Design Tool Subway Map for Undergraduate Design Projects

Dr. Megan Hammond, University of Indianapolis

Megan Hammond received her Ph.D. in Industrial Engineering from Western Michigan University. She is an assistant professor in the R.B. Annis School of Engineering at the University of Indianapolis. Her research interests include cluster analysis, anomaly detection, human centered design, and engineering education.

Dr. Kenneth Reid, University of Indianapolis

Kenneth Reid is the Associate Dean and Director of Engineering at the R. B. Annis School of Engineering at the University of Indianapolis. He and his coauthors were awarded the Wickenden award (Journal of Engineering Education, 2014) and Best Paper award, Educational Research and Methods Division (ASEE, 2014). He was awarded an IEEE-USA Professional Achievement Award (2013) for designing the B.S. degree in Engineering Education. He is a co-PI on the "Engineering for Us All" (e4usa) project to develop a high school engineering course "for all". He is active in engineering within K-12, (Technology Student Association Board of Directors) and has written multiple texts in Engineering, Mathematics and Digital Electronics. He earned a PhD in Engineering Education from Purdue University, is a Senior Member of IEEE, on the Board of Governors of the IEEE Education Society, and a Member of Tau Beta Pi.

Dr. Joseph B. Herzog, University of Indianapolis

Joseph B. Herzog is an Associate professor in the R.B. Annis School of Engineering at the University of Indianapolis. He chose to come to the University of Indianapolis because he is passionate about teaching, is excited about the direction of the new R.B. Annis School of Engineering, is glad to return to his engineering roots, and is happy to be close to his extended family. Previously he was an Assistant Professor in the Department of Physics at the University of Arkansas. He is truly grateful for his time at the University of Arkansas, and enjoyed his department, students, and the campus. While in Fayetteville, he also served as a faculty in the Microelectronics-Photonics Program and the Institute for Nanoscience and Engineering. He received his PhD from the University of Notre Dame working in the Nano-Optics Research Lab with J. Merz and A. Mintairov. After this he was a Welch Postdoctoral Research Associate, researching plasmonic nanostructures at Rice University with Douglas Natelson in the Department of Physics & Astronomy. In the summer of 2017 he was a Fellow at the U.S. Naval Research Laboratory (NRL) in Washington, DC working with Jake Fontana on tunable subnanometer gap plasmonic metasurfaces as part of the Office of Naval Research Summer Faculty Research Program. At the NRL he worked in the Center for Biomolecular Science and Engineering, which is a division of the Materials Directorate at the NRL. His experience also includes working for Intel Corporation both in Hillsboro, OR and Santa Clara, CA; and he worked at the Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung m.b.H. (BESSY - Berlin electron storage ring company for synchrotron radiation) in Berlin, Germany, researching ultra thick high-aspect-ratio microfabrication. His research focuses on experimental nano-optics, including plasmonics, nanofabrication, computational modeling, photonic crystals, and engineering education.

Design tool subway map for undergraduate design projects

Abstract

Engineering curricula featuring senior design experiences may be the first time students have an opportunity to experience a team-based, open-ended authentic design. The curriculum at a small, urban, private school is centered around a series of hands-on, client-based design courses in each of the four years of the plan of study called the DesignSpine®. Projects are completed over the course of a full academic year. Clients for these student projects are mainly external industry partners, with some internal faculty or departmental clients and a small number of competitions. Faculty serve in multiple roles, including technical consultants and project team coaches throughout the program.

While historically successful, semester evaluations and team status reports often referenced uncertainty among student teams for next steps or appropriate tools to progress the design process. A faculty committee tasked with the responsibility to review, develop, and implement design course work was inspired by the Agile subway map to provide students with a comprehensive representation of the school's design process, and alleviate uncertainty. The faculty converted curriculum topics into a subway map representation of the project management, product development, and design tools covered in the course curriculum. All tools and resources have been mapped to the core concepts of the school's design process: Ask, Plan, Imagine, Research, Create, Test & Evaluate, and Communication. The subway map is intended to guide student teams through any problems during the design process that correlate to a particular core concept. In addition to the map, faculty have compiled summary resources for the tools and topics along the core concepts.

This paper will present the DesignSpine® subway map for design, and the development process of the map and its accompanying resources. This resource should be of interest to programs with product/process design and capstone experiences.

Introduction

The 2020 National Academy of Engineering report "Educating the Engineer of 2020: Adapting Engineering Education to the New Century" describes the need for our engineering education system to produce graduates that are not only technically strong, but innovative and entrepreneurial enough to prepare for a rapid pace of change and an intrinsic lack of predictability in projects, challenges, and employment [1]. Engineering programs face challenges of high attrition, a lack of opportunity for students to transfer into programs, and, in many cases, pedagogies that have remained in place for decades.

Successful engineering students should see curricula beyond a rigorous discipline-specific series of courses. The holistic engineering plan of study should include leadership, effective teaming, strong technical skills, and a focus on societal, ethical and environmental effects of engineering decisions. Students in such programs who build a strong 'engineering identity' are typically more successful [2]. A strong engineering identity is tied to student retention, stronger self-efficacy, and higher motivation [3]-[6]. Integrating hands-on, authentic projects into the classroom is beneficial to engineering students. This is especially important as this more closely resembles what the graduate will do in industry [7]-[10].

Engineering curricula has, in many ways, remained unchanged for decades. In fact, a description of engineering from the literature posits:

1) Most of today's freshmen engineering students will never graduate as engineers.
2) Most of those who drop out do so during their freshman year.
3) Most of these dropouts could become good engineers-great assets to our society-if they were properly motivated.

The question "How can we address these issues?" is posed in the manuscript. The authors describe their proposed approach:

> "We believe that one answer to this problem is to get the student personally involved in a realistic engineering experience and, to us, this means a design experience. To be realistic, the design experience should take the form of a project which involves a genuine human need which is not solved satisfactorily today [11]."

While this description could conceivably be from a recent manuscript, *this particular manuscript was written in 1966*. In the past 50+ years, we have seen pedagogical innovations designed to improve first-year engineering programs and the introduction of problem-based learning, but efforts to incorporate authentic engineering designs into the curriculum are nearly always focused in the senior year. This makes sense, since ABET requirements imply a senior capstone experience in their accreditation criteria, but simply maintaining a senior design course fails to address the need for team-based, real-world, open-ended design experiences throughout the curriculum.

Background of the DesignSpine® Program

The curriculum of the DesignSpine® Program at the University of Indianapolis was developed around real-world design experiences. The goal is to produce graduates with strong technical knowledge, project management skills, a strong engineering identity, an exceptional ability to

communicate, and experience in real-world, relevant engineering design. Students receive a traditional, technical engineering education centered around a DesignSpine® course each year [12]-[15].

In the DesignSpine® course, each student is placed in an interdisciplinary team, and each team has an authentic project, for a real-world client. The project spans the entire academic year. Teams work with faculty to create a project charter, documenting the constraints and requirements of the project and describing the criteria for success. Teams then embark on the iterative design process to develop preliminary designs, test and evaluate design alternatives, develop and test prototypes, and compose detailed documentation of final designs.

Like many of our student designs, our curriculum has undergone a number of iterations in effort to continuously improve our system and the learning experience of our students. Table 1 outlines the four phases in our design curriculum [12], along with the primary goals to be accomplished by the end of each phase. To accomplish the goals in each of these phases various design tools can be used. The table also represents a timeline of the design process in our curriculum. Since the implementation of these changes, teams have consistently been on-schedule or significantly closer to the planned schedule than in previous years and client satisfaction during project handoffs have been positive and engaging, which has also resulted in repeated client interest.

Table 1 - Phase definitions along with key phase goals.

Phase I	**Phase II**	**Phase III**	**Phase IV**
Identify Requirements	Develop Preliminary Design	Develop Detailed Design	Final System Design
• Confirm scope • Develop requirements • Identify challenges • Identify resources	• Present the preliminary design and proof of concept • Identify relevant resources needed to develop detailed design	• Present detailed design and engineering prototype • Explain design insights and decisions obtained from testing	• Present final system design, including validation testing and demonstration of product • Communicate the solution and transfer deliverables

What we are doing in our School of Engineering is neither unheard of nor new. There are many design programs within the various engineering education programs and disciplines that have a design methodology and course structure to support student teams. The question we pose in this work is, “how do we best communicate design methodology information to students so that they can apply it to their projects autonomously?”

Student Feedback and Confusion of "What to do next?"

Each student team in the DesignSpine® courses are assigned a faculty team coach (FTC) to provide project guidance ranging from technical insight to project management strategies. The FTC is a coach for the team, and our faculty have various coaching styles, but provide a consistent and primary resource for the team. FTCs are a central figure in the team to solicit feedback on project status and planning. The projects are, in general, student owned but the coaching of faculty members provides the institutional support and guidance toward success, particularly in an environment where undergraduates are engaging with clients external to the School of Engineering.

The structure of the FTC also provides an avenue for curriculum management, with faculty in the position to receive candid and informal feedback from student teams. These messages are then able to be relayed to program coordinators and curriculum committees in real-time, rather than waiting for the end-of-semester evaluations. We have benefited from this access to informal team assessments as real-time feedback to support our continuous improvement of the DesignSpine® course coordination.

The (often candid) interactions between students and FTC allow for low stakes communication between student teams and faculty to present work, tackle hurdles, and propose ideas. The focus of this work is relevant to faculty and student reporting of incidents when student teams are uncertain about next steps in the project, are behind in their planning and execution, or have no structured plan for their design process. The resulting actions of such teams have been observed to either (1) seek out additional support from DesignSpine® faculty/staff or the FTC or (2) remain silent and make little progress within their project. The latter has been of primary concern for our curriculum review and course planning.

Further feedback is available through end-of-semester evaluations and through a "DesignSpine® Comment Box" shared document allowing anonymous feedback. Feedback through these mechanisms tended to be focused toward the 'big picture' of the organization of the course or the DesignSpine® curriculum. All of the feedback is discussed and considered at the end of each semester during a course review.

The faculty feedback and candid remarks of the student teams led the faculty to question, "how can we improve the resources available to students to support student-lead problem solving and project progression?"

DesignSpine® Committee Structure and Purpose

Through the DesignSpine® curriculum, students are instructed on design processes and lead through a number of tools and resources that can be applied within design phases. From the student feedback and faculty observations, it was apparent that some students were not connecting the instruction with the application when it came to client-based projects. The question of how to improve resources for student-lead problem solving and project progression landed in the hands of the DesignSpine® Committee.

The DesignSpine® Committee was created to provide leadership and unifying structure for the effective development and implementation of the DesignSpine® sequence of courses, which are a core component of the School of Engineering's curriculum at the University of Indianapolis. Primary responsibilities of the committee include:

1. Recommending strategies and methods for enhancing the achievement of student outcomes.
2. Developing strategies for effective implementation of the DesignSpine® framework

The committee is composed of faculty members across the disciplines offered in our School of Engineering. This issue of teams struggling with the strategies of the design process fell into category one of the committee's purpose, which led to the development of the Design Tool Subway Map.

The committee hypothesized that students may be missing the links or the flow of how all these design processes and tools can connect with the stages of a design project. The committee's solution was a visualization to help teams when they hit a hurdle, to filter through the available resources and identify the appropriate tool to use. In the past, some courses in the DesignSpine® curriculum required all teams to use all design tools covered, which was not always appropriate for every project. In addition, this became overwhelming and exhausting to student teams, lowering morale and motivation, due to the overload of work (student quote, "busy work"). The important and necessary tool was sometimes lost in the vast array of tools being worked on simultaneously; again, emphasizing the importance of a visual and comprehensive view of how these tools can support a design process.

Design Tool Subway Map Development

The committee began its review of how the tools were currently presented to students in the first course of the DesignSpine® curriculum. Figure 1 shows an early design tool chart that was shared with students. This chart could be overwhelming for students. It listed many tools and limited specific tools to specific categories, which may have discouraged students to use tools

whenever they needed them. This is similar to other tool guides which list potential tools and methods for specific design process steps [16].

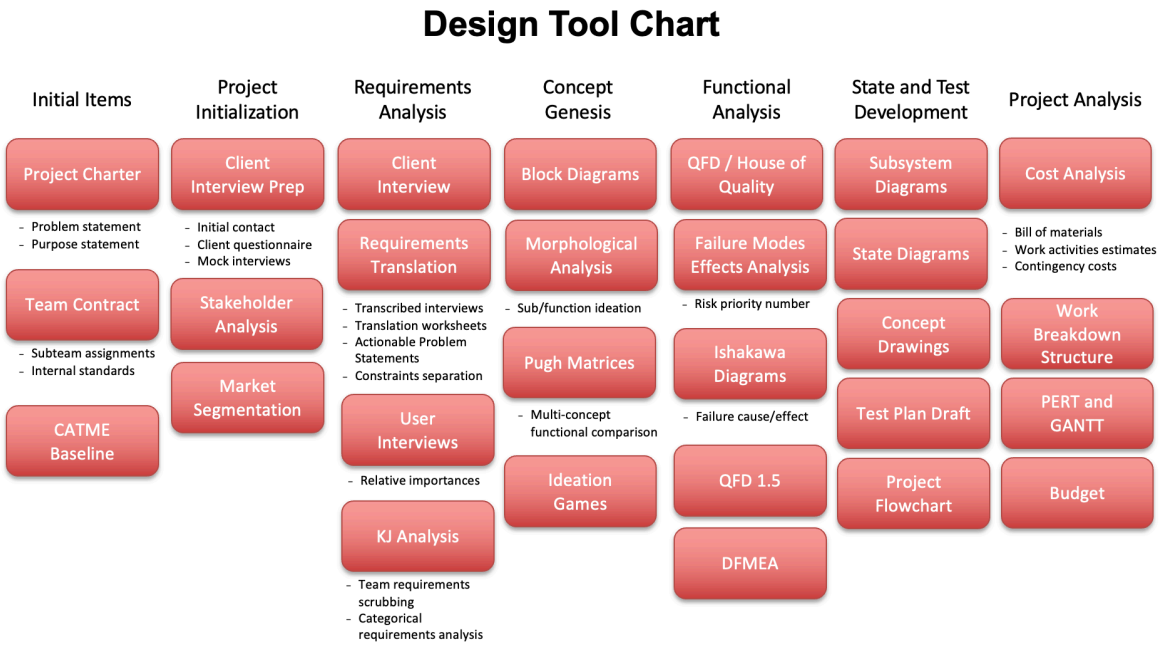

Figure 1 - Early Design Tool Chart - Categorized and listed design tools available to students.

Figure 1 represents the original visualization of the tools covered within our design courses. Although there is organization and categorization, it is not clear how one tool may influence the information needed or developed to be utilized in another tool, or how the categories align within the process of design.

The next stage of our visualization development process was to (as a committee) review these tools and previous projects to identify the frequency of use for each tool as well as the tools that students and FTC struggled to apply appropriately. This became an identification of importance for the various tools and allowed us to develop a prioritization list as we reorganized and investigated alternative materials to support the tools. The committee relied heavily on the experiences with previous team successes and struggles, and subject matter experts within the committee in the fields of design and project management.

After the filtering and prioritizing of design tools, the committee was inspired by the Agile Subway Map [17] as a natural visualization of this interrelated, connected, and often non-linear journey through design. On a subway map the different destinations are stationed along routes or lines. The committee needed to identify the DesignSpine® routes or how it was later phrased the

core concepts of our design process. The core concepts listed align with the design thinking presented in other instructional bodies [18], [19]:

Ask, Plan, Imagine, Create, Test & Evaluate, Communication, & Research

With the filtered and prioritized tools and core concepts, a new visualization for the design tools was developed to help students understand what tools to use and when (Figure 2). Like riding a subway, you do not necessarily need to stop at each stop (use each tool). It depends on the project needs. Also, there is no specific order for using the tools; the map is not a sequential map of tools, but you can go back and forth, or skip tools. One important concept and visualization of this map is that many tools can be used in multiple aspects of the design process. For example Design Notebooks, Flow Charts, and Block Diagrams are tools that can be used for Imagining, Creating, and Communicating. When pictured, the engineering design process often shows a ring of each step in a circle, flowing in a specific order through the steps, repeating the circle. This map illustrates that there are different ways to arrive at the same destination, you do not need to stop at every station, and often you may need to return to the same stop. This academic year the Design Tool Subway Map has been unveiled to the students as a visualization of appropriate tools, a taxonomy, not a process or new pedagogy, but in all sense of the word a map for teams.

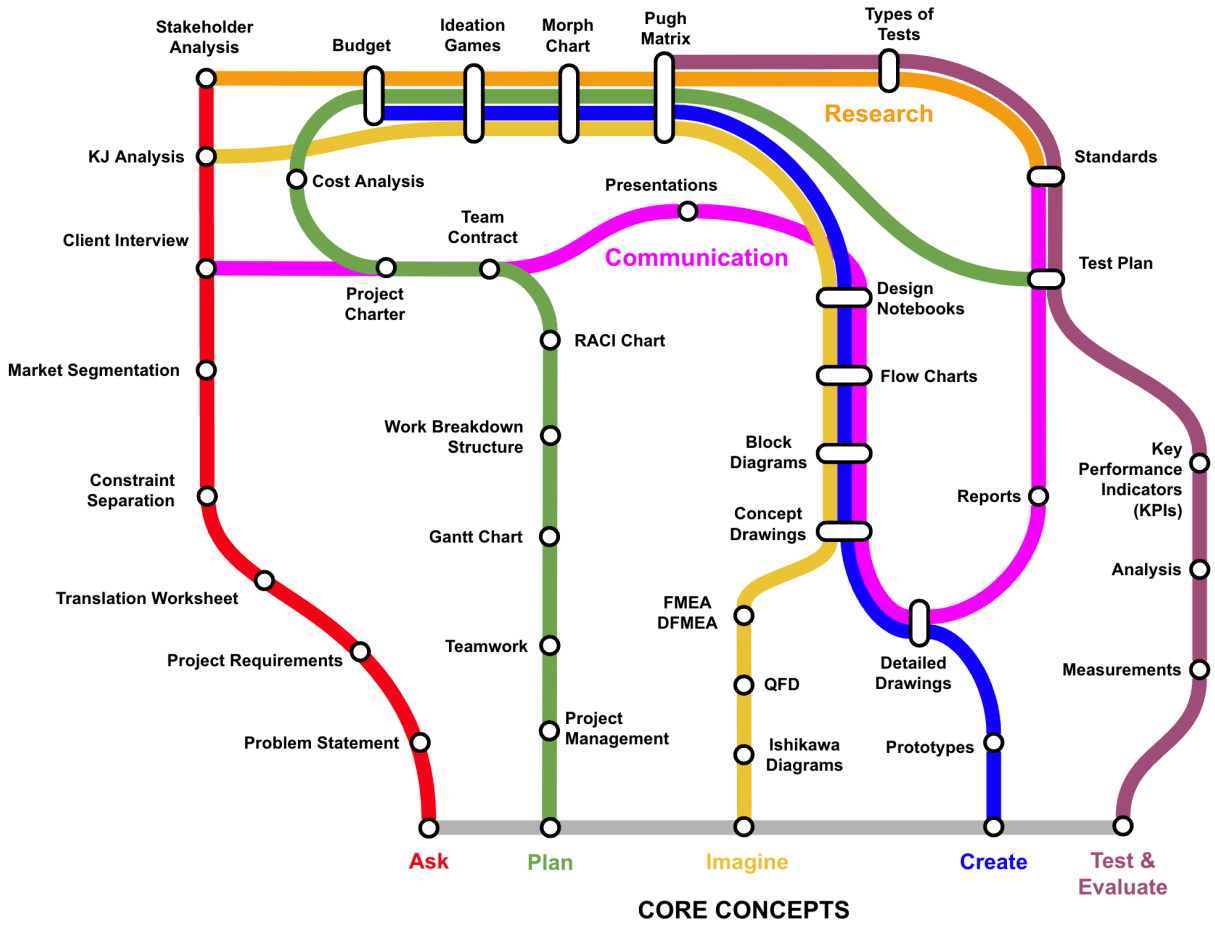

Figure 2 - Design Tool Subway Map. This map shows a taxonomy of key tools and how they can be used in various steps of the design process.

While our subway map resembles a design process, it is not a visualization of a design process, but a visualization of the tools used within a design process. It is not a graphic showing a procedure, but a map showing the relationships between specific tools and design steps. While this may seem like a fine distinction, it is a crucial difference.

Currently, the DesignSpine® Committee and faculty at the School of Engineering are creating an open access repository for templates, how-to instructions, and brief definitions of each of the tools in the map. True to our school's agile nature, we are reacting to student feedback from their design experiences that "[teams] get different information from different faculty about the same question." The committee is taking the opportunity of this tool visualization to pair with resources that all students and faculty can reference when applying the design tools rather than mixing up multiple interpretations. This (ongoing) process has included faculty review and composition of materials of various tools divided and assigned across the FTCs. Material is being presented at bi-weekly lunch and learn sessions and finalized documents are approved at the monthly faculty meetings to be added to the open access repository.

The outcomes of this map development have led to a visualization of the design tools and a repository of consistent school defined tool references. Our goal is to utilize these assets to promote consistency of understanding across students, faculty, and years of projects.

Discussion and Future Work

The implementation of the Design Tool Subway Map launched with a soft rollout of the map both in digital format for all DesignSpine® course materials and learning management system pages, plus an oversized wall decal within our ideation space this academic year (2023-24). At present the visualization is there as the intended map to direct students along their core concept path during the design process. The distribution of school approved resource material is ongoing. However, students do still have course textbooks and material sources to supplement their review of tools as well. A projected full rollout of the map and accompanying repository of tool materials is projected for Fall 2024.

Annual review of the Design Tool Subway Map and the corresponding tools will be included within the school's annual curriculum review. Evaluation of frequency of use of tools by student teams and faculty will continue to be considered. Map adjustments can be made as a result of the annual reviews and evaluations.

Student feedback is collected throughout the year and through end-of-semester student evaluations. Data on the use of the subway map, from student and instructor perspective, will be collected and analyzed. We will assess whether and how the implementation of the subway map enhances the overall effectiveness of the design curriculum.

Our team believes this map concept could be useful for any program with an open-ended design project within its curriculum, whether limited to the senior year or any project-oriented course or program. The map was developed specifically for our design program, and it is our expectation that other programs may wish to adapt the map for their own processes.

References

[1] National Academy of Engineering, *Educating the Engineering of 2020: Adapting Engineering Education to the New Century.* Washington, DC; The National Academies Press, 2005. https://doi.org/10.17226/11338

[2] J. Rohde *et al*., "Design Experiences, Engineering Identity, and Belongingness in Early Career Electrical and Computer Engineering Students," in *IEEE Transactions on Education*, Vol. 62, No. 3, pp. 165-172, Aug. 2019, doi: 10.1109/TE.2019.2913356.

[3] T. Ju & J. Zhu, “Exploring senior engineering students’ engineering identity: the impact of practice-oriented learning experiences,” *International Journal of STEM Education*, Vol. 10, No. 48, 2023, https://doi.org/10.1186/s40594-023-00439-2

[4] N. Mamaril, E. Usher, C. Li, D. Economy & M. Kennedy, “Measuring Undergraduate Students' Engineering Self-Efficacy: A Validation Study. Journal of Engineering Education,” *Journal of Engineering Education*, Vol. 105, No. 2, pp. 366-395, Apr. 2016. 105. 10.1002/jee.20121.

[5] G. Zhang, T.J. Anderson, M.W. Ohland, R. Carter & B.R. Thorndyke, “Identifying factors influencing engineering student graduation: A longitudinal and cross-institutional study,” *Journal of Engineering Education*, Vol. 93, No. 4, pp. 313–320, Oct. 2004. http://dx.doi.org/10.1002/j.2168-9830.2004.tb00820.x

[6] N. Choi, “Self-efficacy and self-concept as predictors of college students’ academic performance,” *Psychology in the Schools*, Vol. 42, No. 2, pp. 197–205, Feb. 2005. http://dx.doi.org/10.1002/pits.20048

[7] J.C. Dunlap, “Problem-based learning and self-efficacy: How a capstone course prepares students for a profession,” *Educational Technology Research and Development*, Vol. 53, pp. 65–83, Mar. 2005. https://doi.org/10.1007/BF02504858

[8] S. Palmer & W. Hall, “An evaluation of a project-based learning initiative in engineering education,” *European Journal of Engineering Education*, Vol. 36, No. 4, pp. 357-365, Jul. 2011. https://doi.org/10.1080/03043797.2011.593095

[9] L. Bucciarelli, “Design knowing and learning: A socially mediated activity.” In C. Eastman, M. McCracken, & W. Newstetter (Eds.), *Design knowing and learning: Cognition in design education* . Elsevier, pp. 297–314, 2001. https://doi.org/10.1016/B978-008043868-9/50013-9

[10] J. Trevelyan, “Reconstructing engineering from practice,” *Engineering Studies*, Vol. 2, No. 3, pp. 175–195, 2010.

[11] G. C. Beakley and T. W. Price, "Motivating Engineering Freshmen through an Authentic Design Experience," in *IEEE Transactions on Education*, Vol. 9, No. 4, pp. 195-197, Dec. 1966, doi: 10.1109/TE.1966.4321987.

[12] M. Hammond, K. Reid, S. Spicklemire, J. Herzog, S. Dharmarathne, D. Olawale, N. Saqib, C. Stanley, & G. Ricco, "Review of a Design Methodology in a Client-Based, Authentic Design Curriculum," in *ASEE Annual Conference & Exposition,* Baltimore, MD, 2023.

[13] M. Bauters, J. Holvikivi, & P. Vesikivi, "An overview of the situation of project-based learning in engineering education," *SEFI 48th Annual Conference Engaging Engineering Conference*, European Society for Engineering Education, virtual, 2020.

[14] D. Olawale, J. Sánchez, & S. Spicklemire, "UIndy engineering DesignSpine: Engineering leadership development through interdisciplinary teams and early exposure to real life problems," *ASEE IL-IN Section Conference*. West Lafayette, IN, 2018. https://docs.lib.purdue.edu/aseeil-insectionconference/2018/innov/1

[15] R. Miller, & B. Olds, "A model curriculum for a capstone course in multidisciplinary engineering design," *Journal of Engineering Education,* Vol. 83, No. 4, pp. 311-316, 1994.

[16] R. Nagel, O. Pierrakos & J. Nagel, (2013). "A Versatile Guide and Rubric to Scaffold and Assess Engineering Design Projects.," *ASEE Annual Conference & Exposition*, Atlanta, GA, 2013.

[17] Agile Alliance, "Agile Essentials: Subway Map to Agile Practices," Agile Alliance, https://www.agilealliance.org/agile101/subway-map-to-agile-practices/ (retrieved Feb. 2023).

[18] E. H. Mohd Shahali *et al.,* "STEM Learning through Engineering Design: Impact on Middle Secondary Students' Interest towards STEM," *EURASIA Journal of Mathematics Science and Technology Education*, Vol. 13, No. 5, pp. 1189-1211, Dec. 2017, https://doi.org/10.12973/eurasia.2017.00667a

[19] C. L. Dym, P. Little, E. J. Orwin & E. Spjut, *Engineering Design: A Project-based Introduction*, New York, NY, John Wiley and Sons, 2009.