Digital Prototyping by Multidisciplinary Teams

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Digital Prototyping by Multidisciplinary Teams

Introduction

This paper reports on research conducted in order to learn about and improve the performance of multidisciplinary design teams using digital tools for design development and collaboration. A computer-aided product realization course and associated product design lab serve as a testbed for conducting this research. In this course, students are initially familiarized with a common set of digital tools, and then formed into design teams. The digital prototyping tools include a cloud-based computer-aided design (CAD) platform, iterative 3D printing, and 3D scanning and scan data processing software. The CAD platform includes innovative freeform modeling capabilities. The multidisciplinary teams include students, mostly seniors, from systems engineering and design, mechanical engineering, bioengineering and industrial design. The design projects consist of biomedical products and devices, and each project includes a sponsor from the healthcare industry. The instructors include faculty from systems engineering and design, industrial design, and bioengineering.

Using this testbed, a graduate student conducted research on reflective practice, design thinking, and how students engage in and use digital tools for design and collaboration. The initial research was conducted in the fall of 2015. Project results include a five-minute video that describes student impressions of their design collaboration experiences, as well as the relative usefulness of digital prototyping tools in meeting design project objectives.

In the paper, we hypothesize that *ready access to 3D printing aids in successful design outcomes*. The following research questions are also addressed: (1) what activities do multidisciplinary student teams pursue in the early stages of design process?, (2) what benefits and challenges with regard to multidisciplinary design collaboration do students frequently note?, (3) what are the students' perceived understandings of the effectiveness of the cloud-based 3D CAD tool on team collaboration?, and (4) what are the students' perceptions of using 3D printing for design concept development? A combination of methods, including audio recordings, reflection journals and surveys are employed to address the research questions.

The results show that the course participants had a positive view of the multidisciplinary composition of the design teams. Another result of this work is that the use of the digital prototyping tools, in particular the use of the cloud-based 3D CAD tool and 3D printing was helpful in promoting collaboration as well as in improving the likelihood of successful design outcomes.

Another key finding from reviewing the design literature was the role and importance of reflection in design education and practice. The paper includes a list of influential publications relevant to the ongoing improvement of the course. These publications fall into the following categories: 1) design thinking, 2) design paradigms, 3) CAD and creativity, 4) physical prototyping, 5) additive manufacturing, and 6) future directions in CAD.

Background Course Information

GE 402, Computer-Aided Product Realization has been taught at the University of Illinois at Urbana-Champaign since 2003. The course was originally designed as an advanced CAD technology course for engineering students, covering such topics as geometric modeling, product design, engineering simulation, and additive manufacturing. In 2009, a faculty member from industrial design began to contribute to the course. The course soon began to admit students from both engineering and art & design, and took on a project-based, product design focus. Over the years, Autodesk has provided support for the course, mainly to promote collaboration between engineering and industrial design.

The course meets in the Product design lab (PDL). Equipment available in the PDL includes collaboration tables, computer workstations, laptops, iPads, a large format plotter, two Dimension 3D printers, and a Creaform handheld laser scanner. Autodesk Inventor, together with Rhinoceros and then Alias were initially used for product modeling, but in recent years Autodesk's Fusion 360 has been used exclusively. Geomagic Design X, formerly Rapidform XOR, is used for scan data processing.

In the summer of 2015, Autodesk provided funding to the course instructors in order to support research in design, focusing on the use of digital tools and multidisciplinary collaboration. A graduate student in engineering was recruited to conduct the research. At around the same time a teaching professor in bioengineering joined the instructional team. With contacts in the healthcare industry, the bioengineering professor was able to provide a number of sponsored medical device projects.

In the fall of 2015, twenty-three students took the course. There were five students from systems engineering and design, five students from mechanical engineering, six students from bioengineering, and seven students from industrial design. Nine of the students were males, with fourteen females.

Research Methodology

In the first six weeks of class, course materials covering the basics of parametric, direct and freeform modeling, 3D printing and 3D scanning technology, as well as design thinking and collaborative design were introduced. This knowledge was then used to develop solutions to design problems involving biomedical devices. Table 1 shows the design project topics.

Table 1: Design project topics, fall 2015

Teams	Biomedical design tasks	Main considerations
1	Neonatal Pneumothorax	Improve functionality and ease of use, reduce harm to patient
2	Nose Retractor	Make it possible for a single physician to perform the procedure
3	Eating Utensils	Develop customized utensils to allow client to eat independently
4 & 5	Multispectral USB microscope	Improve ergonomics, functionality of device
6	Slit Lamp	Improve aesthetics and efficiency of device

Data gathering tools

The data gathering tools used in this study include design protocols, reflection journals and an online survey. The graduate research assistant used the design protocol method to investigate team activities in the early stages of design. The students were expected to keep reflection journals and to complete an online survey in order to gain insight into student perceptions of multidisciplinary team collaboration as well as to assess the impact of using digital prototyping tools in the design process.

Protocol analysis: linkography

Protocol analysis is an empirical research method originally developed in the cognitive sciences to study thinking. One form of protocol analysis calls for subjects to think aloud during the performance of a task. Written transcripts are then analyzed to determine the cognitive processes used during the task. Protocol analysis is also employed in design research. Here a team design session (or a single designer thinking aloud) is recorded and transcribed, segmented, coded, and analyzed. ***Linkography*** (Goldschmidt, 2014) is a specific protocol analysis technique used to assess the productivity of an individual designer, or that of a design team. In our study linkography was used to analyze the cognitive activities of the design teams.

Reflection journals

Students submitted reflection journals (Hey, 2006) three times over the course of the design project period. The main purpose of the reflective writing assignments was to understand student perceptions of the influence of multidisciplinary collaboration on design, as well as to document their experiences using digital prototyping tools.

Survey

The online survey was conducted during the final exam period, after the final design presentations. Participation in the survey was optional. The survey consisted of eleven questions, seven of which were multiple choice, while the remaining four were descriptive. We asked the participants to rate the usefulness of the 3D CAD software, 3D printing and 3D scanning in the multiple-choice questions. The descriptive questions asked the students to describe their experiences using the 3D CAD tools, as well as with multidisciplinary team collaboration.

Literature search

Guided by research questions (can be found in literature search results section) proposed by one of the course instructors, a literature review was started in the summer of 2015. The primary goal was to identify the most important publications within specific research areas (e.g. design thinking, reflective practice, CAD and creativity, 3D CAD, 3D printing, etc.) that are directly related to the computer-aided product realization course. In the search and selection of these publications, we mainly focused on recent research articles and conference papers. Another consideration for selecting literature was the reputation of the publication and the number of times the work has been cited. Our literature review conducted using these measures resulted in a list of twenty-seven publications, organized into six categories, most of which were authored by leading researchers in their respective fields.

Video

Using funding from Autodesk, the Public Affairs Video Services at the University of Illinois was hired to make a short video documenting student impressions of the course in the fall of 2015. The video would consist of footage taken of various class activities, as well as interviews with students and the course instructors.

Results

Linkography analysis results

In order to gain insight into the early stage design activities of multidisciplinary teams, during the semester the graduate researcher made audio recordings of all in-class meetings for all six teams. Due to the sheer volume of the data captured in these recordings, however, the scope of the study was subsequently limited. The second meeting for three of the teams was chosen for this exploratory analysis.

The audio recordings for these meetings were first transcribed. Based on the transcriptions, together with listening carefully to the audio recordings, ***moves*** (i.e., statements) were determined and associated with a particular student. The graduate researcher then evaluated the moves to determine whether they related to the previous one. Related moves are called ***links***, and moves with a relatively large number of links are called ***critical moves***. The researcher then coded each link according to the activity categories described in Table 2, which is adapted from Milne (2000).

Table 2: Activity categories for coding the links (adapted from Milne (2000))

Design Content and Process Related Activities	
Analysis	Evaluating and discussing new ideas or concepts, discussing design requirements
Clarification	Asking questions, providing information, providing explanations to clarify ideas, concepts
Planning	Organizing ideas and concepts, assigning tasks, activities relating to team planning
Other	Other design related communication acts
Social Related Activities	
Social	Communication acts not related to the design task at hand

The researcher then constructed a ***linkograph*** of each design session, representing both a quantitative and qualitative analysis of team activities.

Figure 1 shows the linkograph for Team 2's design episode, while Table 3 summarizes of the data taken from the linkography analysis for all three teams. The ***link index*** is the ratio between the number of links and the number of moves that generate them. The link index, together with the critical moves serve as an indication of the amount of linking activity and is used in evaluating the effectiveness of a design session (Kan & Gero, 2007).

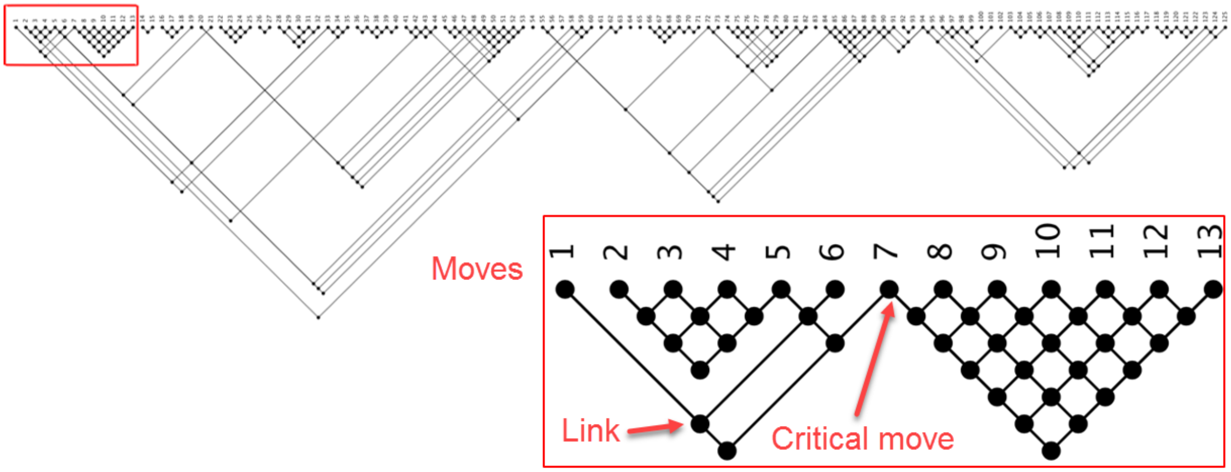

Figure 1: Linkograph for Team 2

Table 3: Quantitative results of linkography analysis

	Team 1	**Team 2**	**Team 3**
Total moves	61	125	202
Total links	122	209	295
Link index	2.00	1.67	1.46

Figure 2 shows the percent distribution of design activities for the three teams for these sessions.

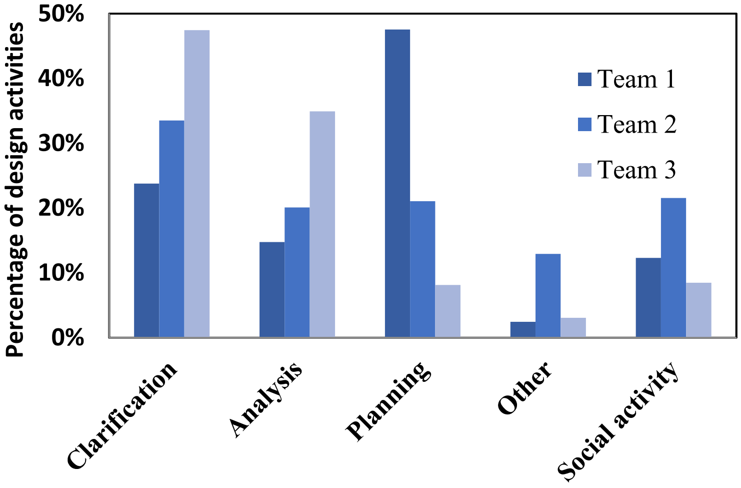

Figure 2: Percent distribution of design team activities

<u>Reflection journal results</u>

The reflective journal entries of the students were collected on three separate occasions. The students and teams expressed differing experiences and varying viewpoints regarding the 3D CAD software, 3D printing and 3D scanning. The majority of the students stated that their teams extensively used the **cloud capabilities of Fusion 360**. They concluded that the cloud features of Fusion 360 reduced the need for face-to-face meetings and enabled effective team collaboration. It was also found that on a number of occasion's team members worked simultaneously on different parts of a design and experienced increased productivity. The following quote from the reflection entries illustrates this point:

> *"My team has recently faced challenges with collaborating on a single CAD model while having varied schedules and while being in different parts of the country over the Thanksgiving break. Fusion 360's cloud system made this challenge relatively easy to overcome by allowing us to each contribute to the model and update it in real time"*

The students frequently noted that it was their first experience being a part of **multidisciplinary design team**, and that this opportunity served as a beneficial learning experience. In addition, the students highlighted how a diversity of skills and knowledge brought from each member complemented one another and enriched their learning of design:

> "*Working with a bioengineer, a mechanical engineer, and another fellow industrial designer has been incredibly pleasant, and possibly more enjoyable, productive, efficient, and valuable than any other group I have worked with in college*"

> "*I would admit working in this set up has accelerated the entire process greatly comparing to my other projects who only work with students from my own department*"

> *"This experience has given me a lot of insights about what my own skills are and what I can learn from my peers. I had not had many opportunities in the past to work with*

> *students in other fields and I really appreciated seeing how other disciplines work through a problem and develop a design*"

Examination of the reflection journal entries revealed interesting findings about student perceptions of **collaboration between engineering and industrial design**. For the majority of the students, taking this course was their first experience collaborating with students from an engineering (industrial design) background. Illustrative statements are given below:

> *"Coming from an engineering background, the mentality is that if it works, then it is good enough. Working on a project with design students has helped me to see beyond just function but to also examine form from both a qualitative and quantitative standpoint. I now take a much broader look at design problems than I previously considered."*

> *"The collaborative aspect of this project has been great so far. Being able to work with a diverse group of students adds an extra dimension of perspectives that I have not encountered in previous group projects (where the groups consisted mainly of engineers). As an engineer, it is great to have feedback from an industrial designer on how organic, aesthetic, and appealing a design might be."*

Besides the advantages and benefits of multidisciplinary team collaboration, two students noted the **downside of multidisciplinary collaboration**. An example follows:

> *"I think this helps the team to avoid wasting time, but it also has its disadvantage that people only do what they are familiar with and not learning new things. However, for the best quality of the team project I think this is a good strategy."*

Survey results

The participation in the survey was optional. Ten out of the twenty-three students participated in the survey. Seventy percent of the students found Fusion 360 to be "extremely useful" in enabling their team to create the geometry needed for their designs, whereas ninety percent agreed that the Fusion 360 software was either "useful" or "extremely useful" as a communication and tool. Seventy percent indicated that 3D scanning was either "useful" or "extremely useful". The finding that all students (100%) viewed their experiences in developing physical prototypes through 3D printing as either "useful" or "extremely useful" is especially significant (See Table 4).

Table 4: Survey responses on the use of digital prototyping tools

Prompts	**Not Useful**	**Somewhat Useful**	**Neutral**	**Useful**	**Extremely Useful**
Our team was able to create the geometry needed for our designs using Fusion 360	0%	0%	10%	20%	70%
Rate the usefulness of Fusion 360 as a communication and collaboration tool	0%	0%	10%	70%	20%
Rate the usefulness of 3D scanning in improving design outcomes	10%	0%	20%	50%	20%
Rate the usefulness of 3D printing in improving design outcomes	0%	0%	0%	20%	80%

Descriptive survey responses concerning the use of digital prototyping tools and the benefits of multidisciplinary teams on design are provided below.

On 3D CAD software: The teams used Fusion 360 extensively during both the concept and the detailed stages of design. Some survey participants indicated that the use of Fusion 360 allowed them to express their design ideas creatively and make design changes easily, while others faced technical issues.

On 3D printing: Several students indicated that the use of 3D printing was very helpful in testing and developing design concepts. The following are example responses:

> *"Can figure out whether our design is functional and practical immediately with 3D printing"*
>
> *"It did allow us to try building different ideas into our grip and physically observing how they would work very quickly"*
>
> *"We were able to notice significant differences in comfort from the 3D prints when making minor dimension changes. Without the prints we probably would not have made these changes"*

On multidisciplinary collaboration: The majority of the survey participants highlighted the different skills and perspectives brought to the team owing to the multidisciplinary team make-up. No common theme emerged in terms of difficulties related to the multidisciplinary team composition. Each student's assessment was unique in the way that he or she evaluated their experiences working with individuals from other disciplines. The general feeling based on their responses is that the students had positive experiences. The following responses reflect this:

> *"I really enjoyed working with students in different disciplines. Everyone added a unique perspective to the project. The most challenging aspects were in terms of communication. The engineers had to explain technical details to the designers and the designers had to take on more responsibility with the aesthetic aspects of the project. "*
>
> *"I had a great experience working with students from other disciplines. It was useful to have multiple perspectives on solutions to the same problem."*

Design outcome results

The design outcomes for the six projects are discussed in the appendix.

Literature search results

The original focus and underlying foundation of the testbed course are CAD tools and technology, or digital prototyping. After several years of collaboration with industrial design, the course has also become a project-based, multidisciplinary design course. Thus, the course rests on two pillars, CAD and design. This naturally leads to the question, what is the relationship between CAD and design? In the summer of 2015, the creator of the course, an engineering instructor, posed a number of questions about this relationship, these being:

- How do digital tools (CAD/CAE/CAM) affect the design process?
- Can freeform modeling be used effectively early in the design process?

- How does the availability of 3D printing accelerate the design process?
- How do teams with a multidisciplinary composition affect the design process?
- How does instruction in design thinking affect the design process?
- How does cloud-based CAD affect design collaboration?
- How does access to 3D scanning technology support the design process?
- What sorts of project characteristics increase the likelihood of a project's success?

To answer these questions, a literature search began in the fall of 2015. The original goal of the search was to identify the most influential papers related to the questions posed above. The result, still a work-in-progress, is a reading list spanning advances in design methods, digital prototyping, and interface between the two. Twenty-seven publications have been identified, including three books. These publications have been organized into six different categories, as shown in Figure 3.

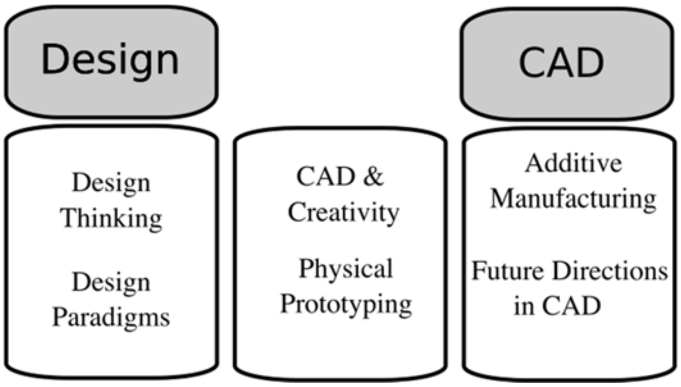

Figure 3: Design and CAD reading list categories

A discuss of these categories is provided below. Note that the citations listed in the ensuing tables refer to the number of times each publication has been cited to date, according to Google Scholar.

Design thinking

Table 5: Design thinking reading list

#	Title	Lead Author(s)	Affiliation	Publication	Year	References	Citations
1	Engineering design thinking, teaching, and learning	Dym, C.	Harvey Mudd	Journal of Engineering Education	2005	174	1483
2	A sampled literature review of design-based learning approaches: A search for key characteristics	Gomez Puente, S., van Eijck, M., Jochems, W.	Eindhoven U of Technology, Netherlands	International Journal of Technology and Design Education	2012	91	24
3	Empirical studies of designer thinking: past, present, and future	Dinar, M.	Arizona State	Journal of Mechanical Design	2015	190	22

Publication 1 (Dym 2005) is one of the most influential articles written on engineering design, with over 1400 citations, according to Google Scholar. Topics addressed in this paper include

questioning, convergent and divergent thinking, design thinking, design systems thinking, design teams, and project-based learning (PBL).

Publication 2 (Gomez Puente 2012) is on design-based learning (DBL). The paper discusses the findings from a literature search conducted on four dimensions of DBL, these being: 1) project features, 2) role of instructor, 3) assessment, and 4) social context.

Publication 3 (Dinar, 2015) discusses protocol analysis, design fixation, and design teams.

Design paradigms

Table 6: Design paradigms reading list

#	Title	Lead Author	Affiliation	Publication	Year	References	Citations
4a	The science of design: creating the artificial	Simon, H.A.	Carnegie Mellon	article	1968		
4b	*The sciences of the artificial*			book	1996		21,563
5	Dilemmas in a general theory of planning	Rittel, H.	UC Berkeley	Policy Sciences	1973		9,219
6	*The reflective practitioner: How professionals think in action*	Schön, D.A.	MIT	book	1983	220	48,318
7	Wicked problems in design thinking	Buchanan, R.	Case Western	Design Issues	1992	55	1,740
8	Comparing paradigms for describing design activity	Dorst, K.	Delft U of Technology	Design Studies	1995	8	400
9	The reflective practice of design teams	Valkenberg, R.	Delft U of Technology	Design Studies	1998	10	302
10	Designerly ways of knowing: design discipline versus design science	Cross, N.	Open U	Design Issues	2001	34	851
11	Educating effective engineering designers: The role of reflective practice	Adams, R.S.	U of Washington	Design Studies	2003	22	298
12	Revisiting Herbert Simon's "Science of Design"	Huppatz, D.J.	MIT	Design Issues	2015	72	2

Two design paradigms (Publication 8: Dorst 1995, Publication 12: Huppatz 2015) emerged in the later part of the 20th century, and their influence is still with us today. These paradigms arguably represent a yin and yang of design activity, or at least two complementary views of design, one positivist and the other constructivist[1]. These models conceive the design process as either 1) rational problem solving or, 2) reflection-in-action. The positivist approach, design as rational

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[1] Positivism, or empiricism, is a philosophy that emphasizes that knowledge of reality should be gained through observable and measurable facts. Constructivism asserts that reality is socially constructed (through social constructs). Objectivity is a key characteristic of positivism, while constructivism tends to be more subjective. Positivism is closely associated with the natural sciences, constructivism with the social sciences. Positivists believe that there is a single reality; constructivists believe that there is no single reality. More at: http://www.differencebetween.com/difference-between-positivism-and-constructivism/

problem solving, is championed by Herbert A. Simon, while the constructivist view, reflective practice, is associated with Donald A. Schön.

Simon is one of the towering intellects of the last half of the last century, having won, for example, the Turing Award in 1975 and the Nobel Prize in Economics in 1978. In 1968, Simon gave an invited lecture at M.I.T., "The science of design: Creating the artificial" (Publication 4a). This lecture was subsequently published as a chapter in Simon's influential book, *The Sciences of the Artificial* (Publication 4b).

Simon's ideas provided some much-needed structure to the study of design. Grounded in the scientific method, Simon's epistemology of design as rational problem solving is based on objective observation and logical analysis. It is an analytical, systematic, rigorous, and algorithmic approach to design. Simon is one of the fathers of artificial intelligence; note his use of the word *artificial* back in 1968.

When viewed as a problem solving approach, design becomes a search process, where you find ways to define and then explore the design space, looking to identify optimal solutions. Simon's science of design works well in situations where the problem is relatively straightforward, but tends to break down when faced with ***wicked*** design problems.

According to Wikipedia, a wicked problem "is a problem so difficult or impossible to solve because of incomplete, contradictory, and changing requirements that are often difficult to recognize." Although originally used in social planning (Publication 5: Rittel 1973), the term is also applied to design problems (Publication 7: Buchanan 1992), especially when there are societal, environmental, or political dimensions to the design problem.

In Donald Schön's seminal work from 1983, *Reflective Practice: How Professionals Think in Action* (Publication 6), he criticizes (Publication 10: Cross 2001) design as problem solving, saying that this method is only good for solving well-formed problems. Schön's approach is to first point out that professionals must constantly deal with messy problems. He puts his trust in the abilities of these competent practitioners, and sets out to explain how they do what they do. Schön defines reflective practice as the practice by which professionals become aware of their implicit knowledge base and learn from their experience.

Designers, for example, work by naming the relevant factors in a design activity, framing the problem in a certain way, making moves toward a solution, and then evaluating those moves, as well as the frame (Publication 9: Valkenberg 1998, Publication 11: Adams 2003). Reflective practice is an iterative practice. Schön speaks of having a conversation with a problem, a situation, or a sketch. In reflecting on a situation as we engage in it (reflection-in-action), we get feedback from the situation, which points a way forward.

This is reminiscent of a quote from Robert Pirsig's book, *Zen and the Art of Motorcycle Maintenance*, "... just *stare* at the machine. There is nothing wrong with that, just live with it for a while. Watch it the way you watch a line when fishing and before long, as sure as you live, you'll get a little nibble, a little fact asking in a timid, humble way if you are interested in it. That's the way the world keeps on happening. Be interested in it."

Whereas Simon's design as rational problem solving works best with well-structured problems, Schön's design as reflection-in-action works best in the conceptual stage of the design process.

Interestingly, although neither Simon nor Schön were designers/engineers/architects, yet together they have had a major impact on design methodology.

CAD & creativity

Table 7: CAD & creativity reading list

#	Title	Lead Author(s)	Affiliation	Publication	Year	References	Citations
13	CAD and creativity: Does the computer really help?	Lawson, B.	U of Queensland	Leonardo	2002	16	60
14	Impact of CAD tools on creative problem solving in engineering design	Robertson, B.F.	U of Sheffield	Computer-Aided Design	2009	33	116
15	Engineering design using game-enhanced CAD: The potential to augment the user experience with game elements	Kosmadoudi, Z., Lim, T., Ritchie, J.	Heriot-Watt U	Computer-Aided Design	2012	244	49

Publication 13 (Lawson 2002) begins with a description of how CAD helps with creativity. For example, CAD allows users to create significantly more complex geometric forms than can be created through hand drawing. CAD also tends to democratize design. Even those who lack basic sketching skills can create quality work with CAD, thus unleashing the creative imagination of non-designers.

On the other hand, CAD tends to inhibit creativity by adding a layer of complexity to the creative process. Whereas sketching is rapid and flexible, thus providing a direct link to creativity, CAD tends to frame the design agenda. Designers must translate their ideas into the language of CAD before they can enter and modify data. Publication 13 concludes that CAD falls short of providing true creativity.

Publication 14 (Robertson 2009) identifies various mechanisms by which CAD tools may influence the creative problem solving process. These include 1) enhanced visualization and communication, 2) circumscribed thinking, and 3) premature fixation.

The capabilities of the CAD tool circumscribe the ideas and thinking of the designer. Using CAD, design decisions can move from what best meets the design criteria to what is easiest, given time and financial constraints. This is similar to Publication 13's contention that CAD sets the design agenda. Additionally, because CAD is good at handling complexity, design goals tend to move from simplicity and sufficiency, towards excellence and perfection. In this way, the CAD tool affords too much creative freedom, introducing unnecessary complexity, and wasted resources.

As CAD models become more detailed, there is a disincentive to make major changes to the model. A large amount of detail and interconnectedness is built too quickly into a CAD model, which leads to premature fixation on certain solutions. Publication 14 concludes that CAD is better suited for detail design rather than for concept design.

Publication 15 (Kosmadoudi 2012), also included in the Future directions in CAD category, is included here because of its section on the limitations of CAD.

Physical prototyping

Table 8: Physical prototyping reading list

#	Title	Lead Author	Affiliation	Publication	Year	References	Citations
16	A study of prototypes, design activity, and design outcome	Yang, M. C.	U of Southern California	Design Studies	2005	25	132
17	The effects of physical prototyping and group work on the reduction of design fixation	Youmans, R.J.	U of Illinois Chicago	Design Studies	2010	63	90

The physical prototyping category includes two articles. The consensus view is that more time spent building prototypes leads to original design ideas, and successful design outcomes. Prototypes are beneficial for several reasons, including that they:

- Provide immediate feedback, and serve as an aid to visualization
- Help reduce the designer's cognitive load
- Help with the detection of design flaws
- Minimize design fixation

Publication 16 (Yang 2005) concludes that simpler prototypes with fewer parts are associated with more successful design outcomes, and that work performed early in design cycle, rather than putting things off until the end, tends to have a positive impact on the design outcome.

The focus of Publication 17 (Youmans 2010) is design fixation, and how the use of prototypes can minimize its effect. Designers have the tendency to fixate on features of pre-existing designs. Design fixation occurs when a designer experiences an example of an existing design, and then creates a new product with features similar to the prior example. Fixation is clearly detrimental to the ideation process. Building prototypes tends to reduce design fixation, and consequently to produce better outcomes.

Additive manufacturing (3D printing)

Table 9: Additive manufacturing reading list

#	Title	Lead Author(s)	Affiliation	Publication	Year	References	Citations
18	Making sense of 3-D printing: Creating a map of additive manufacturing products and services	Conner, B., Manogharan, G., Martof, A.	Youngstown State University	Additive Manufacturing	2014	42	73
19	The status, challenges, and future of additive manufacturing in engineering	Gao, W., Zhang, Y., Ramanujan, D.	Purdue	Computer-Aided Design	2015	348	84
20	*Additive manufacturing technologies: 3D printing, rapid prototyping and direct digital manufacturing*	Gibson, I. Rosen, D. Stucker, B.	Deakin U Georgia Tech U of Louisville	book	2010, 2015		184

In the additive manufacturing (AM) category, the search identified two recent papers and a book. Although the papers are not specific to design, the book (Publication 20, Gibson 2015) has a chapter on design for additive manufacturing.

The affiliation of Publication 18 (Conner 2014) is Youngstown State University. Youngstown, notably, is the home of the National Additive Manufacturing Innovation Institute (NAMII), part of the National Network for Manufacturing Innovation (Manufacturing USA).

Publication 18 creates a map of manufacturing products and services. It does so by using three criteria axes — production volume, level of complexity, level of customization — to map the manufactured product design space into eight regions, as shown in Table 11.

Table 10: Manufacturing Regions

Region	Name	Production volume	Complexity	Customization
1	Mass manufacturing	High	Low	Low
2	Manufacturing of the few	Low	Low	Low
3	Complexity advantage	Low	High	Low
4	Mass complexity	High	High	Low
5	Customized for the individual	Low	Low	High
6	Mass customization	High	Low	High
7	Artisan products	Low	High	High
8	Complete manufacturing freedom	High	High	High

The paper then provides a discussion of these eight product regions, and evaluates the suitability of each region for additive manufacturing.

The goal of Publication 19 (Gao 2015) is to provide an organized body of knowledge on additive manufacturing, as well as to present the challenges that the industry currently faces. The paper provides an overview of AM, barriers and challenges to AM, AM processes, printing attributes of AM processes, building capabilities of AM, AM commercial categories, as well as an educational view of AM.

Future directions in CAD

Table 11: Future directions in CAD reading list

#	Title	Lead Author(s)	Affiliation	Publication	Year	References	Citations
21	T-Splines and T-NURCCs	Sederberg, T	Brigham Young	Association for Computing Machinery	2003	12	679
22	MCAD: Key historical development	Cohen, E., Riesenfeld, R.	U of Utah	Computer Methods in Applied Mechanics and Engineering	2010	29	2
23	Cognitive, collaborative, conceptual and creative – four characteristics of the next generation of knowledge-based CAD	Goel, A., Vattam, S., Wiltgen, B.	Georgia Tech	Computer-Aided Design	2011	137	126

	systems: A study in biologically inspired design						
15	Engineering design using game-enhanced CAD: The potential to augment the user experience with game elements	Kosmadoudi, Z., Lim, T., Ritchie, J.	Heriot-Watt U	Computer-Aided Design	2012	244	49
24	Subdivision surfaces integrated in a CAD system	Antonelli, M	U of Padua, Italy	Computer-Aided Design	2013	40	14
25	An exploratory study on the use of digital sculpting in conceptual product design	Alcaide-Marzal, J.	Polytechnic U of Valencia	Design Studies	2013	55	26
26	Cloud-based design and manufacturing : A new paradigm in digital manufacturing and design innovation	Wu, D., Rosen, D.	Georgia Tech	Computer-Aided Design	2015	68	129
27	Initiating a CAD renaissance: Multidisciplinary analysis driven design; Framework for a new generation of advanced computational design, engineering and manufacturing environments	Riesenfeld, R., Cohen, E.,	U of Utah	Computer Methods in Applied Mechanics and Engineering	2015	25	7

Publication 23 (Goel 2011) focuses on “knowledge-based” or intelligent CAD systems, i.e. CAD that employs artificial intelligence (AI) techniques, rather than the mainstream mechanical CAD systems employed in product design. Still, the four characteristics of knowledge-based CAD systems proposed in this paper are equally valid features of next generation computer-aided product design software. According to Publication 23, future knowledge-based CAD systems should:

- Be based on cognitive studies of design
- Support collaborative design
- Support conceptual design
- Support creative design

Publication 15 (Kosmadoudi 2012) makes the point that digital gaming may present opportunities for improving future CAD platforms, for example by reducing design lead times, promoting decision-making, and sustaining the engineer’s interest and engagement. Publication 15 has also been included in the CAD & creativity category, owing to its section on the limits of CAD in engineering design.

As discussed in Publication 26 (Wu 2015), cloud-based platforms for design and manufacturing support design collaboration by allowing design teams to easily communicate, share data, work remotely, etc.

Freeform modeling (i.e., conceptual, creative) is a subject of three of the Publications (21, 24, and 25). Publication 21 (Sederberg 2003) addresses T-splines, Publication 24 (Antonelli 2013) the use of subdivision surfaces in a CAD platform, and Publication 25 (Alcaide-Marzal 2013) digital sculpting. Publication 21 is the only technical paper in this category, in addition to being the seminal paper on T-splines.

Bezier Award[2] winners have authored three of the eight papers, these being Richard Riesenfeld and Elaine Cohen (Publications 22, 27), and Thomas Sederberg (Publication 21). Publication 22 (Cohen 2010) is included because it provides a concise summary of the development of mechanical CAD software.

Publication 27 (Riesenfeld 2015) begins by pointing out that, as originally conceived by Steven Coons et al. in the early 60's at MIT, "CAD was envisioned as an interactive environment **to support the whole of engineering design**", and that this initial vision included transitioning from conceptual to detailed design, with analysis tools available throughout the process. Instead, although the past 50 years has seen the rapid development of architectural software structures for CAD, computer-aided manufacturing (CAM), and computer-aided engineering analysis (CAE), they have been conducted largely in isolation. Design engineers must spend large swaths of time learning the software and navigating the boundaries between these *stovepipes of excellence*. The authors then describe how today's CAD systems are highly geometry-centric, prematurely requiring far more geometric detail than is reasonably knowable in the early stages of design. They then call for the development of genuine design-centric CAD systems.

Video results

The Public Affairs Video Services at the University of Illinois completed the video of the class in early 2016. The video is just over five minutes in length. The YouTube URL is:

https://youtu.be/VRMGE_p3yyo

Course improvements

Informed by the literature review and the results of the fall 2015 course projects, several changes were made in the fall 2016 iteration of the course, including:

- Ten articles from the literature review were assigned as required reading. These articles were discussed in class, and students were asked to write a brief summary of each article.
- Additional content on brainstorming and prototyping was added to the course. In conjunction with the prototyping activity, prototyping materials (e.g., glue guns, foam board, card, tape, pipe cleaners, playdough, etc.) were made available to the teams for building prototypes.
- The time allotted for the design projects was expanded from eight to ten weeks.
- As part of the design project requirements, a logbook detailing the physical models produced by each team was introduced. The logbook contains photographs and brief descriptions of all physical prototypes and 3D prints produced by the team during the semester.

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[2] Solid Modeling Association http://solidmodeling.org/awards/bezier-award/

- A design quality rubric, adapted from Sobek and Jain (2004), was used to evaluate the design projects. Evaluators (i.e., course instructors, other faculty, and visitors from industry) used the rubric during the final project presentations.

The reflection journal, used for the first time in the fall of 2015, continues to be an assessment component of the course.

Fusion 360 is still a relatively young application, and consequently the Fusion platform has improved considerably since the fall of 2015, in terms of usability, reliability, and capability. Notable improvements include:

- Fusion Learning (or Help), now with a clear learning path and excellent tutorials
- Ability to manage data and collaborate is much better, with tighter integration between Fusion and A360 (a cloud collaboration environment for design teams)
- Software updates are much smoother, and more predictable. It is now much easier for IT personnel to install updates on networks
- Enhanced modeling workflows - working with bodies and components is now much clearer
- Enhanced capabilities – more simulation tools, new mesh environment

Conclusions

The research questions addressed in this study are:

Research question 1*: What activities do multidisciplinary student teams pursue in the early stage of design process?*

Although all of the in-class meetings for all six teams were audio recorded, due to a lack of time only the second meeting for three of the teams was analyzed. Based on this exploratory analysis we can say that, on average, much of the time was spent with team members asking one another questions concerning the design task, i.e., clarification. Planning activities were also common, followed closely by analysis activities.

Research question 2: *What benefits and challenges with regard to the multidisciplinary design collaboration do students frequently note?*

Data obtained from the reflection journals, the survey, and the video show that the course participants highly value their experiences working in a multidisciplinary team setting. Students felt that the combined knowledge of a diverse team accelerated overall team design performance and helped contribute to a successful design outcome. Here, for example, is a quote from the video:

> *"The idea of the project was to get all these majors together from different backgrounds and put all their strengths together to design something really incredible."*

Research question 3*: How do students view the effectiveness of 3D CAD software (i.e., Fusion 360) for team collaboration?*

Overall, student responses suggest that the use of Fusion 360 was viewed positively, in particular with respect to the cloud feature. Course participants frequently noted in their journal entries that the cloud feature provided an effective medium for team collaboration, as meeting outside of class was a common challenge faced by all teams. The students often noted that the cloud capability of the software allowed them to work on design tasks despite being separated by distance, thus supporting effective team collaboration.

Research question 4: *How do students view the role of 3D printing on design concept development?*

The results of the reflective entries and the survey demonstrate that students view 3D printing as being valuable in developing and testing design concepts. All survey participants indicated that developing design ideas through 3D printing is helpful in improving design outcomes. Another frequently mentioned benefit of 3D printing is the rapid feedback gained from the prototypes.

Hypothesis: *Ready access to 3D printing aids in successful design outcomes.*

Based on student feedback appearing in the survey data, reflection journal entries, and video interviews, as well as the design outcomes themselves, we conclude that the results of this study are consistent with the hypothesis. This quote, transcribed from a video interview with one course participant, is to the point:

> *"At the beginning of the semester we didn't really take advantage of the 3D prototyping aspect, and then when we finally realized how useful it was we did it over and over again. Ergonomic (issues) were so easy to spot. We printed the handle, felt it, and said, yeah, that's bad. Even aesthetics, we made this really bulbous model at first, and then we printed it out, and we really had to see the physical model to see that it wasn't going to work."*

The results of this research project have been used to improve the computer-aided product realization curriculum, and may potentially be of use to engineering design educators interested in combining design thinking with the latest advances in CAD technology. The results of the literature review, conducted as part of this research, consistently highlight the value of reflective practice and experience in multidisciplinary collaboration in enhancing student learning and developing professional competence.

Considering the rapid advances and increased availability of digital prototyping tools, there is a greater need for understanding and evaluating their impact on design and on the designer's creative performance. In particular, it is important to investigate the influence of current freeform surface modeling tools (e.g., T-Splines) on creative and conceptual design. With regard to the use of 3D printing, both qualitative and quantitative studies based on the changes made at each iteration of a 3D printed physical model are necessary in order to evaluate how the immediate feedback derived from the use of rapid prototypes aids the design process. Findings from these studies help inform design educators when choosing the appropriate computer design tools, and in coming up with effective teaching strategies towards the goal of preparing effective design professionals.

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APPENDIX: Design Outcome Results

Each design project had a sponsor from the medical industry. Throughout the project period, the student teams worked closely with their respective sponsors in gaining a better understanding of the design task, its objectives and requirements, as well as frequently receiving feedback on their progress. During the design process, the student teams produced a great number of free-hand sketches, virtual and physical prototypes, all of which were collected at the end of the semester. In the following paragraphs, we provide an overview of design outcomes for the six design teams.

Team 1 was asked to design a neonatal pneumothorax device. They used Fusion 360 and the Dimension 3D printer extensively. The team also worked closely with the project's sponsor, a physician, mostly through written communication. A sketch of the device, as developed by the sponsor, was given to the team at the start of the project. The team then developed the virtual and physical prototypes based on the initial design. Throughout the design project period, the team generated a number of prototypes and consistently received feedback from the sponsor on their progress. One of the team members mentioned that the Fusion 360 software was extremely useful in making precise refinements and small feature modifications to the device. Two of the team members continued to work on the neonatal pneumorax device after the project closeout.

This work was mainly aimed at perfecting the fit of the components in order to ensure that the device functions reliabily. The resulting design obtained at the project closeout is shown in Figure A1.

Figure A1: Example concept sketches, rendered image, and 3D prints produced by team 1, neonatal pneumothorax

Team 2 designed a nose retractor, and their design solution is shown in Figure A2. A nose retractor is an instrument used for holding back the nostrils to provide better visualization of the nasal cavity. Their final solution included a retractor with an integrated fiber optic wire and an ear battery pack. The fiber optic wire has an LED used to illuminate the patient's nostrils, and the earpiece contains the battery and circuitry components. Owing to the retractor's ability to self retract, together with the LED light attached to it, the need for an assistant during the medical procedure is eliminated. In this project, Fusion 360 software and the Dimension 3D printer were extensively used by the team.

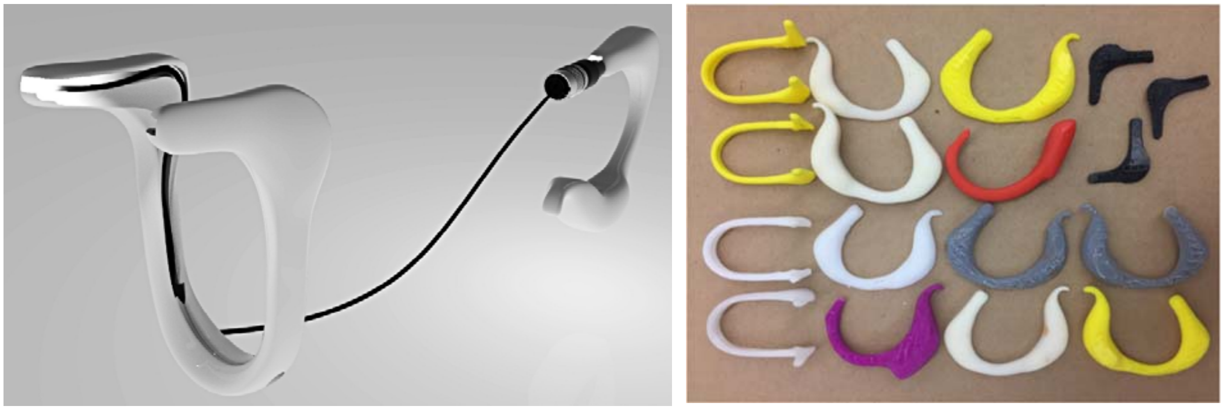

Figure A2: Rendered image and 3D prints produced for the nose retractor project

Figure A3 shows the resulting design solution of the eating utensil project as carried out by team 3. The eating utensil project was specifically developed for an individual with a birth defect, *agenesis of the corpus callosum*. This defect imposes limitations on hand mobility and prevents the individual from eating independently, so that he requires assistance during meal times. From the beginning, the team interacted closely with the end user, his speech pathologist, occupational therapist as well as his mother in gaining a better understanding of his condition and eating habits. The team made multiple trips to the day care center (in Chicago, 150 miles from campus) where the individual is cared for and receives training to help manage more independently. During the visits, the team used clay to capture the preferred handgrip of the individual. Using the resulting handgrip mold, the team constructed custom utensil handles using both the

Creaform handheld scanner and the Dimension 3D printer. The team made multiple iterations and refinements to their design until the individual gained the ability to eat independently. The team continued to work with the day care facility until well after the semester ended, in order to provide a detailed design protocol so that this documentation could be used for similar projects for clients with similar disabilities at the day care facility.

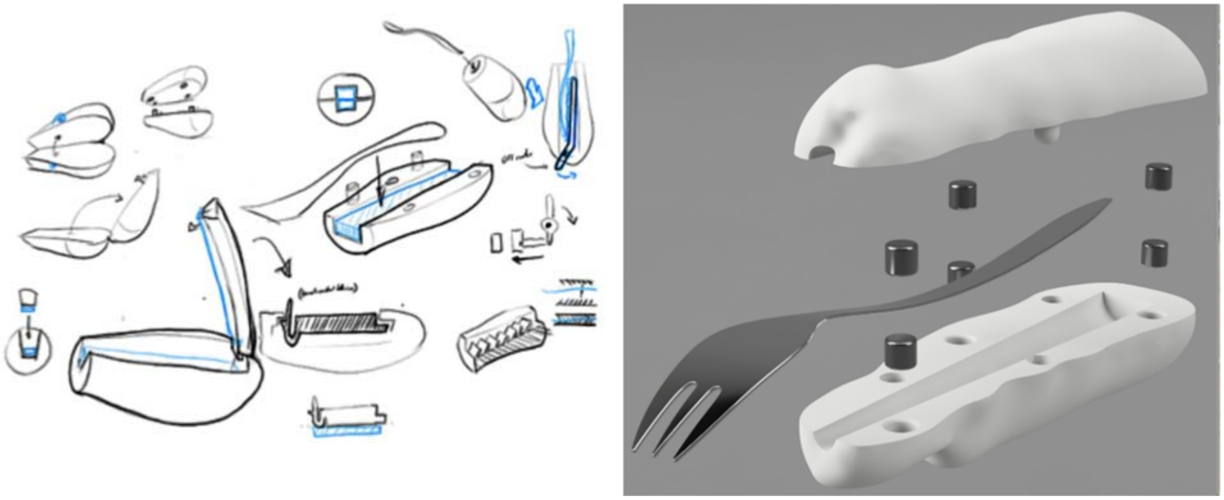

Figure A3: Sketches and exploded view documenting design process for eating utensil project, as developed by team 3

Teams 4 and 5 carried out the multispectral USB microscope design challenge. At the beginning of project, the teams were provided with a prototype for a design solution that had been developed by another design team in a previous semester. This initial solution was considered ineffective, owing to the fact that it was heavy and bulky, with exposed wiring. Therefore, the two design teams placed special emphasis on making the USB microscope more aesthetically pleasing and carefully considered ergonomic factors. The design outcomes of the two teams turned out to be very different from one another. Figures A4 and A5 show these designs. Team 4's solution, shown in Figure A4, consists of a number of moving parts, making the product overly complex. Initially team 4 produced a number of design alternatives, as seen from the concept sketches shown on the left in Figure A4. The team then adopted a specific approach and did not consider alternatives later in the process, despite the complexity of the proposed solution.

Figure 4: Concept sketches, 3D prints, and a rendered image of the proposed solution, Team 4, multispectral USB microscope

Team 5 did not make major changes to the initially provided design of the multispectral microscope in terms of look, but rather made it sleeker and simpler. The resulting handle of the device was very comfortable to grip. One novel aspect of the design was a filter wheel mechanism that allowed the filters to be easily changed by rotating the wheel. Figure A5 on the left shows the solution, while the 3D prints on the right capture the design's evolution. Team 5 utilized the 3D printer extensively at each design iteration, which we believe led to a dramatic decrease in the size of the device.

Figure A5: Rendered image and 3D prints of Team 5's multispectral USB microscope design

The laser scanner, 3D printer, and Fusion 360 were all extensively used by team 6 in the slit lamp design project. In particular, the sculpting environment within Fusion 360 was used to iteratively design an ergonomic chin rest for patients. The design outcome of the slit lamp project is shown in Figure A6.

Figure A6: Concept sketch, rendered image, and 3D prints of slit lamp project, Team 6