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ME 444: REDESIGNING A TOY DESIGN COURSE

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ABSTRACT

Design is a complex process which requires several tools, knowledge and procedures in order to be successful. Although technology provide designers with new and improved tools, those tools should be placed in the right stage during the design process, otherwise they could have negative effects. For example, creativity and innovation not necessarily require high-tech tools to be boosted, and literature suggests that engineers are lacking knowledge on such basic tools as freehand sketching. Also there is previous work showing how Computer-Aided Design (CAD) — under certain circumstances — can affect negatively the design outcome, especially affecting novice designers. This paper presents how we redesigned a CAD and prototyping course at Purdue University in order to offer a better framework for design, creativity and engineer. Our intent was to use principles of design thinking and creativity inspired from industrial design and toy design approaches to transform what was previously a course on CAD modeling, to a course on toy design, while at the same time not losing focus on CAD. The approach used in the previous format of the course is explained, followed by the changes made in the course and the theoretical support behind them. Facilities and other resources utilized are discussed. A discussion of the new main modules included is provided. Since the work is still in process, preliminary observations and conclusions are presented. Some observations are in agreement with conclusions from other authors work, improvement on students approach to the design process. Improvements to be implemented in the near future are discussed. An remarkable conclusion is the importance of study and apply the insights from prior art in order to obtain the benefits of those efforts, and not just let that knowledge stay static on paper.

KEYWORDS

Design, engineering, engineering education, innovation, creativity, freehand sketching, CAD, design fixation, toy design.

1. INTRODUCTION

Design is a complex process which requires and relies on several tools, knowledge and procedures in order to be successful. Although technology provide designers with new and improved tools, those tools should be utilized in the right stage during the design process and designers should be aware of the tools characteristics, capabilities, limitations and advantages. If designers are naive about how tools are affecting their way of working and thinking they could restrict instead of facilitate the designers activity.

We found several literature pointing problems related with conceptual design in engineering, like design fixation, inappropriate using of computational tools, lack of training, etc. We also found that literature already suggests the way to overcome these problems, but it seems that such suggestions have not been widely implemented.

This paper presents how we redesigned a CAD and prototyping course at Purdue University in order to offer a better framework for design, creativity and engineer. The objective is to give students with a framework to increase their innovation and creativity while designing the toys, which in turn are their mean to apply their CAD skills. Our intent is to use principles of design thinking and creativity inspired from industrial design and toy design approaches to transform what was previously a course on CAD modelling, to a course on toy design, while at the same time not losing focus on CAD.

1.1. Motivation

Design is a gradual, iterative process, often beginning from ill-defined or wicked problems [32], which are decomposed and integrated in turns to lead to one of many possible solutions. Early design, therefore, is a space that is unstructured, loosely bounded, and has the richest potential for creative solutions. While it may not be feasible to perceive the entire design space of possible design solutions, generation of a high number of concepts would expand the designers perception of the space. This exploration of the design space is critical to the development and quality of the final concept that is arrived at. At this stage, designers require a natural, intuitive medium, both for thinking and conceiving ideas, and to store any inspiration that strikes them as they think. They predominantly use sketches and words or phrases to express, develop, and store their ideas [36]. This may be explained by research in cognitive science that has suggested a strong connection between semantic attributes and visual attributes [17], [29].

In mechanical engineering design, there has, in recent decades, been a high emphasis on using CAD as a medium. The reason for this is twofold: firstly, there is a strong demand for CAD designers in the industry, and this skill is perhaps justifiably viewed as important by both students and faculty, with respect to industry application. Secondly, CAD has come to replace traditional training in engineering drawing, and is now one of the primary ways in which engineers are expected to communicate their ideas precisely. However, using CAD in the creative early phase of the design process, while aiding visualization and communication, often limits the exploration of the design space [33]. In addition, most CAD interfaces use WIMP-based (Windows, Icons, Menus and Pointers) user interfaces, necessitating that the user learn the CAD software first, and learn to use its features to generate a visual representation of a design. This increases the time and effort invested in generating a concept, and restricts exploration.

Our literature survey reveals the difference in approach to sketching between engineers and industrial designers. We seek to bridge this gap between what we call engineering design and design engineering by redesigning our course using an innovation-oriented framework.

1.2. Literature review

There is plenty of available literature about innovation, design sketching and CAD. Freehand sketching is a well-known and important basic tool for engineers and designers as stated by Ullman [36]. The importance of sketching has been established early, both from the point of view of technical drawing [8], and from that of graphical communication [1]. Back in the 1970s, McKim articulated his thoughts about visual thinking in his excellent book [22], which contains a rich collection of guidelines, suggestions, and insights regarding idea-sketching.

Design fixation is a common issue that inhibits innovation. Purcell and Gero establish different kinds of fixation, and contrast the barriers to innovation between mechanical engineers and industrial designers [30], stating that mechanical engineers tend to get fixated on the underlying principles in the sample design solution to a given problem, especially if it is an innovative solution, while industrial designers seem to concentrate more on differentiating their solutions from that provided in the sample, instead of finding an innovative solution. They also argue that research in the role of sketching in design problem solving can be facilitated via cognitive psychology, in the area of short-term and working memory. Their research indicates that enacted imagery – a combination of sketches and actions accompanying sketches – while not widespread in design problem-solving, seems to occur with particular designers, or where creative solutions are found [31].

Ferguson discusses the risks of creating mediocre engineers, by training them to rely more on analytical skills and tools, while having a poor knowledge of engineering basics, non-verbal tools and the art of engineering [7]. Along similar lines, Ullman et al. point out –in the 1990s– that engineers are trained on drafting but not in sketching [36]. Twenty years later Linsey et al. [20] make a similar statement: *"In general, engineers are not taught to draw, and their skill in sketching may be lacking"*. Goel compared design activity performed with freehand sketching and a computer-based tool, obtaining favorable results for sketching, especially on early design stages, making easier to generate alternatives and preventing design fixation [9]. Yang also argues that it is not common to engineers to be taught idea and concept generation through sketching [43]. It looks like currently freehand sketching is taught in contexts that do not encourage students to see it as a way of thinking and designing, but as a way to learn current CAD frameworks better, such as in technical graphics [26], [5].

However, in disciplines such as architecture and industrial design, freehand sketching is taught as a means for problem solving, idea generation and concept generation, as expressed in Bilda et al.s work about architects [2] and in the work of Eissen and Steur [6]. Tovey shows how product designers rely mostly on freehand sketching for concept generation [35]. McKoy et al. report that sketching, and in general, pictorial tools, are more effective for representing design ideas than other techniques used in the early design phase [23]. For engineers, most of the time, concepts such as perspective sketching have become just an old fashioned way taught before CAD.

To view sketching only from the point of view of CAD is to undermine its strengths, and to concentrate on the enhanced representation aspect of CAD. While CAD does provide one with a detailed representation of a concept, Robertson and Radcliffe have pointed out some potential risks of using CAD software too early in the design process, like circumscribed thinking, premature fixation, and bounded ideation [33]. In a different work by Yang it is concluded that using CAD is a poor choice for supporting early design stages [42]. It has also been suggested by Walther that careless teaching and use of CAD software can stop the divergent process, restraining the possibilities for innovation [40]. In the context of architecture, Lawson also found risks created by careless use of CAD [16]. In other words: CAD could become an "innovation killer" if designers are not trained carefully to avoid these risks and if they do not have other skills to complement the CAD process.

Research also highlights that the design outcome obtained by engineers depends on several factors; Yang [43] concludes that while the design outcome cannot be related only with sketching skills, some characteristics of sketches influence the design more than other ones [41]. Advantages of using sketching for idea generation along other traditional tools had also been shown: Van der Lugt provides us with an excellent case with a "brainsketching" technique [38] and Linsey et al. bring us a comparison of quantity and quality of ideas obtained from different techniques [20].

Cross and Cross give an outstanding example of what we want to achieve. In their case study of Gordon Murrays design methods [4] they show the strategies for his successful designs, the right use of sketching tools and CAD, and the big goal for engineering education: *"I never have engineers that arent designers"*.

2. COURSE FRAMEWORK

2.1. The i8™ framework

The traditional view of engineering design is that of a "systematic process", providing the illusion of a determined set of stages, one logically leading to the other [28]. This has since given way to the more "exploratory"view of design [37], [3]. In spite of this, undergraduate engineering design courses take the prescriptive approach to design, equipping students with "design tools" like functional decomposition, morphological matrices, Pugh charts, and so on. While these tools are important for someone aspiring to become an effective designer, undue emphasis on them takes away from the exploratory, iterative, and "fun" aspects of design. We propose a framework called i8™ which seeks to equip the students with effective practices to aid design thinking, while at the same time engage them in the process of designing and learning by designing [14]. In this, the framework borrows broadly from the Learn by Design™ framework, as well as the idea of studio education [18], [21], both based on active learning approaches.

i8™ stands for Inspiration, insight, ideation, imagination, iteration, implementation, and impact for innovation. The i8™ concept has been created by us, based on Tim Browns inspiration, ideation and implementation cycle [3]. i8™ is the consolidation of the fundamentals for creativity and innovation on engineering design. An abstract representation is provided in figure 1.

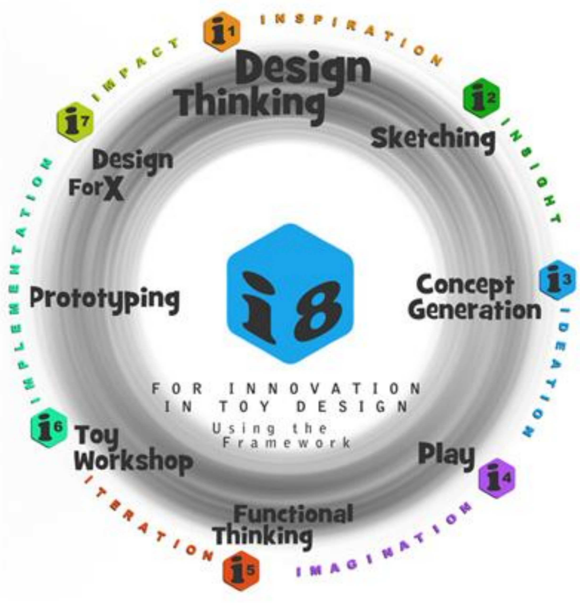

Figure 1 The i8™ framework representation

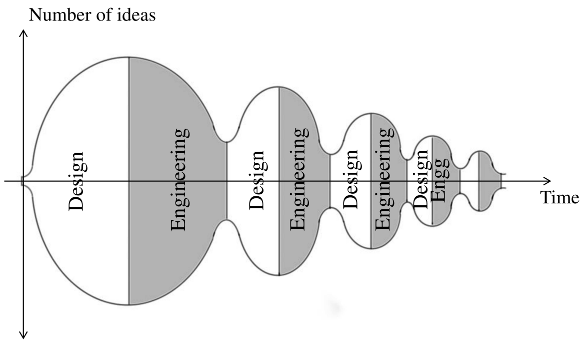

Figure 2 Divergence and convergence on the design process

The i8^{TM} framework involves concepts representing the design process. Inspiration and insight are the starting point. Ideation and imagination support the design concept creation and exploration. Iteration and implementation are present in every design process at every stage and keep the previous four “i”s present all around the process. Finally every design is intended to have impact, by solving the initial problem, satisfying needs or at least originating more ideas. These concepts together form the solid basis for innovation through design, and this applies to all kinds of designers: architects, industrial designers, engineers, artists, teachers and, indeed, everyone.

In a globalized and competitive world, new engineers are encouraged to be not only more productive but also innovative. The mature products and markets we have today force people to look for innovative opportunities [13]. CAD software has been sold as a productivity booster and an essential tool for improving design quality. But CAD tools alone cannot make innovative designers [16]. This is why new engineers cannot ignore the importance of innovation and experience and practice design thinking, combining play and imagination with engineering design. Albert Einstein is quoted to have said: “We can’t solve problems by using the same kind of thinking we used when we created them”. If current problems have been created by over-structured design processes, and tools like CAD, we should probably look for solutions by injecting child-like thinking through flexible processes and imaginative tools, in the form of play [15]. Play used as a part of i8^{TM} framework is critical for imagination, for creating a future that does not exist and for using innovation in engineering as a creative problem solving process (see section 2.4).

Divergent and convergent thinking is also important for design thinking [34]. Divergent and convergent cycles form the basis for ideation and iteration — both part of the i8^{TM} concept. Our interpretation of divergent and convergent stages can be seen in figure 2. We think of design as a creation and expansion stage while engineering is an optimization and reduction process. Thus we tie design thinking with divergence and engineering with convergence. In the first iteration of design, one is expected to have a high number of underdeveloped ideas. These ideas are filtered and the better ones used as a basis for generating the next iteration of ideas. This process, if developed appropriately, will ideally converge into a final set of excellent ideas.

2.2. Course description

Former ME444

ME444 was developed about 20 years ago as an innovative approach for teaching Computed-Aided Design (CAD) and prototyping to students in Mechanical Engineering. Around 2400 students have seen the benefits of this experience. The evolution of the course in the past was directed especially towards developing a “self-paced” CAD learning content for students, as well as towards using the instructors knowledge to integrate CAD based methods into the course. The course was application-oriented in that the students learned CAD concepts, and applied them to a course project to design an “action toy” with significant geometric and mechanical complexity. Both these complexities of the toys have continued to increase during the evolution of the course [19].

With a strong need to address innovation proactively in both, the economy and the students capabilities, we have been transforming ME444. We are embedding new learning towards “design thinking” [3] and “doing” , enabling students to be creative and innovative designers with strong engineering skills.

It is important to mention that this is not a mandatory course on the Mechanical Engineering plan of study, yet our students are aware that CAD has become a fundamental tool for engineers in industry. This is one of the reasons for the popularity of the class. However, almost every engineering school now provides students with this important knowledge. Also, CAD has to be used at the right time in the design process.

This class relies on lecture and laboratory sessions. The lectures provide students with theoretical concepts on CAD along with directions for the project and a brief introduction to advanced topics, as seen in figure 3. The laboratory is basically the hands-on portion of the course; each student has access to a computer with the

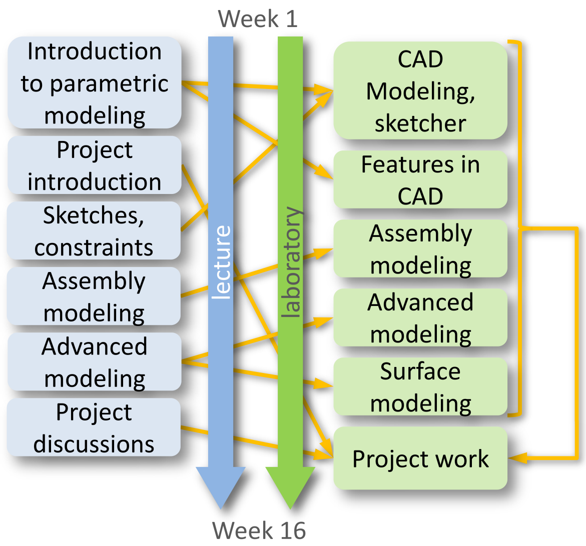

Figure 3 Former ME444 class outline

software. Students have four hours in the lab per each lecture hour, meaning that most of the actual learning of the CAD tool happens in the laboratory.

The prototyping part of the course relies on SLA technology as a means to provide students with the ability to manufacture the complex shapes they can develop with CAD, without getting into more time consuming processes. As a restriction, all teams are given the same limited amount of printing material for their projects.

Previously, the design and prototyping project was viewed at as a way for the students to gain a deeper knowledge of the CAD software by using it in simulated real-world applications, here represented by toy design (figure 4). Due to the focus of the course on learning CAD, the results were evident in the final toys: they were geometrically and mechanically complex, but lacked originality and creativity.

Related courses in Mechanical Engineering at Purdue University

It was also important to check the plan of study and to identify previous mandatory classes on related topics. Unless strictly necessary, the overlapping of topics between courses are best avoided. However the students profile and background knowledge from previous semesters have been a clear indicator of lack of training on design thinking and usage of freehand sketching as a tool for problem solving and idea generation. After analysing the plan of study we found two related classes:

- CG163: Introduction to graphics for manufacturing. This is a required class where students learn the basics of CAD for engineering. Mohler and Miller [26] show us how sketching is used as a tool for improving spatial ability in students in this class, which helps understand the CAD environment better, and aid visualization. Students have a sketching assignment weekly, but these sketches are about existing objects which will be later modeled in CAD. Idea generation or creativity is not the objective of those exercises and the sketching they perform is more like the traditional engineering, rigid kind of sketch.
- ME263: Introduction to mechanical engineering design, innovation, and entrepreneurship. This class is intended to teach student the open-ended nature of engineering design process. For the concept generation module it relies on tools like brainstorming, functional decomposition, modeling and decision matrices. Freehand sketching is not included on the class topics.

It is clear that students are not being trained in the topics we are interested in. This review also shows us that our University confirms the diagnosis made by Ullman, Linsey and Yang: engineers are not being taught freehand sketching as a way to think through ideas.

Redesigned ME444

The challenge is now to provide students with modern computational tools, avoid the potential risks of their inappropriate use, and yet add value to design through innovation. We decided to re-design the ME444 course, applying the i8^{TM} principles, and in turn informing the i8^{TM} framework. Inspiration from other courses on innovation and results from research on engineering education, design education and cognitive sciences was an important starting point [30], [43], [41], [10]. Our approach empowers the students with frameworks for play, value-based innovation, and creation of concepts using the language of the designer: freehand sketching, at the appropriate stages in the design process [36], [35].

The new class relies on laboratory hands-on experience for the acquisition of CAD software proficiency (see figure 5). The lecture contents were modified to offer students with the i8^{TM} frameworks and tools for design. Some lectures were replaced with hands-on workshops. In order to encourage the divergent-convergent process and the generation of more innovative ideas, freehand sketching was chosen as the main tool.

If sketching can be considered to be 2D prototyping [36], [9] we could say we are encouraging students to prototype earlier and cheaper in the design process. There are no modifications downstream for this class,

Figure 4 Toys designed and built in ME444

which means students would still use CAD for detailed design, and the SLA machines for prototyping. Students would still be given a budget for printing and getting other components they would need. Our team understands the importance of exploring the prototyping area, and that topic will be covered in a different project, probably impacting this class or a related one in the future.

The core idea of the new approach is as follows:

- Teach students the CAD content they need to know to be proficient, but do not let them start the idea generation and conceptual stage of the project using computers.
- Students will be allowed to create the CAD model of their design only after a few iterations on divergent and convergent concept generation/ selection processes, using freehand sketching, design thinking, and other tools provided through the play and toy workshops.

We thus maintained a parallel hands-on sketching and design thinking aspect to the students learning, alongside the computer-based training.

Creativity is also influenced by the environment where work is done. In a pedagogical environment, it is important to have a space that is flexible, for instance, the ability to change the focal point of the interaction from one that is between the students and the instructor to one that is among the students: “Learning Studios” as opposed to conventional classrooms [11], [12]. In order to implement the new class approach we have taken advantage of the new facilities just built at the Mechanical Engineering Buildings Gatewood Wing at Purdue University. A classroom with a capacity for 120 students, with large tables facilitating in-class team work and overhead projectors for more flexibility of resources during lectures or workshops was selected. High ceilings and excellent illumination also contributes to improving the students environment in order to encourage them to be more creative [24].

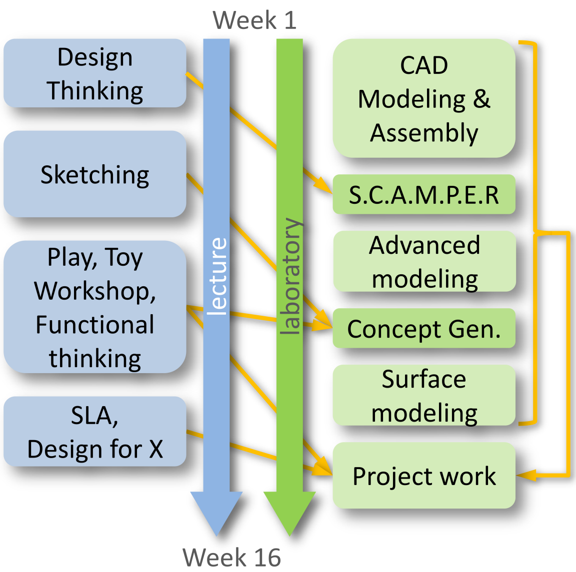

Figure 5 Redesigned ME444 outline

It has also been shown that during the creative, concept generation stage of design, it is beneficial to have the generated ideas all displayed to the design students at once [22]. To prototype this idea for the purpose of the course, it was sufficient to extend the functionality of spaces that are traditionally not included in the category of “innovation spaces”, like the classroom [27]. We achieved this by the modification of seating arrangements in the room during the workshop sessions, and through the use of team-specific display boards for team members to share sketches of their ideas with each other. Instructions or hints pertinent to the entire class were at the same time displayed on the projection systems used for the lectures. Both these are shown in figure 6. As seen, the prototype setup allows design teams their own space for generating and sharing ideas, while visually not interfering with the work of other teams.

We intend to extend the idea of the flexible design space to the laboratory space as well, in order to provide students with a space with better affordances for design and innovation [27].

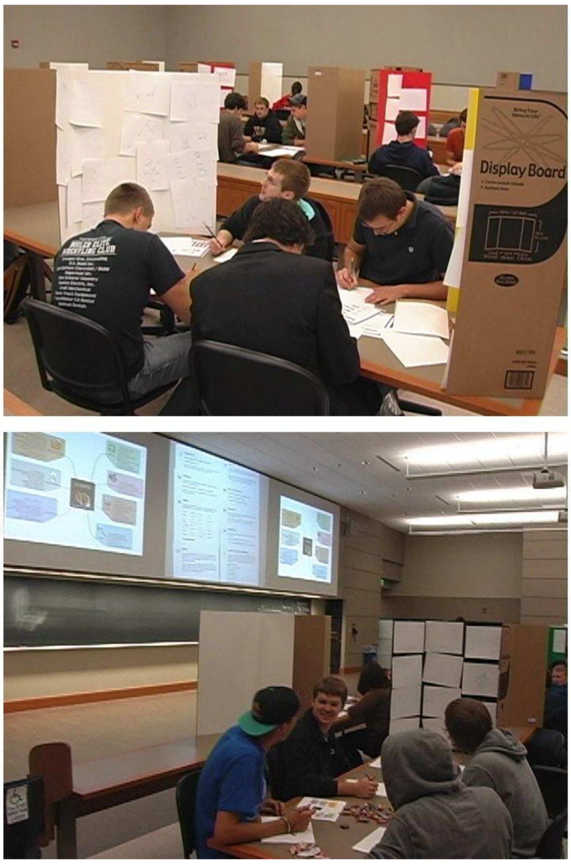

Figure 6 Collaborative ideation environment

2.3. Freehand sketching module

The engineers creativity can be increased by helping them learn a new way of freehand sketching, and build it into their experiential design process, such as toy design, so they have hands-on experience for designing and thinking. This new imaginative engineering and design learning space for all of the i8^{TM} processes to "flow", along with sketching, is a cornerstone of our new ME444.

In the process of rediscovering freehand sketching, some aspects have been identified and tied together in an easy to understand way. Application of perspective, expression of motion, understanding of "soft pencil" sketching, construction of complex shapes in ones mind using primitives, and high speed shape construction, form a short list. Dedicated workshops have been designed to provide these tools to students and the contents have been carefully interwoven into the class timeline.

Engineering drawing is usually taught with a hard pencil approach. Technical drawings are prescriptive, and they do not encourage change or dialogue. Also, students are usually encouraged to have clean drawings with perfect lines and clean edges. In contrast, the soft pencil approach introduces students to the concept of thinking and talking sketch [7], [39].

Following the suggestions of an experienced industrial designer, we provide students with some tools for this module: a blue pencil and a black marker. With a basic training on sketching, those tools can be enough for students to effectively create, communicate, discuss and improve toys concepts before the CAD application stage of their project.

An extra tool is required for sketching: paper. A plain single sheet of paper is probably the best option for this mission. But in aims of keeping the information together and for making easy to analyse students sketches after the course is finished, a notebook was preferred. Having a design notebook and keeping sketches is a practice used by great inventors through history. Leonardo da Vinci's widely recognized sketches, as well as other famous sketches by Thomas Alva Edison and Alexander Graham Bell were used as motivation for the students. Every student has been provided with a notebook with plain white paper sheets. They have been told to keep track of their work on the notebook.

After giving them the tools and before any training our students were asked to sketch an object following some guidelines. The task was designed in order to have constraints, but also being a non-existing device, so students cannot only remember and draw the object but actually design it. The same task will be given to them after the workshops, so we can compare them.

Training on sketching includes techniques from industrial design and features identified in research mentioned on our literature review. They are taught basic concepts like two point perspective, use of ellipses, tips for drawing straight lines and making darker or lighter lines. Expression of movement is important, so use of arrows, notes, express sounds and context of the toy is also explored. Cut-away and exploded views of concepts are also encouraged, so students can discuss more details once the concept starts getting more complex. An example given to students for one of the assignments is shown in figure 7.

Along with the sketching motivation and training the workshops include ideation techniques, as discussed in the next section. We want to be explicit with students, and tell them the affordances of sketching. How sketches can boost their ideation, how to use them to discuss, combine, refine and create even more concepts. Some assignments on sketching were also created in order to make the students practice prior to, and in parallel to the project related ideation tasks.

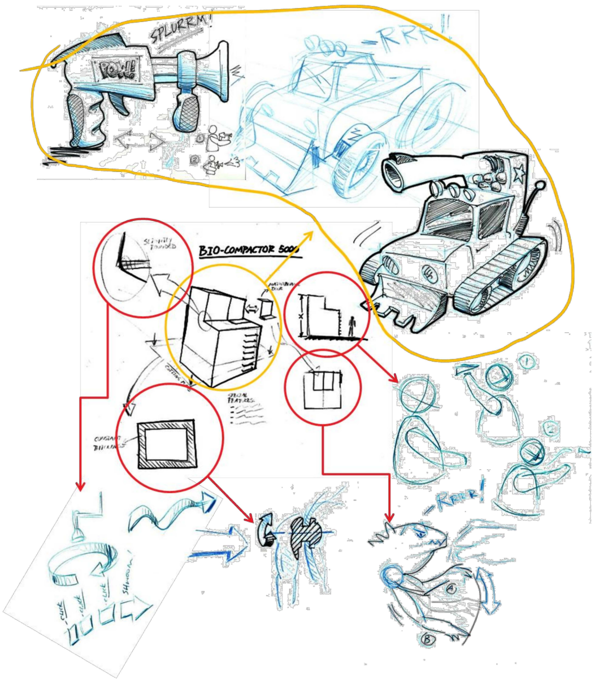

Figure 7 Examples from the sketching workshop (Instructor drawings)

This is the approach we consider better to include design thinking to our students. We are confident that the context of design and the toy creation environment are a perfect fit for introducing those concepts in the curriculum.

2.4. Injecting play values

Kudrowitz and Wallace [15] differentiate work and play as being on opposite ends of the same scale. Play is defined as "the quality of mind during enjoyable, captivating, intrinsically motivated and process-focused activities", and work is defined as "undesirable chore". Play allows for fun and free movement within given affordances, whereas work does not. They also define the term "Play Value" as the "likeliness that a toy will be played by the user", or even "a measure of the benefit of the play".

We incorporated the ideas of Kudrowitz and Wallace into the ME 444 course for two purposes:

- One of the mainstays of the course is the toy design project, which would benefit greatly from the students understanding of play values, and
- By making the concept generation process more engaging and fun, we attempt to increase the play value of the concept design activity, and consequently the quality of concepts generated.

The students were introduced to the concept of play value, and as a classroom activity, asked to classify a given set of toys according to their scales of play [15]. They were also introduced to the idea of crossing product concepts, and using creativity techniques like SCAMPER [25]. The project teams were then encouraged to use quick sketching to generate concepts, and then use the play values, product crossing, and SCAMPER techniques, to extend their concepts. The concepts are currently being presented to the course instructors and a visiting industrial designer for feedback and improvements, and some interesting preliminary observations have been made, which form part of the discussion section.

3. DISCUSSION

The introduction of sketching techniques, creativity techniques, and concepts of play, and our study of the progress of the students have resulted in some interesting observations, and have also posed interesting questions. Our preliminary observations are as follows:

While quick sketching and concept generation helps in generating the initial volume of ideas, the ideas thus generated are observed to be lacking in depth and quality. A comparison of different speeds of concept generations and their quality would be interesting, and important towards guiding such exercises.

It was observed that teams that collaborate while sketching together seem to have better concepts, which was already stated by van Der Lugt [39]. This observation aligns with the idea of brainsketching [38] explored by the same author, and would be an interesting study to follow up on.

Is there a correlation between sketching ability and concept quality? Studies by Yang [41] on junior design students indicate there are no correlations, but in the view of quick sketching and initial concept development, it might be interesting to perform the study on senior engineering students who are trained in sketching.

While it has been shown that sketches have consistently been more effective as an ideation and communication tools as compared to text and speech, our preliminary observations suggest that a hybrid approach — sketches with accompanying explanatory terms — could be more effective.

We intend to pursue these and other research questions that arise through, and as a result of, this new change of course.

4. CONCLUSIONS

We have attempted to redesign our Computer-Aided Design and Prototyping course, ME 444, in order to exploit the power of freehand sketching, and creativity techniques.

We have developed a framework that we call the i8™ framework: inspiration, insight, ideation, imagination, iteration, implementation, and impact for innovation. Through this framework, we intend to equip engineering design students with knowledge of innovation in design, and using the right tools at the right time.

Currently, CAD software is being used for teaching design, from the concept to the final detailed design stage, in spite of various research findings that indicate the disadvantages of using CAD too early in the design stage. Introducing freehand sketching as a means of both design thinking and communication at the early stages of design has shown interesting preliminary results, and has raised important research questions.

Conclusions and insights from different research should not just stay on paper. Application of knowledge that emerges from research is important in order to avoid or correct mistakes in education practices and tools, and improve the capabilities of our future professionals. Our literature review shows that sketching, fixation and idea generation have been extensively studied, but the trend in engineering schools seems to indicate it is not yet standard practice to keep sketching in the curriculum and emphasize its relevance as a design tool.

Collaboration between design teams is a much more active and participatory activity early in the design stages, and while teaching creativity techniques that embed such collaboration we are also in the process of observing the nature and the effects of such collaboration among design teams in the course. This is the first stage of redesign of the course, and we intend to use our research findings to further refine the course, both to better understand the creative design process, and to help create the next generation of truly innovative design engineers.

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References

[1] Gary R. Bertoline. *Introduction to Graphics Communications for Engineers*. WCB/McGraw-Hill (Boston), 1999.

[2] Zafer Bilda, John S. Gero, and Terry Purcell. To sketch or not to sketch? that is the question. *Design Studies*, 27(5):587 – 613, 2006.

[3] T. Brown and B. Kātz. *Change by design: how design thinking transforms organizations and inspires innovation*. HarperCollins, New York, NY, 2009.

[4] Nigel Cross and Anita Clayburn Cross. Winning by design: the methods of gordon murray, racing car designer. *Design Studies*, 17(1):91 – 107, 1996.

[5] J.M. Duff and W.A. Ross. *Freehand sketching for engineering design*. General Engineering Series. PWS Pub. Co., 1995.

[6] K. Eissen and R. Steur. *Sketching: The Basics*. BIS, Amsterdam, NL, 2011.

[7] Eugene S Ferguson. *Engineering and the Mind's Eye*, volume 28. The MIT Press, Boston, MA, 1992.

[8] Frederick Giesecke, Alve Mitchell, Henry Spencer, Ivan Hill, John Dygdon, and James Novak. *Technical drawing*. Prentice Hall, Upper Saddle River, New Jersey, 2002.

[9] V. Goel. *Sketches of thought*. MIT Press, Boston, MA, 1995.

[10] Gabriela Goldschmidt. To see eye to eye: the role of visual representations in building shared mental models in design teams. *CoDesign*, 3(1):43–50, 2007.

[11] Inc. Herman-Miller. Research summaries: Adaptable spaces and their impact on learning, 2009.

[12] Inc. Herman-Miller. Research summaries: Engaging students: Using space as a tool to connect with millennials, 2009.

[13] W.C. Kim and R. Mauborgne. *Blue Ocean Strategy: How to Create Uncontested Market Space and Make Competition Irrelevant*. Harvard Business School Press, 2005.

[14] Janet L. Kolodner, Paul J. Camp, David Crismond, Barbara Fasse, Jackie Gray, Jennifer Holbrook, Sadhana Puntambekar, and Mike Ryan. Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by design(tm) into practice. *Journal of the Learning Sciences*, 12(4):495–547, 2003.

[15] Barry M Kudrowitz and David R Wallace. The play pyramid : A play classification and ideation tool for toy design. *International Journal of Arts and Technology*, 3(1):36 – 56, 2010.

[16] Bryan Lawson. Cad and creativity: Does the computer really help? *Leonardo*, 35, 2002.

[17] Bryan Lawson. *How designers think: the design process demystified*, volume 3rd revise. Elsevier, 2006.

[18] Stefani Ledewitz. Models of design in studio teaching. *Journal of Architectural Education (1984-)*, 38(2):pp. 2–8, 1985.

[19] Alexander Lee, David Anderson, and Karthik Ramani. Toying to learn for 21 st century product development environments : Computer-aided design , collaboration , and rapid prototyping. *Engineering Education*, 2003.

[20] J. S. Linsey, E. F. Clauss, T. Kurtoglu, J. T. Murphy, K. L. Wood, and A. B. Markman. An experimental study of group idea generation techniques: Understanding the roles of idea representation and viewing methods. *Journal of Mechanical Design*, 133(3):031008, 2011.

[21] Patrick Little and Mary Cardenas. Use of ‘studio’methods in the introductory engineering design curriculum. *Journal of Engineering Education*, 90(3):309–318, 2001.

[22] R.H. McKim. *Experiences in visual thinking*. General Engineering Series. PWS, Boston, MA, 1980.

[23] Felicia L McKoy, No Vargas-Hernandez, Joshua D Summers, and Jami J Shah. Influence of design representation on effectiveness of idea generation. In *Proceedings of ASME Design Theory and Methodology Conference*, 2001.

[24] Joan Meyers-Levy and Rui (Juliet) Zhu. The influence of ceiling height: The effect of priming on the type of processing that people use. *Journal of Consumer Research*, 34(2):pp. 174–186, 2007.

[25] M. Michalko. *Thinkertoys: a handbook of creative-thinking techniques*. Ten Speed Press, Berkeley, CA, 2006.

[26] C.L. Mohler, J.L. Miller. Improving spatial ability with mentored sketching. *Engineering Design Graphics Journal*, 72(1):19–27, 2008.

[27] James Moultrie, Mikael Nilsson, Marcel Dissel, Udo-Ernst Haner, Sebastiaan Janssen, and Remko van der Lugt. Innovation spaces: Towards a framework for understanding the role of the physical environment in innovation. *Creativity and Innovation Management*, 16(1):53–65, 2007.

[28] G. Pahl and W. Beitz. *Engineering Design: A Systematic Approach*. Springer, 1996.

[29] A. Paivio. *Images in mind: the evolution of a theory*. Harvester Wheatsheaf, 1991.

[30] A. Terry Purcell and John S. Gero. Design and other types of fixation. *Design Studies*, 17(4):363 – 383, 1996. Special Issue: Design Cognition and Computation.

[31] A.T. Purcell and J.S. Gero. Drawings and the design process: A review of protocol studies in design and other disciplines and related research in cognitive psychology. *Design Studies*, 19(4):389 – 430, 1998.

[32] Horst W J Rittel and Melvin M Webber. Dilemmas in a general theory of planning. *Policy Sciences*, 4(2):155–169, 1973.

[33] B.F. Robertson and D.F. Radcliffe. Impact of cad tools on creative problem solving in engineering design. *Computer-Aided Design*, 41(3):136 – 146, 2009. Computer Support for Conceptual Design.

[34] Shuang Song, Andy Dong, and Alice M Agogino. Time variation of design ”story telling” in engineering design teams. In *Proceedings of the International Conference of Engineering Design (ICED)*. The Design Society, 2003.

[35] M. Tovey, S. Porter, and R. Newman. Sketching, concept development and automotive design. *Design Studies*, 24(2):135 – 153, 2003.

[36] David G. Ullman, Stephen Wood, and David Craig. The importance of drawing in the mechanical design process. *Computers & Graphics*, 14(2):263 – 274, 1990.

[37] D.G. Ullman. *The Mechanical Design Process*. McGraw-Hill, third edition, 2003.

[38] Remko van der Lugt. Brainsketching and how it differs from brainstorming. *Creativity and Innovation Management*, 11(1):43–54, 2002.

[39] Remko van der Lugt. How sketching can affect the idea generation process in design group meetings. *Design Studies*, 26(2):101 – 122, 2005.

[40] J. Walther, B.F. Robertson, and D.F. Radcliffe. Avoiding the potential negative influence of cad tools on the formation of students' creativity. Department of Computer Science and Software Engineering, The University of Melbourne, 2007.

[41] Maria C. Yang. Concept generation and sketching: Correlations with design outcome. *ASME Conference Proceedings*, 2003(37017b):829–834, 2003.

[42] Maria C. Yang. A study of prototypes, design activity, and design outcome. *Design Studies*, 26(6):649 – 669, 2005.

[43] Maria C. Yang and Jorge G. Cham. An analysis of sketching skill and its role in early stage engineering design. *Journal of Mechanical Design*, 129(5):476–482, 2007.

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