*International Journal of Engineering Education* Vol. 38, No. 6, pp. 1694–1703, 2022
Printed in Great Britain
0949-149X/91 $3.00+0.00


# The Key Ideas of MDW XII: A Summary

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This paper provides a high-level summary of the presentations and associated discourse from the Clive L. Dym Mudd Design Workshop XII, "Designing Through Making: 2-D and 3-D Representations of Designs in Campus Facilities and Remotely," conducted online and coordinated from Harvey Mudd College from May 27 to 29, 2021. An attempt is made to encapsulate the key ideas that emerged from both the presentations and discussions of the participating engineering design educators, practitioners and researchers.

## 1. Introduction

There is a tradition to attempt a summary of the Mudd Design Workshops and the discussions arising from the panel preventions. This time (MDW XII) the biennial series of workshops was focused on Designing Through Making: 2-D and 3-D Representations of Designs in Campus Facilities and Remotely and was organized from Harvey Mudd College, in Claremont, California, from May 27 to 29 of 2021 but was conducted entirely online.

Due to travel restrictions from the coronavirus pandemic as well as the closing of the Harvey Mudd College Campus the workshop organization was modified significantly from prior versions [1–11]. The organization of the workshop was similar in many ways to the previous iterations and included two keynote addresses, five panel sessions, and a poster session. As noted, the most significant difference was that all were conducted entirely online. Consistent with prior iterations, the panel discussions were arranged to promote discussion among workshop participants. Discussions were both similar but different as they took place in breakout rooms online rather than around tables. This shift an area of significant concern to the author who was unsure if online discussions would retain the robust and collegial discussions that hallmark the workshop. Thankfully, this issue had been previously tested and addressed in the partner Canadian Design Workshop, permitting the borrowing of their well-conceived and executed format for use at the MDW. This prior experience with the online format and generous sharing of lessons learned is gratefully acknowledged. The transition to online posters also borrowed heavily from the CDW and resulted in a series of informative presentations and clustered discussion. It is believed that the online experience was very positive for attendees, though many still yearn to return to an in-person workshop for the next iteration if safe to do so.

One result of the transition to breakout room discussions with brief reports back to the larger group was that much of the discussion happened in isolation from the larger group. This sometimes meant that the brief discussion reports lacked the complexity and nuance of the full discussion and discussion questions were not posed to the larger group or to the authors until the session was completed, often running to or over the time limit for the session. The presentations are described below in the order delivered to assist the reader in understanding the workshop attendee experience. Summaries of the presentations are necessarily limited to that of the viewpoint of this author and, though the best effort was made to reflect the concepts and perspective of the speaker, this is inherently imperfect. Some speakers were kind enough to share permission for their talks to be shared through the Mudd Design Workshop website. Readers are encouraged to explore the speakers in their own words through those links where available.

## 2. Day One Presentations and Discussions

### *2.1 Keynote Presentation, Dorothy Jones-Davis, Made for Design: Leveraging the Maker Movement to Enhance Engineering Design Education*

#### Keynote 1

Dorothy Jones-Davis, our first keynote speaker, spoke to us on Made for Design: Leveraging the Maker Movement to Enhance Engineering Design Education. Her excellent talk explored the shortcomings and opportunities related to incorporation of makerspaces and the making movement within academic programs. While it is admirable that many programs, including many engineering programs, have developed well-equipped makerspaces at significant expense, these programs sometimes fail to meet the aspirational objectives intended.

There is not a single reason for the limited achievement of campus-based makerspaces and maker-movements. However, one frequent issue has been the isolation of makerspaces in terms of their intended and supported purpose. Such siloization of a makerspace to purposes of hobby building or course specific skills development is surprisingly common and, for wealthier institutions, can result in redundant tools in spaces that are under-utilized to a significant degree due to the restriction on purpose. Such restricted use makerspaces limit the opportunity for inter-disciplinary and multi-disciplinary collaborations benefiting design education efforts.

Another factor that detrimentally impacts makerspaces is the undervaluation of the skills and experiences of maker-focused students. The talents and experiences gained in making may be discounted in an educational setting. Exacerbating this issue is a tendency to view high technology solutions as superior to traditional making skills in the majority of endeavors. Skills such as woodworking, sewing, welding, and artisanal crafting have become regarded as curious or eccentric hobbies, or worse, as beneath engineering students to learn, rather than valuable tools for exploration and execution.

The goal of developing a competent, skilled, and excited engineering workforce may be better served through recognizing the value of both traditional and modern skills together as well as integrating the purpose of physical spaces to serve academic and co-curricular purposes. Academic institutions are uniquely positioned to combine the skills of their students, the tools available to them, and the local and global business, civic, and maker communities to address authentic engineering and broader needs. Such training can serve the needs of partner institutions by helping develop the net generation of engineering design thinkers.

### *2.2 Session 1: Making Beyond the Physical, Session Chair: Kathleen Sienko, University of Michigan*

- Innovating and Self Actualizing through Prototyping and WorldBuilding, Ade Mabogunje, Stanford University.
- Overview of the inaugural Canadian Design Workshop (CDW1): from Vision to Evaluation, Meagan Flus, University of Waterloo.
- Semantic Fluency in Design Reasoning, Jenny Quintana-Cifuentes, Purdue University.
- Designing a Design-Driven Human-Centered Engineering Program, Avneet Hira, Boston College.

Our first speaker spoke on teaching creativity and innovation using a learning environment applying hypothesis-testing, prototyping, and experimentation. This approach mimics the way that people naturally learn through a process of trial and error. However, the goal of this work is to extend beyond learning outcomes to include the broader development of the individual through increased autonomy and self-actualization as well as awareness and self-acceptance.

Beyond this, the goal is a community of learners and makers that will be able to boldly embrace continuous reinvention of themselves rather than just the artifacts they create through prototyping and innovation. Such efforts enable – or even demand – creativity in the establishment of their new order without a tacit dependence on the old models of making and living. The stated goal is to helping students develop the skills and process to invent a life where they live with a sense of wonder and enhanced personal fulfillment.

Our second speaker discussed the establishment of the Canadian Design Workshop (CDW) focused on advancing engineering design education and research topics unique to Canadian institutions. This biennial workshop was, in part, modeled after the Clive L. Dym Mudd Design Workshops in format. The new workshop's intent is to advance engineering design education within the Canadian context. This goal recognizes that important distinctions (and also the important similarities) to the United States in educational systems and cultures.

Logistical issues were a primary consideration of the workshop organization. It required unexpected considerations due the coronavirus pandemic including transitioning to an online format. This format was noted to provide challenges and opportunities. The format is preferable in the ability to gather multiple perspectives at lower cost than traveling, however, the degree of interaction may be more limited. This evaluation was part of the overall evaluation of the themes arising from the workshop with the intent to continue the CDW.

Our third talk explored Semantic Fluency in Design Reasoning. Multiple forms of reasoning shape a designer's perspective and decision process. Semantic fluency is the ability to effectively transition between the different forms of reasoning. This talk introduced the concept of semantic fluency and illustrated the process using a design review conversation with a middle school student.

The student selected for this example was unusual in that he employed a three-quadrant transition rather than the far more common two-quadrant transition (or no transition) used by his peers. It is interesting that semantic fluency is demonstrated in novice designers. It is proposed that guidance through appropriate questioning in design review context can expand the designer's semantic fluency.

The fourth talk in this session described the unusual opportunity to create a design-driven engineering program at Boston College. A high-level description of the process was shared at MDW XI. The program has continued to include human-centeredness, design thinking, and reflective practice in the program. The establishment of an engineering program within a liberal arts college enjoys opportunities to combine the technical and humanistic strengths of this college. For example, by housing the department of engineering within the college of arts and sciences, it is hoped that students will be given opportunities to appreciate the complex aspects of sociotechnical problems as well as understand the impact of their work on society.

This program includes courses co-taught by liberal arts and engineering faculty to better contextualize the challenges faced by engineering beyond solely solving technical problems. Interestingly, such courses are open to students in all university majors. The additional anticipated coursework in and beyond engineering including service-oriented capstone project and a foundation of reflective exercise were described. This interesting challenge and the atypical approach to building the engineering program appear to challenge assumptions on the division of the liberal arts and engineering fields.

### *2.3 Session 2: Perception and Graphical Representation, Session Chair: Micha Lande, South Dakota School of Mines and Technology*

- Improving Engineering Sketching Education through Perspective Techniques and an AI-Based Tutoring Platform, Morgan Weaver, Georgia Institute of Technology.
- Building Confidence and Embracing Failure through Sketching, Madhurima Das, Massachusetts Institute of Technology.
- CAD as a prototyping method: Uses and timing of computer-aided design artifacts throughout the design process, Hannah Budinoff, University of Arizona.
- Student Perception of Construction Problems and their Process Design Strategies, Farshid Marbouti, San Jose State University.

The first talk in this session explored Improving Engineering Sketching Education through Perspective Techniques and an AI-Based Tutoring Platform. The talk described the benefits of freehand sketching to quickly describe concepts within a design process and noted that there is a general lack of instruction in such skills within the great majority of engineering programs. A potential solution to this instructional gap may be borrowed from the industrial design space through the application of a software tool called Sketchtivity, an intelligent tutoring system. The tool is able to automatically generate feedback on sketching by students.

The talk explored the use of such a tool for engineers in terms of if and how well tutoring software can improve learning outcomes, the degree to which perspective training improves freehand sketching ability, and the degree to which sketching ability is helpful in an engineering design context. It was interesting that while no improvement was noted between the traditional and perspective based instructional styles, there was an improvement in sketching ability through the use of the software tool. Even when compared to a three-week instructor taught program, the use of the software tool for six weeks of AI based instruction showed greater benefit. It is noted that the question of AI instruction assistance beyond the topic of sketching may be of significant future interest.

The session's second talk addressed Building Confidence and Embracing Failure through Sketching. Resiliency is of growing interest to engineering educators and industrial practitioners. This trait of embracing failure in order to grow may be developed in many ways. The talk explored the use of low-stakes sketching practice replete with opportunities to fail and to grow. Sketches are evaluated for smoothness, proportion, accuracy and ability to be understood.

Students found the sketching activity productive in increasing comfort with failure. Throughout the course, student sketching smoothness improved. Coincident with the smoothness improvement, student sketching confidence increased. It was noted that women had a higher initial confidence in sketching and that men experienced a greater growth in sketching confidence reducing the gap. The confidence difference was supported by higher scores for women in smoothness and proportion/accuracy of sketches.

The third talk explored the use of Computer Aided Design as a prototyping method: Uses and timing of computer-aided design artifacts throughout the design process. The use of CAD has been traditionally considered most useful in the detailed design process. Recently, the value of CAD as a tool earlier in the design process has been explored. This talk explores the purposes and timing of Cad throughout a design process. In particular, scholarly work exploring the use of 3D CAD as a tool to explore designs has been evaluated.

Exploration of CAD purpose and process timing in a prototyping process was evaluated through coding. The use of this process for virtual prototyping was common including in the early conceptual design phase. CAD prototypes were used for both communication and technical interrogation of design alternatives. The talk also described the benefits of 3D CAD models for virtual prototyping.

The final talk of this session was on the topic of Student Perception of Construction Problems and their Process Design Strategies. The construction process can be multiply-constrained and ill-defined. Engineering students working on such problems may not fully appreciate the degree of complexity and might approach problems they face as though they are well-structured. This talk applies a systems thinking framework to enhance the design thinking around such problems. The framework employs a hierarchical approach to these problems through addressing critical aspects of the design throughout six sequential levels, each of which builds upon the prior level.

Students attempted to address construction engineering problems both with and without the use of the framework. They produced feedback on the work of their peer student teams and received feedback on their own work. The framework permitted a faster transition to higher level design thinking. For example, those employing the framework exhibited a better understanding of the relationship between materials, structures, and processes, a critical competency for construction management. Acceleration of the learning process is demonstrated through the framework developed.

## 3. Day Two Presentations and Discussions

### *3.1 Keynote Presentation, Amar Hanspal, When Two Disciplines Collide: Design meets Manufacturing for Seamless Product Innovation*

**Keynote 2**

Our second keynote was delivered by Amar Hanspal whose excellent talk was titled When Two Disciplines Collide: Design meets Manufacturing for Seamless Product Innovation. He noted the separation of the manufacturing and design stages of product development. In extreme cases designers could deliver blueprints or CAD files to the manufacturing group without consideration of process capabilities. This can lead to beautiful designs that cannot be produced or cannot be produced at the scale required.

Conversely, advanced robotic manufacturing facilities which are unable to economically build the cutting-edge products required are ineffective. Optimization for production requires carefully matching the production capabilities with the product design. Inefficient alignment will result in significant financial loss, needlessly increasing the cost of production.

Traditionally this tension between design and production can restrict design innovations to those able to apply the existing manufacturing processes or may incur unanticipated costs needed to increase production capabilities, sometimes with little benefit to the product. Joint development of design and production is an ideal which has been difficult to achieve.

Recent developments in design tools and manufacturing including adaptable robots, computer vision, machine learning, and drafting software have potential to integrate these aspects of product development. It is now conceivable for designers to understand the manufacturing costs of their design decisions almost as they make them. Similarly, production can understand the changes needed to optimize with respect to design changes. The development time required for new products may be significantly reduced with better performance and production alignment through this integration of information. Development of this integration is an exciting opportunity for engineers to explore and may enhance creativity in the design process.

### *3.2 Session 3: Early Prototype Education and Interaction, Session Chair: Sunand Bhattacharya, Boston College*

- Design in the freshman year: the roles of prototyping, Mathematics, Physics, Social Science and Arts and Humanities, Christine Yogiaman, Singapore University of Technology and Design
- The impact of appropriate prototyping choices on achieving design functionality for novices, Matthew Wettergreen, Rice University
- Community-Engaged Learning, Prototypes and Requirement Development, William Oakes, Purdue University
- Using practitioner strategies to support engineering students' intentional use of prototypes for stakeholder engagement during front-end design, Ilka Rodriguez-Calero, University of Michigan

The first talk in this session discussed Design in the freshman year: the roles of prototyping, Mathematics, Physics, Social Science and Arts and Humanities. In particular, issues with constructivist educational approaches based on prior engineering science knowledge proves challenging without formal training in the field. Moreover, many underclassmen lack nuanced evaluation skills which are helpful for the evaluation of designs. To address this, the Singapore University of Technology and Design has incorporated support of prototyping, mathematics, physics, social sciences, arts and humanities faculty in their first-year design course.

This eight-year investigation has permitted evaluation of prototyping as a process for students to integrate different domain knowledge. Specifically, a two-dimensional project spanning the first year design course covering the range of topics is investigated for its effectiveness in addressing these issues.

The sessions second talk, the impact of appropriate prototyping choices on achieving design functionality for novices, addressed the thorny topic of selecting the most appropriate prototyping tools for students to learn in a design course. It can be the case that prototyping capability in terms of instruments and tools exceed that necessary or even useful with respect to projects generally. This talk researched how well prototypes met the core or secondary project goals and the prototyping tools that were taught to the teams and evaluated skill development with these tools. The degree of skill development for use of different tools was measured by project team.

The time required for skill development was found to negatively correlate with the potential for the amount of growth, though skill development was possible for all tools. Eighty percent of students self-rated a skill decrease after training on a tool, indicating an initial higher than accurate self-assessment. Interestingly, the post skill level assessment of students and reviewers closely matched. Skill development was correlated with achieving functionality. The researchers suggest that the model of teaching the fewest tools necessary is superior to teaching as many as possible that might be useful.

The third talk of the session addressed Community-Engaged Learning, Prototypes and Requirement Development. The utility of community-based projects for engineering design programs may offer benefits over traditional industrial sponsored projects with respect to the impact on local and global communities. Purdue's Engineering Engagement Program has used a human-centered design experience involving community-engaged learning to create benefits students educationally and create tangible benefits to community organizations.

The program addressed a broad range of projects and applications of prototypes and prototyping to understand and address problems. One aspect explored was a prior result reported in the literature that students were less aware of specification development than other phases of human centered design. Interventions were explored which had no statistical difference from the control group indicating an enhanced learning from the design experience itself.

The final talk of the session, using practitioner strategies to support engineering students' intentional use of prototypes for stakeholder engagement during front-end design, explored the use of prototyping early in the design process while engaging users and other stakeholders. The use of prototypes early in the design process is useful to understand stakeholder needs. However, research suggests that novice designers are not as intentional or encompassing in their use of prototypes in the early stages of the design process as more experienced designers.

This work uses narratives from real-world design practitioner experiences in the front-end of design problems to describe how using prototypes enhanced stakeholder engagement. The narratives and strategies for their use in classrooms were presented including appropriate context and opportunities to understand their value to the process. In addition, methods to support more intentional student use of prototypes in the front end of a design process are described.

### *3.3 Session 4: Virtual and Remote Experiences, Session Chair: Maria Yang, Massachusetts Institute of Technology*

- Experiences with Prototyping and Making in Virtual Classes, Reid Bailey, University of Virginia.
- Multinational study on Fast Feedback and Team Member Behavior Change, *Gordon Krauss, Harvey Mudd College.*
- Successful Strategies for Remote Making: A Case Study of the SmithVent Experience, *Susannah Howe, Smith College.*
- Iterating Overnight: Using Cardboard to Teach Audio During a Pandemic, *Colin Gray, Purdue University.*
- Implications of Psychological Safety to Facilitate an Inclusive Environment in Remote Design Team Collaboration, *Lawrence Domingo, Stanford University.*

The first talk in this session addressed the application of prototyping in virtual engineering class settings predominantly as a result of the transition to online teaching necessitated by the coronavirus pandemic. It is noteworthy that prototyping remotely in courses might have been unimaginable prior to the pandemic. The study included two focus groups and four institutions to understand the effectiveness of this transition and the potential for continued use post-pandemic.

It was observed that remote prototyping was easier to accomplish for closed-ended prototyping or for appropriately scoped open-ended prototyping, which may involve less ambitious outcomes. An increased desire for individual prototyping work was observed in students which may have conflicted with a desire to encourage collaboration in the prototyping process. Overall, team approaches needed to be managed differently and were more successful than anticipated.

The session's second talk explored the creation and monitoring of teams in the face of the pandemic and compared responses of students based in North America with students based in Europe. Student team formation is a challenging issue in that it seeks to inspire collaboration but sometimes results in significant conflict regarding project direction or degree of commitment. An online tool was introduced to monitor team member feedback in product development courses at two schools with the intent of both establishing a standard of performance and accountability through its existence and monitoring for early signs of conflict requiring instructor intervention.

There were significant differences between the responses of students in the different schools. Overall, the students in North America were more aware of the feedback tracking tool and mindful to meet team member expectations than students based in Europe. North American students were also more likely to desire intervention from instructors than European based students who expressed far greater desire to manage team members on their own.

The third talk of the session explored a ten-week collaborative designing and making activity in response to the coronavirus crisis. A group of thirty geographically distributed participants collectively designed, produced and validated a simplified ventilator. This cost-effective ventilator was the winner of the CoVent-19 challenge, the SmithVent. The talk connected the topics of nature of the work, common ground, collaboration readiness, technology readiness, and management to this effort as well as remote collaboration and remote making.

The learnings from this successful effort are generalized and presented as a model for remote making collaborations. This is of particular interest as courses with hands-on or making components have grown more common due to the coronavirus crisis and industry has begun to embrace remote work. Both cases have traditionally been very limited in their making activity and the example of the SmithVent success can be useful in their successful implementation.

The session's fourth talk explored prototyping as an engineering competence which requires understanding the appropriate level of fidelity for required design tasks. An interesting impact of rapid fabrication techniques and their popularization in part through the maker movement that may contribute to a reluctance of design students to rapidly create lower but appropriate fidelity prototypes to address design questions. Even the far faster realization of higher fidelity prototypes using such technology may result in slower design process progress.

The speaker presented research conducted in an engineering lab course that was additionally challenged by relocation of the prototyping lab resulting in more limited equipment access and the coronavirus crisis resulting in transition to online instruction. The students were assigned the development of functioning loudspeakers using cardboard and the resulting outcomes and process applied were described.

The final talk of the session addressed psychological safety in the context of engineering project teams. The premise of the talk is that psychological safety and an environment where "wrong" thoughts can be shared without fear is critical to creative problem solving. Thoughts considered to be wrong may include factually incorrect understanding leading to the appearance of incompetence or socially prohibited perspectives either of which may result in reprisal. The study examined the response of team members to conditions with and without a method for concept generation and problem analysis.

Among the findings, the study found that identification of degree of psychological safety was not possible through interpreting facial expressions or body language, that psychological safety can change rapidly, that teams conducting brainstorming had higher fluctuations in psychological safety than those conducting analysis. These findings provide challenges to faculty seeking to create or encourage an inclusive and collaborative team environment on project teams and show that psychological safety is not necessarily persistent or activity independent.

## 4. Day Three Presentations and Discussions

*4.1 Poster Session: Session Chair: Chris Rennick, University of Waterloo*

- An Exploration of Prototyping Strategies Used By Students and Practitioners in Remote Engagements with Stakeholders During Front-End Design, *Nick Moses, University of Michigan.*
- Explorative Product Development through Poly-NURBS modeling in the Early Phase of PGE – Product Generation Engineering, *Leonard Sporleder, Karlsruhe Institute of Technology.*
- Impact of a Statics Sketch Tutoring Application Through an Open Ended Design Problem at Multiple Universities, *Josh Taylor Hurt, Georgia Institute of Technology.*
- Modified Design Process for Origami-Based Hybrid Soft Robot, *Dina Abulon, University of California, Irvine.*

- Tinkering to Learn Engineering, *Micah Lande, Dakota School of Mines & Technology.*

The format of our poster session was somewhat different for our online workshop. Authors were permitted less time to present their work but were able to discuss it further in breakout rooms with attendees.

The first poster presented research on the impact of geographically distributed design team participants on the front end of the design process. In particular, this study examined the use of prototypes with respect to stakeholder engagement early in the design process for teams of remote student designers and design practitioners. The strategies identified in the semi-structured interviews were compared to literature on non-remote front-end design activities and used to identify emergent strategies specific to remote teams. Th findings indicate at least one new useful strategy and adaptation of existing strategies by remote learners and practitioners.

The second poster explored the use of a powerful CAx tool in engineering design contexts intended to create virtual prototypes of varying detail in order to specify and document the product and make forecasts about the eventual product. This is of particular importance in the early phases of the design process where the downstream impacts can accumulate. The virtual prototype may serve to aid in fast, flexible, idea-stimulating generation, implementation, and testing of ideas in the early phases of product. explorative CAx methods need a low entry barrier, fast result provision, good adaptability and modifiability with the goal of supporting the product developer in his work in an idea-stimulating, flexible and situation-oriented manner. The study conducted examines ease of use and quality of concepts generated through the platform, with a twenty-minute introduction four of five teams were able to generate concepts and were more likely to iterate or attempt new variants than with traditional CAD. Participant felt the tool helped to increase team performance particularly with respect to communication.

The third poster examined the challenge associated with creating meaningful and creative engineering education experiences in introductory courses, particularly those with large enrollments. The research explores an artificial intelligence system that is capable of meeting challenges of teaching such content in large introductory engineering courses on topics such as statics. The specific AI system, called Mechanix, generates automatic and meaningful feedback to assist in understanding complex 2D systems such as truss designs. Evaluation of the system suggests an increased understanding of complex engineering concepts related to introductory statics sketching.

The fourth poster investigated a modified design process that was used in the development of an origami hybrid soft and rigid gripping tool that could alter morphology for access through a small port and then grasp an object. The process applied in design was heavily prototype oriented and included developing prototypes at the different stages of a design process. Moreover, nonlinear progression through the design stages was increased compared to typical approaches. The research suggests that increased prototyping and rapid recursion may enhance design approaches without predecessor examples.

The final poster examines how students learn through making and prototyping and what the attributes of making in an engineering classroom? Making and maker communities can serve multiple functions for engineering learning including communication of artifacts and recipes, development of practical ingenuity, community building, enhanced personal investment in projects, self-directed learning, increased playful invention, and risk taking. There is significant alignment between these skills and the NAE Engineer of 2020 report and ABET program learning objectives. The study evaluated what students were being taught, what they thought they were learning, and what they were demonstrating. A framework for applying a making-based pedagogy is presented. The authors observe that the skillsets of making may enhance rather than compete with the traditional engineering education, in part through greater self-efficacy in their educational goals and professional activities.

### *4.2 Session 5: Prototype Models and Processes, Session Chair: Ada Hurst, University of Waterloo*

- Predicting Success of Engineering Student Makers: Relationships between Makerspace Involvement, *Morgan Weaver, Georgia Institute of Technology.*
- Student perspectives of "deep modeling": What it is, why it is important, when it is useful, and how to do it, *Robin Adams, Purdue University.*
- Engineering students' performance of prototyping: Process, Purpose, and perception in the design classroom, *Todd Fernandez, Martin Jacobson, Georgia Institute of Technology.*
- Understanding Anchors Associated with Secondary School Students' Engineering Design Experiences, *Medha Dalal, Arizona State University.*

Our first talk in this session addressed the increased availability of makerspaces on college campuses with student performance in engineering programs. One positive aspect of student involvement in makerspaces has been an increased self-efficacy in design. Increasing student involvement in makerspaces opens additional questions regarding the impact of makerspace participation on students.

This study considers makerspace involvement in a design-centric program. Students with earlier involvement in makerspaces tended to have increased retention in engineering studies. This is important as higher anxiety regarding design results in both a lower makerspace involvement and a lower retention of students. Interestingly, no correlation was noted between grade point average and student makerspace involvement, however the authors note that the program studied required makerspace participation.

The second talk in the session explored deep modeling as a method to describe ideas in terms of how they work and may be used, what they achieve, and why they meet needs. Such models may be 2D or 3D graphical representations or physical or virtual prototypes. Such models permit deeper exploration and encourage visual thinking and collaborative design. This is one aspect of becoming an informed designer.

The study examined the understanding of deep modeling by students in a capstone course for how students understand the nature and purpose of deep modeling and the associations for how and when deep models are employed. Three specific cases are examined to address these questions and the results are contextualized in terms of prior work in the field and implications for future studies and practice.

The third talk considered prototyping in the context of design process performance instead of evaluation of prototype functional performance. This examination of prototypes as design process tools seeks to address the ways that students prototype to lesser effect than professionals in the design process. Recontextualizing prototypes in this manner was conducted in a biomedical engineering curriculum with juniors and seniors test subjects through a mixed-methods interviews and surveys approach.

The study suggests that students in this program regard prototyping as a required goal of the design process to demonstrate accomplishment, indicating an attachment of prototyping to the context in which it occurs. This includes such goals as learning to build in the realization of the desired prototype. Altering the perceived intention of prototypes in a design context appears to have a significant impact on the approach of students to prototyping.

Our final talk of this session evaluated the anchors associated with secondary students engineering design experiences. Relatively few secondary students are exposed to the engineering field despite efforts and interest in increasing engineering knowledge and skills in that educational timeframe. This study examined the experiences of pre-college students across the United States conducting increasingly complex engineering design projects.

The study found that four themes that identified how design experiences served as anchors for engineering pathways. The study examines a complex interplay of learning activities within educational contexts that influence higher educational and career choices. This understanding proposes methods that may be applied to increasing student recruitment and retention within engineering.

## 5. Discussion

When considering the workshop theme of Designing through Making and 2-D and 3-D Representations of Designs, we confronted issues that were not as settled as we may have originally believed when the theme was conceived. One of the initial questions was is making necessarily designing and is it necessarily engineering? This question can veer into the incorrect hierarchical questions of what is more important or more meaningful. The question also supposes a separation of design and making that may exist in a strict sense in many forms of design and production but is unlikely to exist in a maker community. Confounding this question is what qualifies as making and what qualifies as designing? For example, if a designer creates a CAD drawing and a maker causes that drawing to become realized as a 3-D artifact, it may appear that the role of designer and maker are clear and obviously differentiated. But we may ask, is the CAD drawing itself a prototype? What if the maker in this scenario only hits a start button on a 3-D FDM printer or laser cutting machine? When does a maker become a designer or when does the designer become a maker? The theme became the topic of interesting discussion and exploration.

We considered the purpose of 2-D and 3-D representations. Perhaps the challenging question of what a prototype is and its purpose in design and design education was one of the most discussed in our breakout sessions. Some asserted that a sketch or even a description may be a prototype as, in the proper context, it may serve to address a question. Others seemed unconvinced and wondered then if an idea might be a prototype. Adjacent to this discussion was the question of where engineering analysis or mathematical or computational modeling serve as prototypes or are independent of prototyping. There were a wide range of categorizations for 2-D and 3-D representations within categories of documentation/communication, prototyping, analysis and modeling or others without clear resolution.

While the question of what prototypes are lacked a crystalized resolution, the concept of prototyping as a means to answer a question for a specific means or integrated design alternative was a commonly accepted reason to prototype. Conversely, the name prototype was also attached to the final deliverable from a student design team. Coupled with a lack of clarity on the term itself was a lack of clarity on intent of the 2-D/3-D representation and its actual application within a design or making process.

Attention was also given to the skill development gained in making and how this helped to inform design and use of artifacts in the design process. This included exploration of appropriate resolution prototypes for different phases of a design process and purposes. Development of skills for prototyping or design representation are sometimes conducted independent of a design process without contextualization of the application of the tools more completely within the process of design. In some cases, the extension to design applications are direct. In other cases, the skill development itself may be the goal of the exercise. Students may not always be able to connect the specific skill development to their appropriate positioning in the design process.

The conversation regarding making and skill development was interesting in that the directly applicable stills for a design project are clearly connected but skill development in general may be beneficial. This may be especially true for skills students choose to develop. Conversely, a high tool skill set development independent of context may be confusing or distracting. Self-efficacy and intentionality of skill development may be critical aspects of making within a design setting. Those without prior opportunity to cultivate making skills may especially benefit from such self-directed learning.

Prototype evaluation similarly requires contextualization of its intention within a design process. How contextualized evaluation fits within the topic of making (or making skill development) in a student design project is subject to some debate and requires a closer examination of the purpose of the project. Certainly, development of making skills may be informative for engineering students even when the specific skills are not particularly relevant to the project. This observation reopened a long-standing debate on the purpose of a student project. Is the purpose of a design project to serve the student education or to achieve the project outcomes? This is especially important for projects proposed and sponsored by industry or other external partners.

## 6. Wrapping up and Looking Ahead

The five panels, two keynotes, and poster session challenge us to examine making and the resulting artifacts created either in a making exercise or design project. The line between these activities – which may have felt clearer at the start of the workshop– continued to blur for many participants. There was not complete consensus on the purpose or domain of making and where 2-D and 3-D representations exist within or adjacent to the design process. This lively discussion encouraged attendees to adopt other perspectives to consider the purpose of each activity which may include broadening interest and increasing participation rather than solely educating. Perhaps the most impressive aspect of the workshop was the serious and collegial engagement on these topics. Given the unusual online nature of our proceedings and the unfamiliar nature of our workshop in an online format, there was certainly no guarantee that this would happen. The prevailing atmosphere remained positive and deeply engaged. Somewhat surprisingly, a significant number of participants were eager for continued engagement between workshops on topics of interest. This will be a challenge engaged more specifically in future versions of the workshop.

*Acknowledgements* – The author is deeply grateful to each of the 60 contributors who attended and participated in the many presentations, discussions and conversations of the Clive L. Dym Mudd Design Workshop (XII) and to the members of the Organizing Committee for their efforts in making MDW XI successful: A. M. Agogino, *University of California, Berkeley*; A. Altman, *United States Air Force Research Laboratory*; R. Bailey, *University of Virginia*; S. Daly, *University of Michigan*; G. Fine, *Boston University*; A. Ibrahim, *Yorkville University*; M. Kokkolaras, *McGill University*; G. G. Krauss, *Harvey Mudd College*; M. Lande, *South Dakota Mines*; C. L. Magee, *Massachusetts Institute of Technology*; K. H. Sienko, *University of Michigan*; M. Siniawski, *Loyola Marymount University*; J. P. Terpenny, *George Mason University*; J. Turns, *University of Washington*; V. Wilczynski, *Yale University*; and M. C. Yang, *Massachusetts Institute of Technology*.

The author wishes to express additional thanks to Harvey Mudd College's Sydney Torre who managed and coordinated the online meeting activities with the help of Harvey Mudd College Computer Information Systems group, especially James Sadler and Elizabeth Hodas. In addition, Harvey Mudd College undergraduates Max Castro and Ethan Carroll assisted with session organization and timing as well as managing breakout rooms and participating in discussion.

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