Teaching Design for Manufacturing of Plastics Using Computer-Aided Engineering

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Plastic manufacturing is one of the largest industrial areas in the United States. It accounts for approximately $304 billion in annual shipments and 1.5 million jobs (Society of Plastic Industry, Inc., 2000). Today's business environment is driving manufacturers to bring better products to market faster, with higher quality and lower cost. This is true in the plastics molding and manufacturing industries, as stressed in a 1999 industry trend report prepared by the Plastics Molders & Manufacturing Association of the Society of Manufacturing Engineers. This trend forces original equipment manufacturers, molders, toolmakers, machine manufacturers, and material suppliers to work together and be involved at the earliest stage of product development in today's intensely time-conscious, competitive environment. In developing a new product, the design stage will typically cost 5% of the total cost breakdown (see Figure 1). However, studies by various companies (Boothroyd, Dewhurst, & Knight, 1994) have shown that design decisions made during new product development directly affect 70% to 80% of the final manufacturing cost (see Figure 2). Therefore, the workforce needs to be attuned to designing with manufacturability in mind to avoid difficult and costly situations in later stages.

Today, technology tools such as computer-aided design/manufacturing (CAD/CAM), computer-aided engineering (CAE), computer numerical control (CNC) machining, solid modeling, and stereolithography (SLA) are available to help manufacturers achieve the goal of an ever-decreasing life cycle of a product from concept to market. CAE has been widely used by the plastic injection industry to verify the manufacturability of a design, as evidenced

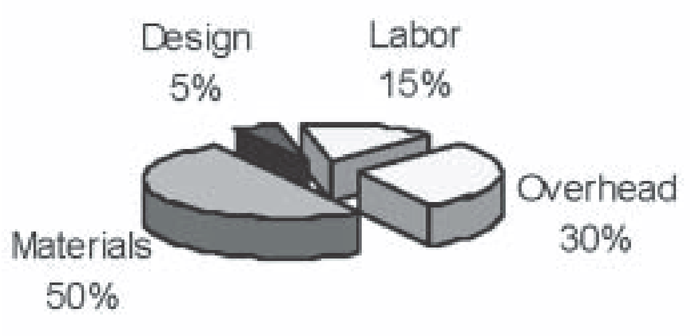


Figure 1. A typical breakdown of total manufacturing cost of a new product development (Boothroyd, Dewhurst, & Knight, 1994).

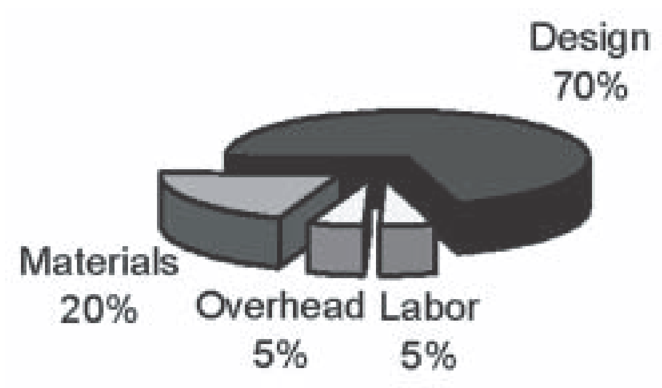


Figure 2. The percent influence on overall manufacturing cost of developing a new product (Boothroyd, Dewhurst, & Knight, 1994).

Table 1. Summary of Commercial CAE Packages Available to Plastic Industry

Company Name	Headquarters Location	Telephone
Axsys	Wixom, MI	248-926-8810
C-Mold (purchased by Moldflow in 2000)	Louisville, KY	502-423-4350
Cadkey	Marlborough, MA	508-229-2020
Injection Molding Ind.	Orion, MI	248-391-1405
ITI	Milford, OH	513-576-3900
M-Base	Aachen, Germany	+49 (241) 9631450
Madison Group	Madison, WI	608-231-1907
Moldflow	Wayland, MA	508-358-5848
Plastics & Computer	Dallas, TX	972-934-6705
SDRC	Milford, OH	513-576-2400
Stress Engineering	Mason, OH	513-336-6701

Note. Adapted from "Software, CAE," 2001.

by the number of commercial software packages available today (see Table 1; "Software, CAE," 2001).

Injection Molding and Product Development

Injection molding is a process that softens a plastic material with heat and forces it to flow into a closed mold. Then, the material cools and solidifies, forming a specific product. The manufacturing of quality injection-molded parts depends on the successes of part and mold design, process control, and material selection. A study identified more than 200 different parameters that had a direct or indirect effect on the complicated process (Bryce, 1996).

Traditionally, experienced molding personnel have relied on their knowledge and intuition acquired through long-term experience, rather than the theoretical and analytical approach to determining the process parameters that is used today. The length of the time in finding the right conditions to manufacture quality parts was dependent on the experience of molding personnel. Furthermore, the development of new products and part and mold designs as well as selection of materials and machines also remained a matter of personal judgment. It was considered normal that a mold be returned to the mold maker for modification at least once or twice before it could produce parts meeting the user's specifications. About 20% of the cost of a mold commonly went into redesign and remaking (Bernhardt, Bertacchi, & Moroni, 1984).

The development of computer-aided engineering simulation in the injection molding industry has eliminated various trial-and-error practices and greatly streamlined the product development cycle. CAE can be used to check process feasibility, evaluate runner systems, determine optimal process conditions, and estimate the cost of processing a part. Its application can provide the industry with benefits such as resource saving, reduced time to market, and improved quality and productivity. However, one of the causes for reluctance to make use of and realize the whole advantages of CAE is that a significant portion of the industry still lacks the technical skills needed to apply the simulation technology (Berhardt, Bertacchi, & Kassa, 2000). Integration of CAE into higher education should provide trained personnel to reap the benefits of simulation in the injection molding industry.

The Course

This article shares the highlights of teaching the integration of CAE packages with hands-on activities in the laboratory and covers issues of designing for manufacturability in injection molding in a course taught by the author. The major points of this article are teaching methods, tools available, competencies for designing for manufacturability in injection molding, and students' feedback about the effects of the integration of CAE on their learning.

The course *Polymer and Composite Processing* covers polymer and composite processing, each receiving eight weeks of coverage. Since industrial technology students have previously learned about plastic materials and available industry processes in a course on *Non-Metallic Manufacturing Materials and Processes*, it is logical to provide a systematic view of plastic manufacturing that focuses on the design for manufacturability using a specific and popular process such as injection molding. This broadens their view of industrial practices, since 60% of manufacturing processes within the plastic process industry are injection-molding types (Michaeli, Kaufmann, Greif, & Vosseburger, 1992).

Teaching strategies were concentrated on presentation and demonstrations, team environment with limited cooperative learning experience, and hands-on experimentation in laboratory. The recent introduction of a new injection molding machine and three CAE packages provided the author ample leverage to include simulations in teaching, as well as to redesign the contents of the class. The addition of field trips and seminars by industrial experts in the class further enhanced students' learning experiences. Available for laboratory experiences are:

1. A new Boy 22M electronic fully closed-loop controlled injection-molding machine. This machine features a microprocessor-based control system, which includes programmable injection and holding pressures, variable injection speed, capability of monitoring 12 processing parameters simultaneously, and statistical process control.

2. CAE packages, including:

2.1 Dr. C-Mold, from Advanced CAE Technology, Inc., also known as C-Mold Company. Dr. C-Mold is an early version of the desktop CAE tool. It uses seven steps, which are listed in Table 2, to optimize the design. Although it does not provide graphical presentation in mold filling, the seven steps offer the typical sequence a designer uses in checking the manufacturability of injection molded plastic parts.

2.2 3D QuickFill, also from C-Mold Company. This advanced package can read a solid model from its stereolithography (STL) file into the program and perform injection simulations. By choosing injection points, the analysis provides not only advice and specifications for the design, but also graphical presentations regarding melt-front advancement, pressure and temperature distributions, cooling time, orientation, weld lines, and vent locations.

Table 2. Summary of Seven Steps in the Design Process

Design Objective	Criteria to Achieve Objective
1. Enter Design Parameters	Enter the design description, and the part and mold geometry.
2. Compare Resins	Compare resins and select one that can reach a maximum flow length greater than the target flow length, under suggested processing conditions.
3. Compare Machines	Compare machines and select one that has enough clamp tonnage under suggested process conditions, or determine the number of cavities that can be accommodated by the selected machine.
4. Minimize Nominal Thickness	Most parts are designed thicker than they need to be. Determine how thin the nominal thickness can be, while still achieving a feasible process window of reasonable size (runners are not included in the calculation of the feasible process window).
5. Optimize Injection Conditions	Determine optimal injection conditions based on an optimal process window of adequate size.
6. Optimize Cooling Conditions	Determine cooling conditions that will achieve the shortest possible cooling time.
7. Optimize Holding Conditions	Determine holding conditions that will minimize part shrinkage without overpacking.

Note. Adapted from *Dr. C-Mold User's Guide,* 1998, p. 29.

2.3 Moldflow Advisors, from Moldflow, Inc. This package offers all the features of 3D QuickFill. It also gives designers the ability to find the optimal injection points, build runner systems, check the balance of the runner systems, and share and report the results through the Web templates built in the program. It is the most sophisticated desktop CAE package for injection molding in the industry.

The Projects and Design Issues

The competencies of design for manufacturability for injection molding that should be covered in students' learning experiences were derived from several resources (Boothroyd et al., 1994; Bryce, 1996, 1997, 1998; Malloy, 1994; Menges & Mohren, 1993). The major headings are listed below. (A complete outline is available from the author on request.)

- Concurrent Engineering vs. Sequential Engineering
- Materials Selection
- Process Parameter Control
- Part Design Considerations
- Mold Design Considerations
- Cost Estimation

The intended learning outcomes for students were to gain knowledge of the above competencies, to possess the necessary skills to utilize CAE packages to check designs for manufacturability, to obtain hands-on appreciation of the injection molding process and important parameters, and to be able to deal with real-life projects by integrating the aforementioned knowledge, skills, and experience. With these outcomes in mind, the assessment activities not only included quizzes and tests but also asked students to work on seven design projects.

The first four projects required students to go through tutorials in the three CAE packages in order to familiarize themselves with the tools and their applications such as checking process feasibility, evaluating runner system, determining optimal process conditions, and estimating the cost of processing a part. The fifth project asked students to apply various design and processing parameters such as materials, gating schemes (numbers of gates used and locations of gates), melt and mold temperatures to experience their effects on other operating variables such as sizing machine, weld line formation and location, injection pressure, cooling time, etc. The simulation results provided students with an understanding of the complexity of injection molding product development within a short period of time without lengthy injection operations in the lab.

Austin (1996), the founding chairman from 1978 to 1994 of Moldflow Pty Ltd., noted that CAE simulation is just a tool for an extensive design. Molding experience is required for effective and efficient use of CAE in design for manufacturability of plastic parts. The last two projects challenged students to verify their simulation results with hands-on injection molding operations. A four-cavity mold is available in the lab (see Figure 3). The

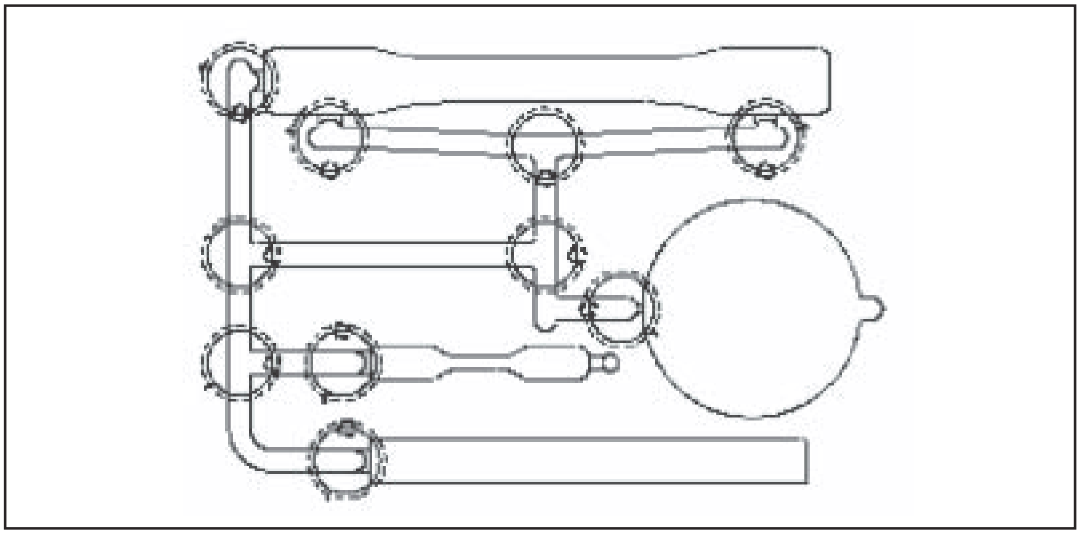


Figure 3. The four-cavity mold available in the lab. (The dash-lined circles represent shut-off valves enabling the selection of various combinations of the four cavities.)

mold is equipped with shut-off valves in its runner system, allowing the four cavities and their combinations to be selectively chosen for different groups in the class. In the sixth project, students then used Dr. C-Mold following the seven steps listed in Table 2 to generate a machine set-up sheet as shown in Figure 4. Students then used the information listed in the set-up sheet, such as melt and mold temperatures, injection and holding pressures, and injection and holding times, to set the process parameters and run the injection operation. During injection molding, they made adjustments on various molding parameters to get quality products.

The last project asked students to construct the assigned cavities in a CAD solid model form and then to run simulations using the Moldflow Advisors package. The results were then verified through the real-life injection molding process. Figure 5 shows the simulation result for a two-cavity molding at two molding conditions. The Confidence of Fill result, one of many simulation results from the CAE software, displays the probability of a region within the cavity filling with plastic by three colors: green, yellow, and red. Green means that the part is easily molded and part quality is acceptable; yellow predicts that the part may be difficult to mold or quality may not be acceptable; and red indicates the part will be extremely difficult to mold or quality may be unacceptable. Figure 6 shows the progression toward a quality product by adjusting the processing parameters such as melt temperature and injection pressure in an injection molding

Description: 2-cavity C & D mold				Date: 12/11/99			
Resin: PE-LD (base)							
Machine: Boy 22M 24mm							
				Suggested Value		Set Value	
Temperature	Melt Temperature		(F)	428			
	Barrel Temperature	Nozzle	(F)				
		Front	(F)				
		Middle	(F)				
		Rear	(F)				
	Mold Temperature		(F)	104			
	Coolant Temperature	Fixed Plate	(F)				
		Moving Plate	(F)				
	Ejection Temperature		(F)	176			
Time	Injection Time (Filling Time)		(s)	0.5			
	Cooling Time (s)	Holding Time	(s)	12.4	2.5		
	Mold Open Time		(s)				
	Cycle Time		(s)				
Pressure	(P_r :P_h) Resin/Hydraulic Pressure Ratio			9.1	:1	9.1	:1
	Injection Pressure (psi-b)	P_r	P_h	6527	721	$P_{r,max}$	$P_{h,max}$
	Holding Pressure (psi-b)	P_r	P_h	3336	369		
	Back Pressure		(psi-b)				
	Screw Rotation		(RPM)				
Position	Cushion		(in)				
	Switch-Over Position		(in)				
	Shot Size		(in)				
	Decompress		(in)				

Figure 4. A machine set-up sheet generated by Dr. C-Mold simulation.

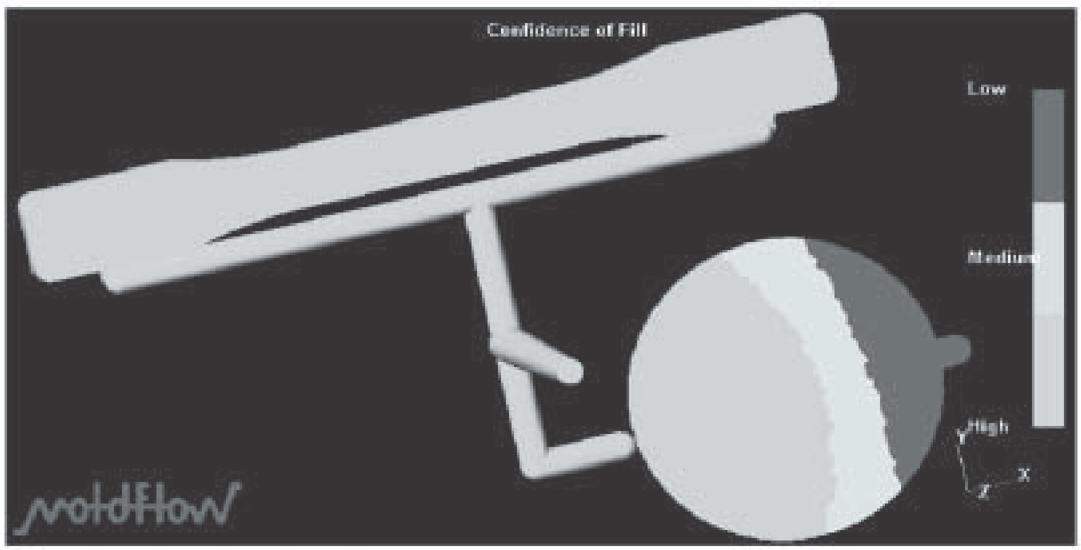
operation carried out by the students in the lab. The results are compatible with the prediction of the simulation shown in Figure 5.

A presentation about the up-to-date plastic database, the Prospector of IDES, Inc., and various plastic parts from an industry expert further enhanced students' understanding of the diversity of plastic materials and related processes. At the end of the semester, a field trip to a nearby custom molder using CAE in its operation further improved students' connection of what they had learned in class to the application in a real industrial setting.

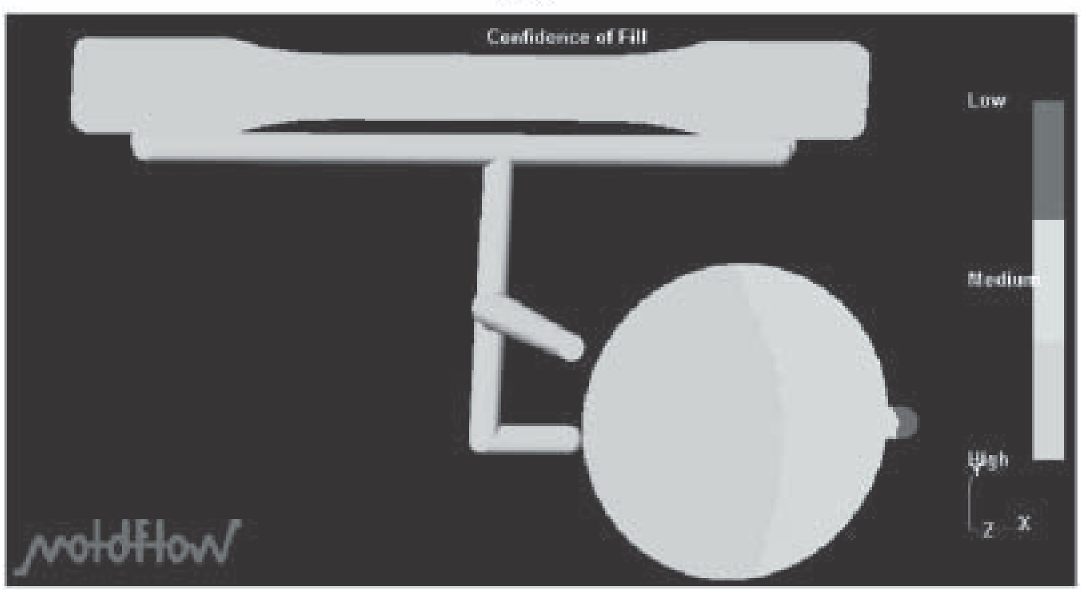
Response to the Course and Future Plans

I conducted basic attitude surveys in Fall 2000, Spring 2001, and Fall 2001 classes to determine student attitudes toward their learning experience in class and toward a career in the plastics industry, and to seek their inputs for improvement. Thirty-two students rated 11 questions on a scale of 1 to 10 and provided comments as shown in Table 3.

Most of the students thought they were proficient users of computers and gave a very high mark for the department's hardware



(a)



(b)

Figure 5. The simulation results of Confident of Fill by Moldflow Advisors at two different molding conditions; the cavities are progressively filled up by adjusting the melt temperature from (a) at low temperature to (b) at high temperature.

Table 3. Survey Summary of 32 Industrial Technology Students

Survey Questions	Average	Standard Deviation
I am a proficient computer user.	8.17	1.67
I was proficient in using computer-aided engineering (CAE) packages before I took this class.	3.56	2.87
The departmental computer facilities are among the best at the University.	8.03	1.45
It was interesting to learn to use the CAE software.	8.56	1.27
CAE lab projects helped me build competence in using the CAE software.	8.63	1.19
CAE helped me to gain insight into the behavior of molten plastics during the injection molding process.	8.16	1.55
The CAE packages enhanced my ability to design injection-molded parts for optimum manufacturability.	7.84	1.55
CAE can help plastic companies to cut cost, improve product quality, and shorten lead-times for new products.	9.34	0.83
The class helped me to improve my understanding of the plastics manufacturing industry.	8.84	1.22
What I learned in this class will help me to be successful in manufacturing.	8.47	1.44
I think that it would be interesting to pursue a career in the plastics industry.	7.30	1.52

Note. A scale of 1 to 10 was used to rate each question (1 = *strongly disagree* and 10 = *strongly agree*).

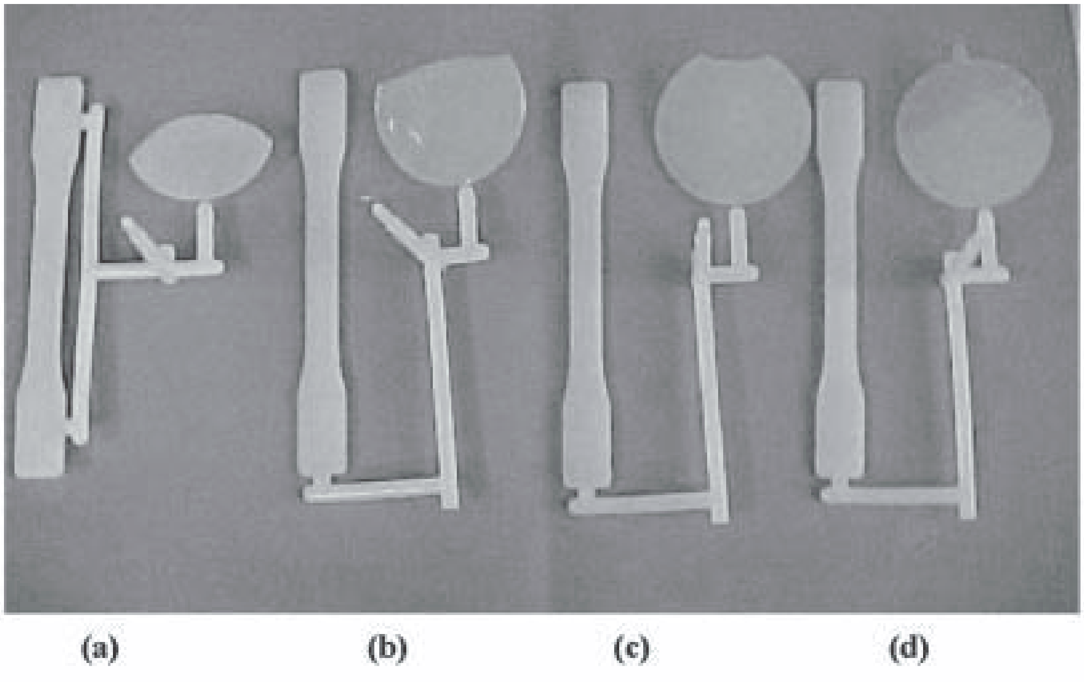


Figure 6. The progressive results of students' injection molding operation by adjusting the molding conditions following the simulation results of Moldflow Advisors. The melt temperature is progressively increased from low (a) to high (d).

facilities. Most of the students had CAD experience, but not CAE, before enrolling in the class. The survey results indicated that students liked the learning experience as well as its usefulness for their study. From their own experience and the demonstrations by industrial personnel during the seminar and the field trip, students perceived the usefulness of CAE for the plastic industry. Also, the contents seemed to promote students' understanding and career interest of the plastic industry.

The advanced desktop CAE simulations are effective and economic tools to teach the injection molding process and control since they provide visible presentation of how plastics behave in the mold during the process. Furthermore, their capability to address design issues in product development of injection molding makes them the ideal apparatus for students in learning the design for manufacturability and concurrent engineering practices. A preliminary survey has shown that their applications along with hands-on lab exercises, seminars, and field trips are an effective way to enhance students' learning experience in the area of injection molding process and product design.

To enhance students' learning experience in the area, the following content will be incorporated in future classes:

- Acquire an advanced CAE package such as Moldflow Plastic Insight analysis software to conduct in-depth study of injection process and product development.
- Continually evaluate and modify current projects and solicit industrial projects so students can make a connection of learning experience with current industry practices.
- Research the impact of CAE teaching on the effectiveness of students' learning the competencies of design for manufacturability of plastic parts.

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