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# A Student-Centered Learning Approach to Design for Manufacturability: Meeting the Needs of an Often- Forgotten Customer

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# A Student-Centered Learning Approach to Design for Manufacturability: Meeting the Needs of an Often-Forgotten Customer\*

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A hands-on learning module was implemented at Marquette University in 2012 to teach biomedical engineering students about basic manufacturing processes, lean manufacturing principles, and design for manufacturability. It incorporates active and student-centered learning as part of in-class assembly line simulations. Since then, it has evolved from three class periods to five. The module begins with two classroom presentations on manufacturing operations and electronics design, assembly, and testing. Students then participate in an in-class assembly line simulation exercise where they build and test an actual product per written work instructions. They reflect on this experience and suggest design and process changes to improve the assembly line process and quality, save time, and reduce cost and waste. At the end of the module students implement their suggested design and process improvements and repeat the exercise to determine the impact of their improvements. They learn of the importance of Design for Manufacturability, well-written work instructions, process design, and designing a product not only for the end user, but also for the assemblers and inspectors. Details of the module, and its implementation and assessment are presented along with student feedback and faculty observations.

**Keywords:** design for manufacturability; assembly; process design

## 1. Introduction

A major driver for the development of the original ISO 9000 family of standards was to establish a focus on the customer as part of a company's product development process. Design education emphasizes the importance of identifying and understanding the customer's problems and unmet needs. Capstone design courses, engineering design textbooks, and design thinking programs emphasize customer needs in new product development and value creation.

The customer is often defined as either the person who orders or uses the product, or both. One often forgotten customer is the assembly line worker (and other production personnel) responsible for manufacturing the product. Students and inexperienced engineers often ignore the needs of these customers and fail to recognize the impact of their designs on assembly time, material waste, cost, and potential repetitive motion injuries. Consideration of these and other Design for Manufacturability (DFM) issues in engineering curricula or capstone design courses can benefit students, potential employers, and future customers.

The Design Controls section of ISO 9001:2015 requires specific elements to be part of a product design and development program [1]. These include design and development planning, design input, design output, design review, design verification

and validation, and design transfer. Familiarity with each of these helps prepare students for careers in industry. Ideally, engineering design curricula would provide experience with each of these elements.

Students should understand that their role on a project team in industry will not end after design validation and verification and that they will often be involved with design transfer tasks which include the transfer of all design information such as drawings, assembly instructions, bills of material, and test procedures to the production facility in preparation for production. Due to time, cost, and resource constraints, and a lack of large scale manufacturing facilities available to students, it is beyond the scope of most capstone design courses to require students to complete all design transfer activities. To expose them to the entire design process and improve their understanding of professional engineering practice, capstone design courses should, at the least, make students aware of what the design transfer phase involves.

In a 2005 survey of capstone design instructors, less than 30% of respondents indicated that their courses included lectures on manufacturing processes, DFM, or other related topics [2]. This lack of familiarity with manufacturing related topics produces a knowledge gap among many engineering students in the areas of manufacturing processes, lean manufacturing principles, and DFM.

An understanding of manufacturing processes allows engineers to design products that can be manufactured at a reasonable cost. The ability to apply lean manufacturing and DFM concepts can help speed assembly operations, avoid repetitive motion injuries among production workers, and reduce waste and scrap, which result in time and cost savings.

A 2009 survey of capstone design instructors indicates that the duration of capstone design courses varies [3]. As a result, some courses only require paper designs, while others course require construction and testing of prototypes as the final deliverable. In a 2015 survey of capstone design instructors, 55% of the respondents indicated that their course requires a prototype or working device as a final deliverable [4]. By requiring a prototype, students are required to consider how their designs can be translated into a physical object and understand the impact of their design on manufacturability.

A study of all manufacturing industries conducted by the Society for Manufacturing Engineers identified competency gaps among new engineering graduates in process design and control and manufacturing processes and systems [5, 6]. The lack of experience with or knowledge of manufacturing processes is not limited to graduates of any one engineering discipline.

To address these competency gaps, faculty at Wayne State University implemented a series of coordinated, hands-on laboratory activities, in multiple undergraduate engineering courses, with a unifying theme of designing and constructing a model engine [5]. This project was based on the goals of the Learning Factory (LF) model, described elsewhere [7–9]. It was a modification of the original LF model which intended to promote experiential learning in design, manufacturing, and product realization. It involved courses in computer graphics, manufacturing processes, process engineering, and computer aided design and manufacturing. This approach allowed coverage of design, manufacturing, and product realization topics, through hands-on laboratory based experiences, as part of four different existing courses.

Another approach to addressing the lack of manufacturing knowledge among students is to create new courses or require existing courses on these topics. For programs with no room for additional courses, an alternative would be to create a module on design transfer as part of the capstone design course. This module could cover basic manufacturing processes (cutting, molding, casting, etc.), lean manufacturing principles (just-in-time, 6-sigma, 5S, reduced waste of materials, motions, and time, etc.), and DFM. Lectures, video presenta-

tions, in-class activities, and other student-centered learning tools can be used to help students learn about these topics.

## 2. Senior capstone design at Marquette University

The senior capstone design course at Marquette University has been described elsewhere [10]. It includes biomedical, electrical/computer, and mechanical engineering students. Three faculty members (one representing each of the three disciplines involved) teach the course over two semesters. Course enrollment is typically around 200 students in two sections. The course meets twice a week for lectures on various topics important to student projects and professional engineering practice.

The focus of the course is on the design project of which there are typically thirty-five project teams consisting of three to six students from the mix of engineering disciplines enrolled in the course. Approximately half of the projects are industry-sponsored, with some proposed by students, some by faculty, and others requested on behalf of clients with disabilities.

The course schedule and required team deliverables are based on the design control requirements of ISO 9001 and reflect the design process used in industry. Required team deliverables include the Project Definition, Customer Needs/Target Specifications Document, Generated/Final Concepts Document, Formal Proposal, Prototype/Mock-Up, Project Notebook, Oral Proposal, and Peer Review in the fall semester. A Project Schedule/Risk Analysis, Experimental Verification Document, Prototype, Project Notebook, Peer Review, Oral Report, and Final Report are required during the spring semester.

The course deliverables provide students with experience with almost all requirements of the design process including design and development planning, design input, design output, design review, and design validation and verification. However, students do not learn much about or gain experience with the design transfer phase. Recognizing the importance of manufacturing processes and related issues to design, it was decided to incorporate lectures and in-class activities related to this important phase of the design process into the capstone design course through the development of a learning module on design transfer.

## 3. Module design and implementation

In August 2011, a *Shaping Entrepreneurial Engineers* (SEE) workshop sponsored by the Kern

Entrepreneurship Education Network (KEEN) was presented in Eagle, Wisconsin. The workshop included several hands-on activities designed to teach faculty about design for manufacturability, design for serviceability, and design of experiments. It emphasized what new engineers should know about manufacturing when they graduate. One of these hands-on activities involved a simulated assembly line exercise that if adapted to a single class period, would be an excellent in-class active learning exercise to teach students about lean manufacturing and DFM.

Active learning is an instructional method that engages students in the learning process during which they conduct meaningful learning activities and think about and are connected to what they are doing. In the education literature, active learning most commonly refers to activities that are introduced in the classroom. Active learning is often contrasted to the traditional lecture format where students passively receive information from an instructor. The benefits of active and student-centered learning methods reported in the literature suggest that a hands-on classroom activity could be more effective in teaching manufacturing related topics to capstone design students than reading assignments and lectures alone [11, 12].

In spring 2012, a module on design transfer was presented to the capstone design students at the time they were building and testing their prototypes [13]. It began with two 50-minute lectures and one 50-minute hands-on in-class activity. In 2013, two 50-minute in-class activities were added to the module.

#### *Class period #1:*

Lecture on manufacturing processes, lean principles, design for manufacturing and assembly, and cost issues:

- Overview of predominant manufacturing processes used for medical devices
  - Material removal (cutting, drilling, boring, grinding, etc.)
  - Surface finishing (polishing, etc.)
  - Melting, flowing (molding, extrusion)
  - Bending, forming (casting, forging, etc.)
- Principles of lean thinking (efficiency - time, energy, motion, steps, etc.)
- Selection of appropriate manufacturing processes
- Design modifications to reduce cost
  - Reducing the number of parts
  - Changing draft angles, etc., to allow for easier molding and assembly
  - Using standard hole sizes
  - Using alternate materials
- Tips for talking with manufacturing personnel

- Involve manufacturing and manufacturing engineering personnel early in the project
- Design engineers working with production personnel to demonstrate assembly of product, explain importance/criticality of specific dimensions and tolerances

#### *Class period #2:*

Lecture on design for electronics manufacturing, assembly, and testing.

#### *Class period #3:*

In-class assembly line simulation activity (described below).

#### *Class period #4:*

In-class meetings of each assembly line team (two to three per class) to discuss their observations and propose improvements to the assembly line and product design changes that will make the product easier to assemble. At the end of this class, each team submits a “shopping list” of tools and materials needed to implement their assembly line and product design improvements.

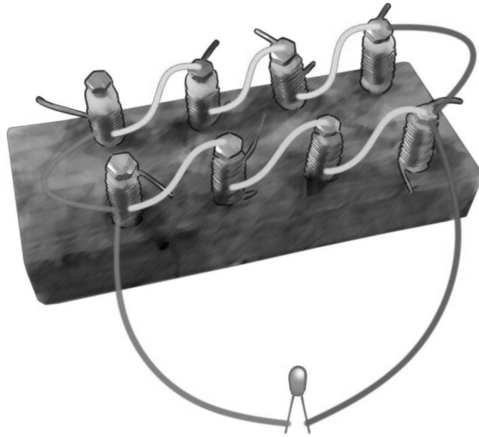
#### *Class period #5:*

Repeat of the in-class assembly line activity (class period #3) with the implementation of the proposed improvements developed by the students during class period #4. At the end of the class, the class reflects on the impact of each teams’ improvements in the assembly line process.

Due to the large number of students in the capstone design course, the in-class activity is conducted with biomedical engineering students only during a breakout session while students of the other disciplines each meet separately to discuss discipline specific topics. Priority is given to biomedical engineering students due to the lack of manufacturing topics included in the biomedical engineering curriculum, typical of most of undergraduate biomedical engineering programs around the country. The smaller class size allows for a more manageable active learning exercise.

#### *In-class assembly line simulation activity*

The activity consists of an assembly line simulation to produce a water battery comprised of a wooden base, copper wires and coils, paper towels, galvanized screws, alligator clips, and an LED as shown in Fig. 1. Wet paper towels placed between copper coils and zinc-coated screws provide a path for current flow between these two components in each single cell. This produces a voltage across each single cell which when connected in series, results in a battery that can light an LED bulb. The battery design is intended to meet the fictional



**Fig. 1.** Assembled water battery consisting of a wooden base, copper wires and coils, paper towels, galvanized screws, alligator clips, and LED.

customer's requirement of powering a light bulb. Through this in-class activity, students experience first-hand the impact of process flow, line balance, work design, product and process documentation, repetitive motion, lean principles, quality control, production variation, and design trouble-shooting on the resulting product. They develop an appreciation for why product designers need to know how their products will eventually be made, and how this knowledge can be used to improve a product's design.

Before class, tables and chairs are moved to create two parallel assembly lines made up of four tables in each line aligned lengthwise, with the ends of the tables touching. Each table accommodates two students and all students in the same assembly line face the same direction. Each student is assigned a specific job to perform in the assembly line and is provided with written work instructions on how to perform their assigned assembly, test, or inspection operation. Work instructions, assembly materials,

and tools are placed at each workstation during classroom setup. An example of a work instruction is shown in Fig. 2. A team of eight students are assigned the following jobs in the following order:

1. Coiler—wraps precut lengths of copper wire around a mandrel to form copper coils.
2. Electrolysis Strip Maker—cuts strips of paper towels.
3. Core Roller—rolls paper towel strips around galvanized screws.
4. Cell Assembler—assembles copper coil over cores.
5. Cell Installer—screws each cell into wooden base board.
6. Battery Activator—pours water over cells mounted in base board.
7. Wiring Installer—using alligator clips, connects cells in series (copper to zinc).
8. Electrical Checker—measures voltage produced by connected cells; confirms battery's ability to light a light emitting diode (LED).

The student assembly workers are asked to note opportunities for design or process improvements. Students who are not part of either assembly line are asked to serve as quality assurance personnel and observe one of the lines, make notes of problems and bottlenecks they see, and develop a list of recommended improvements to the assembly line. They are asked to pay particular attention to the various forms of waste (based on lean principles) such as:

- *Transport*—moving products when not actually required to perform a process
- *Inventory*—all components, work-in-process, and finished product not being fully processed
- *Motion*—people or equipment moving or walking more than is required to complete an operation

### Work Instructions - Cell Assembler



- 1) Receive a coil from the Coiler
- 2) Receive a paper towel and screw core from the Core Roller
- 3) If either part is defective, send back to appropriate station
- 4) If not, screw Core into Coil
  - a) Leave even amounts of paper towel protruding from either end of coil
  - b) At least three threads should be available at end of screw
  - c) Paper towel should be just up against underside of screw head
  - d) Paper towel should be a snug fit into the coil. If not, ship Core back to Core Roller for more paper towel

**Fig. 2.** Work instructions for cell assembler.

- *Waiting*—waiting for the next production step
- *Overproduction*—production ahead of demand that can lead to one-piece flow
- *Over processing*—additional steps in a process resulting from poor process, tool, or product design
- *Defects*—effort involved in inspecting for and fixing defects
- *Unused human talent or equipment capacity*

One student volunteer per line is selected to serve as supervisor and is responsible for ensuring that assembly workers have what they need to perform their jobs, keeping the lines moving, and answering questions regarding work instructions. Student Line Supervisors are also provided with a set of rules governing the assembly line including:

- Workers must follow work instructions provided at each workstation
- Defects must not be passed downstream
- Defects received from a previous workstation should not be corrected; they should be sent back upstream to the station that did the work. Once corrected, the product should be sent back downstream.
- Workers must not reach into another workstation
- When work is complete at each workstation, workers are to place the finished product on the border of workstations.

At the end of the assembly line, the completed water battery assembly is inspected and tested for correct wiring. Voltages produced by the water battery are measured, polarities are checked, and its ability to light an LED is confirmed.

#### 4. Results

Unknown to the students, some information is intentionally excluded from the written instructions. Similarly, some simple tools that would make specific assembly operations easier are intentionally withheld. Soon after the assembly line began students discover ambiguous, confusing, and missing parts of work instructions. They also realize that they need better tools to complete specific operations. Some students create their own tools to make a specific job easier. For example, to aid in cutting paper towels to the correct width, one student rolled up a dollar bill to the correct width for use as a template for cutting paper towels.

Since the first implementation of this module in 2012, students (1) observed and cited many similar examples of bottlenecks and waste, (2) proposed several improvements to the assembly line process, and (3) proposed several product design changes

that improved the assembly line process and product function.

##### 4.1 Examples of bottlenecks and waste:

- Wire coiling was difficult and created an early bottleneck; one hand was needed to hold mandrel and the other used to wrap copper wire around the mandrel to form the coil. (*Over processing, Waiting*)
- Some core assemblies were assembled as described in the work instructions but were not usable during installation at a later workstation. This resulted in several core assemblies being returned back to the core assembly workstation for rework that held up the line for a short time. (*Defects*)
- Some work instructions did not include enough specific details; too much was left up to the interpretation of the workers which often resulted in additional steps. (*Over processing*)
- Students at downstream workstations were idle while waiting for product from upstream workstations to arrive. (*Waiting*)
- Screws were difficult to screw into wood base; created a bottleneck in the assembly line. (*Waiting, overproduction*)
- Too much consulting between supervisor and assembler due to incomplete work instructions. (*Over processing*)
- Some tasks were faster and easier than others resulting in bottlenecks and inventory pile-ups. (*Waiting, overproduction*)

##### 4.2 Improvements to the assembly (or testing) process:

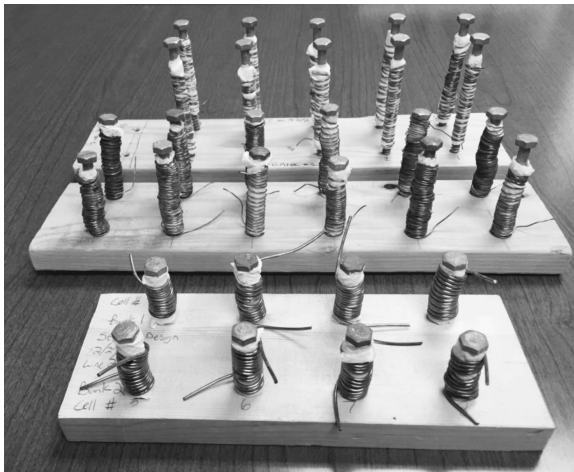
- Mount the mandrel in a fixed base to make both hands available for wire coiling.
- Use smaller diameter copper wire to make coiling easier; increase number of coils to maintain surface area of copper in contact with paper towel.
- Provide a ruler to allow cutting of the paper towels to the required 1.5 inch width.
- Provide a paper cutter to improve the cutting operation.
- Use double ply towels to allow use of shorter strips of paper towels.
- Increase diameter of predrilled mounting holes in wood base or add a workstation to drill larger holes to make screw attachment easier.
- Provide socket wrenches to assist in attaching screws to the wood base.
- Assign more people to or rebalance the work of the labor-intensive operations such as coiling and screw attachment.
- To reduce waiting and idle time, allow students at downstream stations to help with upstream tasks

until product begins to flow into downstream stations.

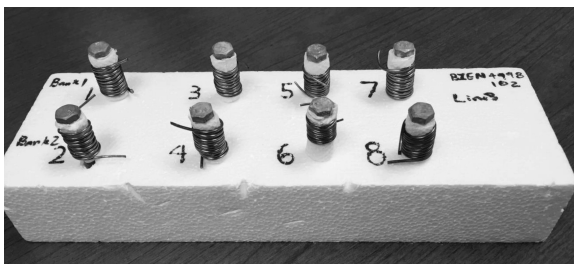
- To reduce idle time, students at test stations can arrange leads for cell connections ahead of time while waiting for product to arrive.
- Improve communication between workstations.
- Spend time prior to beginning assembly explaining what needs to be done.
- Test each cell subassembly prior to wiring or attaching to wood base.
- Add metal washers just below the screw heads; attach alligator clips to metal washers to make testing of cells easier.

#### 4.3 Product design changes to improve the assembly process and product function:

- Use salt water to increase concentration of electrolytes in the water to improve movement of electrons between zinc screw and copper coils.
- Replace copper wire coils with copper tubing to eliminate labor intensive coiling operation and increase copper surface area.
- Use longer screws to increase zinc surface area.



**Fig. 3.** Redesigned versions of the water battery. The original battery design with 8 standard cells is shown in the front image. The middle and back images show batteries with thinner copper wire, longer screws, and additional cells (12 and 10 cells, respectively).



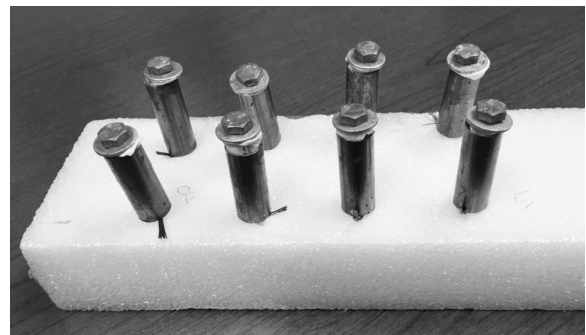
**Fig. 4.** Alternate design of battery replacing the wood base with Styrofoam to make the cell installation operation easier.

- Replace wood base with Styrofoam to make cell installation operation easier and faster.
- Add four screws to create additional cells and increase total voltage.
- Replace zinc screws with aluminum screws or nails to increase the difference in electrochemical potential between copper and the screw material and increase the voltage produced by each cell.

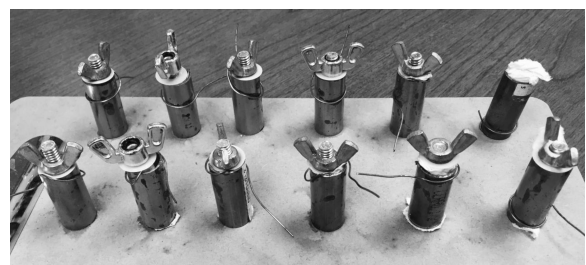
Figures 3, 4, 5, and 6 reflect alternate battery designs suggested by students to improve assembly and battery function. The wire connections have been removed in these images for clarity.

#### 4.4 Student feedback

To determine the value of the in-class activity on student learning, students were asked to provide feedback on their experiences. Feedback collected from students after the first year of module implementation in 2012 (three class periods instead of five) was presented previously [13]. An email survey was sent to students immediately after completion of the expanded module during the spring semesters 2015, 2016, and 2017. The survey remained open for approximately one month in 2015 and 2016, and one week in 2017. Response rates were 17%, 8%, and 34% for 2015, 2016, and 2017, respectively, resulting



**Fig. 5.** Alternate design of battery replacing copper coils with copper tubing to eliminate labor intensive coiling operation and increase surface area of copper to increase current produced by cell.



**Fig. 6.** Alternate battery design with Styrofoam base, 12 cells, and copper tubing. Note the zinc screws installed upside down in a Masonite base, with wing nuts at the top to improve the grip of alligator clips used during testing.

**Table 1.** Summary of student survey responses collected in 2015, 2016 and 2017

Questions and responses	Student responses
<b>What did you learn from this module on Design for Manufacturability and Lean Methods?</b>	
• Importance of considering the manufacturing process during product design to ensure that products can be manufactured.	37%
• Value of pilot production runs, optimization of production processes, and a common team mindset in creating an efficient production process.	34%
• Problems with assembly lines, ways to improve assembly lines, and how a good production process can reduce product cost.	32%
• Importance of well written work instructions and good communication to efficient assembly lines and production processes (eliminating waste, reducing cost, saving time, etc.).	32%
• Other (already learned about this topic in co-op or internship experience).	5%
<b>Will your experience with this module impact how you will design products in the future?</b>	
• Yes.	82%
• No.	0%
• No, because I will not be working as an engineer.	18%
<b>Do you prefer learning about these subjects through reading, lectures, or in-class hands-on activities?</b>	
• Reading.	0%
• Lectures.	0%
• In-class, hands-on activities.	92%
• Combination.	8%

in a total of 38 individual responses during this time. These responses are summarized in Table 1.

The following are representative examples reflecting common themes among student responses to the survey:

**Q1: What did you learn from this module on Design for Manufacturability and Lean Methods?**

*I learned that there are multiple ways that a manufacturing process can be improved both from a design viewpoint and a production viewpoint. This exercise helped me understand how vital it is to get the opinion of people who work in production about the manufacture of a device. Although you think your design is good, it may not be the best for production. (2017)*

*I learned how important communication between the engineers and the people working the line is when instructing how a product is built. It is extremely important for the engineers to effectively inform the people working the line exactly what is being built and how it should be built. Details are very important. (2017)*

*I worked in a Manufacturing Engineering setting for a semester during one of my Co-Op terms; therefore, I feel that the main concepts addressed in this module were previously addressed during that work term. This module was still a great learning opportunity because I was able to apply what I had learned in class and in the workplace. I think manufacturability is a concept that is often overlooked in academia. For those students who do not participate in the Co-Op program, this module would be invaluable. (2017)*

*I gained perspective on what issues might arise in a*

*manufacturing/assembly line, given the roles and materials provided. This included issues in a linear assembly line, where a bottleneck might occur, and improper instructions without knowledge of previous and forthcoming steps in the process. (2017)*

*I loved this project. It not only allowed me to use my hands, but I also got to use my engineering skills to further develop the battery we were creating. This module strengthened my skills in analysis and manufacturing. (2015)*

*Even if you create the perfect design that meets all the customer needs, if you can't manufacture or produce it you don't have a product to sell. (2015)*

**Q2: Will your experience with this module impact how you will design products in the future?**

*This experience helped me understand the costs associated with the manufacturing process and the tradeoffs that are included by increasing the complexity of the project. (2017)*

*Yes. I learned that it is important not just to think of the product as a whole, but as a construction of many component parts. Furthermore, I think it is important to put yourself, as the designer, in the assembly line worker's position. This type of thinking should reduce the number of defects and the production time, while still ensuring the product is safe and carries out its purpose. (2017)*

*I knew some of this method of thought to a certain extent already, but it will nevertheless impact how I design products. Lean methods are always beneficial to a company, and always help efficiency in a line. Additionally, having the instructor question us and*



*ask what we would change about the product and the line was super beneficial, because it forced us to USE the methods we had been talking about. Taking the leap from learning to doing is important and prepares us much better for working in industry and the real world. (2017)*

*I am going to medical school after undergrad, so my exposure to actual device design will most likely be limited in the future. However, looking for ways that I can improve what I am doing – whether it is carrying out research or treating patients as a doctor – is definitely important to me, and I think that this module helped provide me with at least a start to how I can approach this, even if it is not specifically tied to product design. (2017)*

*This module taught me how important it is to design things in a way that can be assembled as easily as possible. This module gave me strong insight into the fact that the simpler the design, the better in regards to manufacturing. It is better to not focus on creating fancy, complicated products and simply design products that work and meet the customer needs, instead. (2017)*

*This module will have a great impact, as I now will consider the practicality of a design in a production line as a key portion of the design process. In addition, I will consider the level of description in my product assembly instructions associated with my product. (2017)*

*Talk to the manufacturing representative early and often throughout the design process. They will have important insights that the core engineering design team may not think of or overlook the significance. (2015)*

**Q3: Do you prefer learning about these subjects through reading, lectures, or in-class hands-on activities?**

*I prefer hands-on activities because they are more engaging. I also feel that the learning objectives are much easier to remember after a hands-on activity rather than after a lecture or a reading. (2017)*

*The hands-on activities are more fun and a good way to get people to work together. (2017)*

*I learn better when I physically perform a task. (2017)*

*I prefer learning about this through hands-on activities like we did, as it makes it more interesting, fun, and shows the theory in practice. (2017)*

*I am a visual learner, so I liked learning about this topic with a hands-on approach. (2017)*

*I usually prefer reading, but I thought this hands-on activity helped to conceptualize the role of design for*

*manufacturability. I can read about this topic all day, but until I see it in action it is hard to understand how analyzing a production process and making changes to this process can be done in real life. (2017)*

*I prefer hands-on tasks. The lectures are often difficult to pay attention to the entire time, especially when the topic being discussed does not directly apply to the job I have already accepted. I will remember this activity much better 5 years from now than I will any of the lectures previously given this year. (2016)*

*I prefer a variety of activities to enhance my learning. I prefer lectures the most but accompanied by in-class activities. (2015)*

## 5. Discussion

The observations made by the students involve process and product design changes and clearly demonstrate the students' understanding of lean principles and the impact of product design on manufacturability. The results of the in-class exercise indicate that students (1) understood the various forms of waste as presented in the lecture on lean principles, (2) recognized problems, bottlenecks, and forms of waste that occurred during the in-class exercise, and (3) were able to propose solutions to improve the process.

Participation in this active exercise allowed students to apply what they learned from previous lectures. Witnessing problems first-hand during this activity helped create an awareness of the impact of product design on the ease and cost of assembly and helped students recognize that the assembly worker is another customer whose needs must also be met through good design. Students realized that good product and process design helps speed assembly operations, avoid repetitive motion injuries, and reduce waste and scrap, resulting in time and cost savings. This appreciation of design for manufacturability will better prepare them for professional practice and careers in engineering. We agree with the students' comments that they learned more from this active learning exercise than they would have from reading and/or lectures alone.

Students were intentionally not provided with work instructions prior to the in-class activity. They were told that the activity would be a simulation of a pilot run often used in industry to test the assembly line process for a new product prior to large scale production. The pilot run, combined with a Kaizen or continuous improvement session, is often used to “debug” the assembly line process by identifying bottlenecks and other problems. It allows production personnel to develop solutions to optimize product flow, minimize forms of waste, and reduce costs and the potential for repetitive

motion injuries. It also allows product designers to identify potential design changes that can improve manufacturability and lower costs without affecting product function. The intentional ambiguity created by not providing time to train student assemblers prior to this in-class exercise, along with providing often vague work instructions creates a low level of confusion and frustration among students. However, we feel that this helps reinforce the need for complete work instructions and an optimized assembly process, and helps students appreciate the value of these important components.

During the first year of the module, some unanticipated outcomes of the in-class activity occurred. The assembly line simulation involved two parallel assembly lines with two production “supervisors”. Both lines were told to start at the same time after receiving similar instructions. Once the activity began, we noticed that the two supervisors were competing to see whose line could complete the water battery assembly first. This competitive attitude resulted in some negative interactions between one supervisor and a few workers. This supervisor appeared to take on a different personality as he behaved in a manner that he perceived to be how a production supervisor should behave. Students did not appreciate this behavior. To prevent this from reoccurring, in 2013 we began emphasizing the learning goals of the activity and make it clear that it is not a competition between assembly lines. This in-class activity made these students more aware of the affect of the supervisor’s behavior on assembly worker morale, motivation, and productivity. These are important characteristics for students to think about and become aware of as they prepare to move into any type of management position later in their careers.

Another unanticipated outcome occurred when workers were assigned to stations involving tasks requiring greater hand strength. When the supervisor noticed that a female worker was not able to coil wires as quickly as her male counterpart in the “competing” assembly line, he told her to switch with a male student at a station involving a task that did not require as much hand strength. Because of this event, a quality assurance observer reported “offensive, sexist remarks”.

## 6. Conclusions

At the end of the module, students understood the importance of designing a product not only for the end user, but also with the assembler and inspector in mind. The in-class activity was a fun, hands-on active learning exercise that helped students learn about design for manufacturability, lean principles, and design transfer. Experiential learning occurred

in a relatively short timeframe. The exercise did not require access to a full-scale manufacturing facility, thereby making it feasible to implement at any school. Based on feedback from students, we feel that students learned more about these topics through this hands-on, active-learning exercise than they would have if they had only read about or listened to lectures on these topics. We feel that this module enhances student learning and better prepares students for professional practice and careers in engineering.

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## References

1. M. B. Teixeira and R. Bradley, *Design Controls for the Medical Industry*, Marcel Dekker, New York, 2003.
2. S. Howe and J. Wilbarger, 2005 National Survey of Engineering Capstone Design Courses, *Proceedings of the 2006 ASEE Annual Conference and Exposition*, Chicago, IL, pp. 11.4.1–11.4.21, June 2006.
3. J. Pembridge and M. Paretto, The Current State of Capstone Design Pedagogy, *Proceeding of the 2010 Annual Meeting of the American Society for Engineering Education*, Lexington, KY, pp. 15.1217.1–15.1217.13, 2010.
4. S. Howe, S. L. Poulos and L. M. Rosenbauer, The 2015 Capstone Design Survey: Observations from the Front Lines, *Proceedings of the 2016 ASEE Annual Conference and Exposition*, New Orleans, LA, June 2016.
5. M. Ssemakula, G. Liao and D. Ellis, Closing the Competency Gap in Manufacturing Processes as it Applies to New Engineering Graduates, *Advances in Engineering Education*, American Society for Engineering Education, Spring 2010.
6. T. Cebeci, Broadening the Manufacturing Practitioner’s Education, Guest Editorial, *Manufacturing Engineering*, **130**(1), 2003.
7. J. S. Lamancusa, J. E. Jorgensen, J. L. Zayas-Castro and J. Ratner, The Learning Factory—A New Approach to Integrating Design and Manufacturing into Engineering Curricula, *Journal of Engineering Education*, **86**(2), pp. 2262–2269, April 1997.
8. E. C. DeMeter, J. E. Jorgensen and A. Rullen, The Learning Factory of the Manufacturing Engineering Education Program, *Proceedings of the SME International Conference on Manufacturing Education for the 21st Century*, San Diego, CA, pp. 7B5.12–7B5.17, March 1996.
9. J. Domblesky, J. Rice and V. Cariapa, Closing Competency Gaps in Manufacturing Throughout Student Learning Factories—One Approach, *Proceedings of the 2001 ASEE Annual Conference and Exposition*, Albuquerque, NM, June 2001.
10. J. Goldberg, V. Cariapa, G. Corliss and K. Kaiser, Benefits of Industry Involvement in Multidisciplinary Capstone Design Courses, *International Journal of Engineering Education*, **30**(1), 2014, pp. 6–13.
11. M. Prince, Does Active Learning Work? A Review of the Research, *Journal of Engineering Education*, **93**(3), 2004, pp. 223–231.
12. J. Goldberg and M. Nagurka, Enhancing the Engineering Curriculum: Defining Discovery Learning at Marquette University, *Proceedings of the 2012 Frontiers in Education Conference*, Seattle, WA, October 2012.
13. J. Goldberg and D. Rank, A Hands-On, Active Learning Approach to Increasing Manufacturing Knowledge in Engineering Students, *Proceedings of the 2013 Annual Meeting of the American Society for Engineering Education*, Atlanta, GA, June 2013.

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