of Industry Involvement in Multidisciplinary Capstone Design Courses, *International Journal of Engineering Education*, **30**(1), pp. 6–13, 2014.
12. A. J. Dutson, R. H. Todd, S. P. Magleby and C. D. Sorensen, A Review of Literature on Teaching Engineering Design Through Project-Oriented Capstone Courses, *The Research Journal of Engineering Education*, **86**(1), pp. 17–28, 1996.
13. S. Howe, Cultivating the Capstone Ecosystem to Educate the Engineer of 2020, *International Journal of Engineering Education*, **34**(2(B)), pp. 653–658, 2018.
14. B. D. Jones, C. M. Epler, P. Mokri, L. H. Bryant and M. C. Paretti, The Effects of a Collaborative Problem-based Learning Experience on Students' Motivation in Engineering Capstone Courses, *Interdisciplinary Journal of Problem-Based Learning*, **7**(2), pp. 34–71, 2013.
15. R. H. Todd and S. P. Magleby, Elements of a successful capstone course considering the needs of stakeholders, *European Journal of Engineering Education*, **30**(2), pp. 203–214, 2005.
16. L. Fernandez-Sanz, T. Villalba, J. Medina and S. Misra, A study on the key soft skills for successful participation of students in multinational engineering education, *International Journal of Engineering Education*, **33**, pp. 2050–2060, 2017.
17. M. S. Rao, Enhancing employability in engineering and management students through soft skills, *Industrial Commercial Training*, **46**, pp. 42–48, 2014.
18. M. M. Robles, Executive perceptions of the top 10 soft skills needed in today's workplace, *Business Communication Quarterly*, **75**, pp. 453–465, 2014.

19. G. Theyel, N. Theyel and E. Garnsey, Matching resources to opportunities for emerging technology ventures, *Management Research Review*, **36**(10), pp. 1011–1023, 2014.
20. D. Whitney, Assemble a technology development toolkit, *Research Technology Management*, **50**, pp. 52–58, 2007.
21. R. Cooper, Managing technology development projects, *Research Technology Management*, **49**, pp. 23–31, 2006.
22. U. Hogman and H. Johannesson, Applying stage-gate processes to technology development, *Journal Engineering Technology Management*, **30**, pp. 264–287, 2013.

## Appendix A – Senior Engineering Student Project Example

The goal of the project was to create a significant and positive impact in the cervical cancer diagnostic space by developing a cost effective and minimally invasive solution to enable women to accurately test for cervical cancer in low-resource settings. The ability to diagnose cervical cancer is less of an issue in the developed world, as preventative care and regular cervical cancer screenings, such as pap smears, are available to aid in early detection. Those in low-resource settings rarely have access to such tests for a variety of reasons, including high cost and lack of laboratory infrastructure. This team project leveraged new research to create a low cost, visual cervical cancer screening tool for early stage cervical cancer to serve as an alternative to the existing costly and invasive methods. Data for this diagnostic will be collected by their partner NGO in their target location and outcomes will be measured by assessing its use in several clinics.

The team attended all three workshops, completed all the homework assignments, and met with the instructor to discuss each of the modules. The team gave insightful feedback on the benefits of the workshops. For example, for the customer needs workshop, the team made two important revelations. First, because their project setting was Kenya and they were not able to travel there, they relied on their project sponsor to communicate customer needs. This was less than ideal compared to talking directly to likely users of their test. Second, based on the workshop, they learned to expand their definition of customer. In addition to the actual users of their test, other customers include people administering the test, labs responsible for processing the test, the families of the women being tested, and the entities likely to fund the deployment of the test. Understanding the needs of other customer groups affected the design of the team's test such as its ease of use and processing and its cost.

For the manufacturing engineering workshop, the team offered great insight. Prior to this workshop they had not fully considered the design of the product, how it would be manufactured, what the per unit cost would be, and how this cost could be reduced. The team revealed that they had thought design for manufacturing decisions and production planning were beyond their project scope. As a result of this workshop, the team enthusiastically addressed product design, manufacturability, and cost of goods and production. They embraced the idea that if you cannot make something that is functional and can be produced at a cost that the payer can afford (even if it is a foundation or government), then deployment is not likely. They learned that manufacturing engineering is an important consideration, especially during the early product design phase.

For the pilot studies workshop, the team had not envisioned the benefits of getting user feedback on product design and usability, so this experience helped the team see how product design is continuous. The team designed and implemented a small pilot study of their test, which helped teach them the approach, but also gave them insight on how to improve their test design.

The workshops helped the team better understand the technology development process, which in turn helped them to develop a product that more closely met their client's expectations. Additionally, these workshops helped to simulate the questions and concerns that arise in an industry environment, allowing the team to begin developing skills needed in their first engineering jobs.

**Gregory Theyel** is the Director of the Biomedical Manufacturing Network in Berkeley, California and Professor of Management at California State University.

**Allan-Baez Morales** is the Director of Program and Partnerships at the Frugal Innovation Hub at Santa Clara University.

**Evangelia Bouzos** is Assistant Program Manager at the Frugal Innovation Hub and the BioInnovation and Design Lab at Santa Clara University.

**Prashanth Asuri** is the Director of the BioInnovation and Design Lab and Associate Professor of Bioengineering at Santa Clara University.