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Teaching Industrial Design in Mechanical Engineering: A Laboratory for Design and Engineering*

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The introduction of novel information technologies has changed the product development process in industry. There is an ongoing integration between mechanical and industrial design, with both fields using somewhat similar design tools. Unfortunately, a large gap still exists between these two professions in academia. Mechanical design and industrial design are typically taught in different schools, using different educational methods, and emphasizing different topics in their curricula. Integration of these two academic disciplines in an academic course is rarely encountered. In order to overcome this limitation, we introduced a new laboratory course for design and engineering where we teach engineering undergraduate students, in addition to mechanical engineering practice, basic concepts of industrial design and allow them to gain hands-on experience. Each semester 16 undergraduate ME students participate in the laboratory. A survey conducted among students who completed the laboratory studies yielded very positive feedback: the majority of students responded that they appreciate learning and implementing the concepts of industrial design and integrating engineering practice with creative design.

Keywords: mechanical design; industrial design; product design; design education

1. Introduction

1.1 Terminology

Design is the process of turning ideas into material things [1]. Design can also be defined as the process of creative problem solving [2]. *Product design* is the process of creating a new product for commercial use [3]; it is a term used broadly that sometimes overlaps with *industrial design* and includes *engineering design*. The Industrial Designers Society of America [4] describes industrial design as the "professional service of creating and developing concepts and specifications that optimize the function, value and appearance of products and systems for the mutual benefit of both user and manufacturer." The process of engineering design entails "devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic science, mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective" [5].

Dumas [1] writes that industrial design can be either subsumed in engineering design or regarded as "running parallel" to it. However, when industrial design activity involves aesthetic concerns or a product's style, it is also closely correlated with manufacture. Although it mainly focuses on the research of market and user needs, research on technology development is essential [6]. This may explain the ambiguity and misunderstanding surrounding the terminology's use. In the literature reviewed in the next two sections, the terms product design and industrial design are used interchangeably.

1.2 Engineering design and industrial design

New product design methodology is industry-dependent. Companies that develop products which are used in areas such as defense, energy, or mining are mainly interested in good engineering design in which "the end goal is the creation of an artifact, product, system, or process that performs a function or functions to fulfill customer need(s)" [7]. These industries want primarily to develop a product that is functional, reliable, affordable, and easy to operate and maintain. Their clients are governments, municipalities, armies, or large industrial companies. The cultural and aesthetic aspects of these products are only of secondary importance. In these industries, according to Dumas [1], engineering design and industrial design "run in parallel."

Consumer product markets view product design differently: namely, that the aesthetic, cultural, and technological elements should be reflected in the design. One of the better explications of consumer product design philosophy can be found summarized in Maeda's *The Laws of Simplicity* [8] as ten design principles.

1.3 Design intent

Industrial designers and mechanical engineers approach design intent differently. Laursen and Moller's [9] study comparing between industrial designers' and design engineers' understanding of design intent investigated the differences that make

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collaboration between them difficult. The results showed that the more complex and abstract elements of industrial design knowledge, such as the meaning, semantics, values, emotions, and social aspects of the product are less important to design engineers. These researchers also found that design engineers' understanding of industrial design is very limited. Micheli et al. [10] studied communication patterns between new product development managers, many of them engineers and industrial designers. They discovered that managers and industrial designers do not use a completely different language, as previously supposed; some terms are common to both and others are specific to each. Managers are commercially oriented, whereas designers are interested in iconic design.

1.4 Design education and project-based learning

The currently most-favored pedagogical model for teaching engineering design is project-based learning (PBL) [11]. In their thorough literature review of design-based learning in engineering education, Gomez Puente et al. [12] also examine studies on problem-based and project-based learning. The latter has been used as a tool to motivate and integrate learning [13] and also to encourage and support teamwork and cooperation [14]. Kolb [15] explains that "experimental learning" is commonly defined as a form of learning from life experience, often contrasted with lecture or classroom learning. Finally, PBL offers design or project experience, which are what experimental learning chiefly comprises.

The mechanical engineering (ME) department at the Politecnico di Milano developed a graduate course that integrates product design and product engineering in a new course called Industrial Design and Engineering [16]. According to the more so-called traditional view, product designers specialize in consumer products and mechanical engineers, in machinery. Product designers tend to focus more on shape, styling, and consumer attributes, while engineering designers tend to focus more on products' functionality and technology. The Politecnico's graduate course aims to impart to engineers the skills, including use of computer-aided design (CAD) tools, that are needed in both product design and engineering [16]. This course gestures towards the type of framework that can merge design and engineering education with multidisciplinary design, using knowledge and tools from both areas.

1.5 The design studio

The heart of the industrial design curriculum is the design studio, where students learn to visualize problems graphically and think like a designer [17]. Initially, the modern design studio focuses not only on aesthetics but also on usability and manufacturing design [17]. The instructor-student ratio is roughly 1:12, thereby enabling increased personal interaction and supervision. The type of problems that are assigned in the design studio are open ended, thus students are expected to devise their own solutions rather than conform to a preconceived one [18].

Studio-Based Learning (SBL) methodology is a variation of problem-based and project–based learning, which centers on design problems that are grounded in the realities of professional practice [19]. Typically, the instructor provides students with a project specification that describe an ill-defined problem that students must address through their design work in the studio [19]. Design links theory and practice, bridging scientific activities with creative ones in order to deal with such ill-structured, open-ended problems [20].

In the next section, we introduce our course called Laboratory for Design and Engineering, which was developed to teach ME undergraduates the practice of mechanical design as well as some of the basic concepts of industrial design. It shares the content of an older ME laboratory course [21] but was modified by adding a weekly hour taught by an industrial designer. We describe the effect of the new laboratory activities on the product design process over a period of three consecutive semesters. We then present and discuss the results of a survey that was given to participants who completed their projects.

2. The laboratory for design and engineering

Enrollment in the laboratory course is limited to only 16 students a semester. The students are asked to team up on their own in groups of four and each is assigned a project with similar specifications. By the end of the 13-week semester, each team must develop and build a functioning product. In the earlier laboratory course [18] only the functional requirements for each assignment were specified, which entail designing, manufacturing, and testing of simple machines or mechanisms. In the new laboratory for design and engineering, we also requested our students take into account the preferences and tastes of a potential client.

The lab is supplemented by frontal-style teaching of the following topics relevant to industrial design: (a) marketing aspects, among them the links between global trends, products, and consumerism; (b) visual aspects of product characterization and branding: namely, shape, material, texture, color, image, and text; and (c) introduction to human factors.

Over the semester, each team is assigned a number of tasks that they must report on to the class: (a) client characterization, specifically needs and expectations; (b) specification of the conceptual design, with a focus on visual aspects; and (c) the conceptual design (CAD model) of the product. In the second half of the semester, students must then (d) prepare a production plan for their model, including selection of materials; (e) produce needed parts; (f) assemble a functioning product; (g) submit a project report; and (h) present the project in front of the class. We found that the design process and the design methodology of a new product development, are quite similar in both disciplines and work in harmony along the project. In both, understanding the customer's needs and using creative design thinking are essential to developing new concepts and finally a functional and aesthetic product.

The mechanical requirements of the assignment in the new course have remained essentially the same as in the older version of the course [18]; namely, students are asked each semester to design a mechanism with linear and rotational motion, supplied by two step motors. But after adding client requirements and introducing industrial design (ID) concepts, we observed a significant difference in the appearance of our student's completed projects. Instead of bare metal mechanisms that merely met the functional requirements, we began seeing colorful products, pleasing to the eye, tailored to the needs and desires of a potential customer.

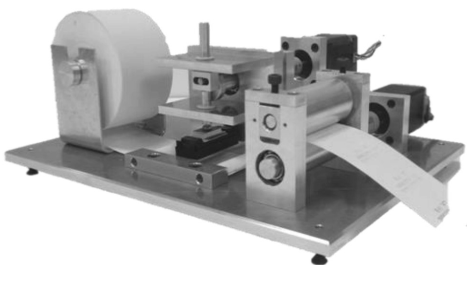

Fig. 1. Functioning print-stamping machine.

The change evolved gradually over a period of several semesters in what may be described as three main steps:

1. The *exposed design*; namely, a pure ME design that meets a set of functional specifications. It represents typical products used to be developed by students in the older version of laboratory course [18].
2. The *enveloped design*; the ME and industrial design elements are developed separately. After the mechanical system is designed, an aesthetically pleasing "envelope" that meets the client's needs and tastes is designed by applying ID concepts. Finally, the aesthetic case is used to enclose the functional mechanical mechanism.
3. The *embedded design*; the mechanical functional elements and industrial design elements are integrated into a single unit that must meet both the engineering specifications and the client's needs. The functional elements and the aesthetic elements of the product are inseparable.

In the next three sections, we will illustrate each category with a different student project.

2.1 Exposed design

A product that represents a typical exposed design is a machine that prints a logo on a paper strip at the rate of 100 stamps per minute. The mechanism that lifts the stamp up and down is powered by a rotating motor, and the paper is advanced by two rollers powered by a second motor. Our ME students learned how to design this mechanism, select bearings and couplers, and build a functioning product. The stamping mechanism remained bare, with all its chiefly aluminum-made moving parts visible. The system met all the engineering specifications (speed of printing and paper feeding, weight, size, reliability, and more). No further specifications were given with respect to the potential client, user interface, appearance, or any other ID requirement. Fig. 1 shows a functioning print-stamping machine.

2.2 Enveloped design

In the next semester, the teams were asked to design

Fig. 2. CAD models of three design concepts for automatic pencil sharpener.

an automatic pencil sharpener according to assigned engineering specifications, but this time with a specific market niche and customer in mind. One team, for example, designed a high-end product suitable for an executive's work space and specified the visual elements and materials needed to express quality, elegance, and functionality. This team proposed three preliminary design concepts, shown in Fig. 2. On the left is the prestigious design; in the middle, the colorful one; and on the right, the minimalistic one.

Of the three proposed concepts that were evaluated in the preliminary design review (PDR), the prestigious design was selected and developed into a final product as shown in Fig. 3.

Fig. 3. Automatic pencil sharpener; built and functioning product.

Fig. 4 shows the sharpening mechanism (on the left) and the same mechanism placed within an attractive case (on the right), which were each developed separately. As the figure clearly shows, the product design is not fully integrated, and each part, the mechanism and the case, were designed separately.

2.3 Embedded design

The following semester, students were asked to design and build a machine according to a specific set of both engineering and industrial design requirements, the former stated as follows: design a machine for coating a 3/8'' spherical piece of candy with sugar syrup four separate times within a distance of approximately 20 cm. The team design shown in Fig. 5 uses a skid for conveying the syrup and a wheel for raising the candy up four times, once for each coating cycle. After the fourth cycle, the mechanism stops and the candy is ready. The potential customers that the team identified for this particular design are children, families, mechanical-gadget lovers, and toy manufacturers. The ''Six Flags'' brand name was chosen because of its association with emotions related to experiences in amusement parks, pleasure, family, and vacation. The visual elements, round and diagonal lines, that were used in the design conveyed quality. The

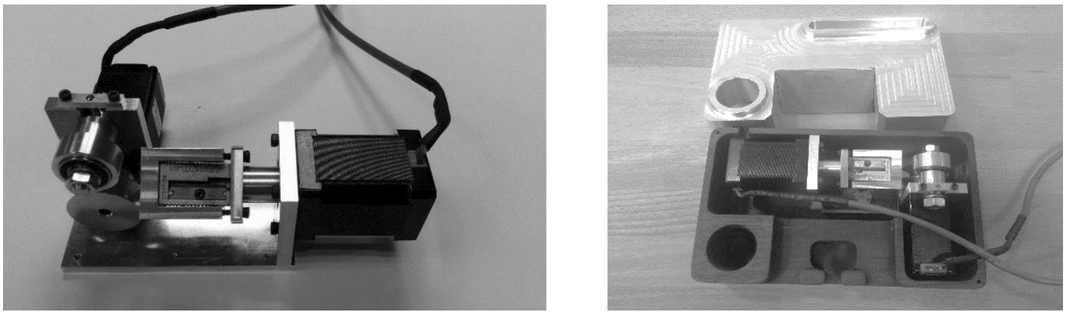

Fig. 4. Automatic pencil sharpener; the mechanism (left) and the mechanism assembled in a case (right).

Fig. 5. Three preliminary design concepts for candy-coating project.

Fig. 6. Candy-coating project; "quick models" of the selected concept.

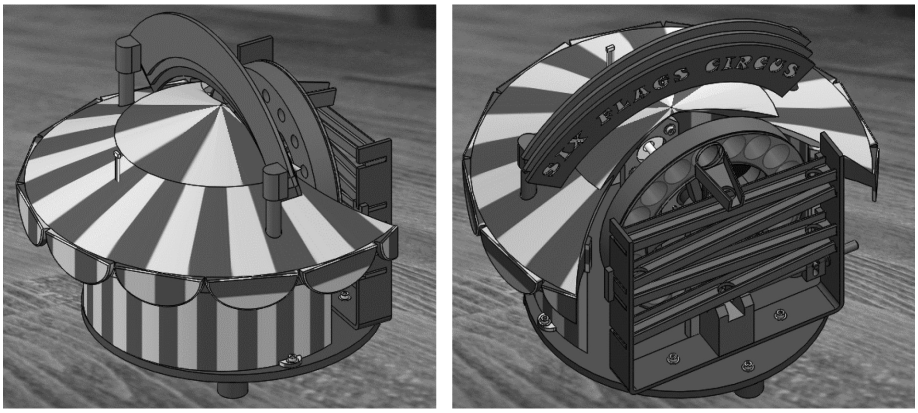

Fig. 7. Candy-coating project; CAD model.

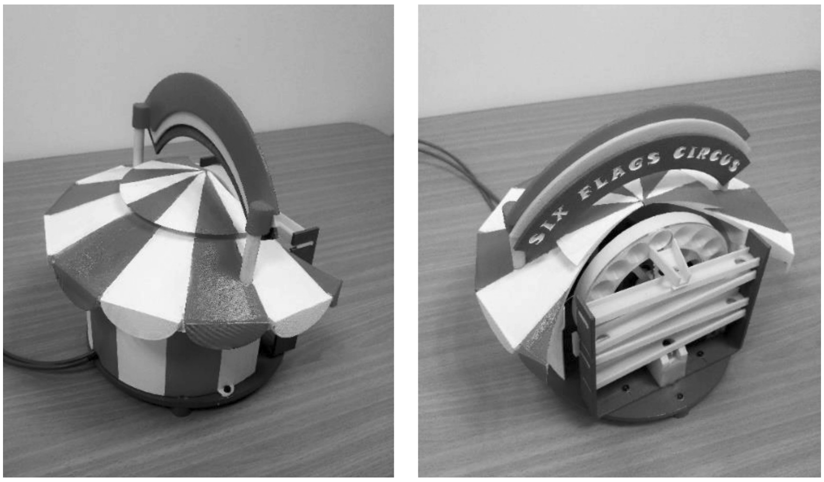

Fig. 8. Candy-coating project; the final functioning product.

preliminary three CAD models created by this team are presented in Fig. 5.

During the preliminary design review (PDR) a leading concept was selected and the students were asked to create a "quick model" of the selected product made of paper and styrofoam as presented in Fig. 6.

The CAD model of the selected concept is shown in Fig. 7 and the final working product that the team built and demonstrated in class, in Fig. 8.

Embedded design is possible chiefly thanks to additive manufacturing technology (AMT), which makes it possible to produce elegant parts with functional mechanical properties and visual and

Table 1. Comparison of product design methods

	Exposed design	Enveloped design	Embedded design
Meet functional requirements	V	V	V
Meet customer's need or taste	–	V	V
Structural elements	Functional elements only	Functional elements separated from aesthetic elements	Structural elements inseparable from aesthetic elements
Technological enabler	Machining	Machining and Additive Manufacturing	Mainly Additive Manufacturing (Colorful 3D printing)
Look	Exposed mechanism, elements made of metal	Metal mechanism covered by aesthetic envelop	Elegant, colorful parts with functional mechanical properties

structural components. A comparison of the main characteristics of the three design methods is described in Table 1.

In summary, over a period of three semesters, a strictly functional machine that was designed to meet only mechanical requirements evolved into one that was designed to meet the aesthetic tastes and needs of the client. And finally, the embedded design that uses same parts to perform functionality and decoration where the enabler is AMT.

3. Student survey

Twenty eight students participated in the survey. The survey included two sections. In the first section, the students were asked to grade their answers on a rating scale from 0 to 5, where 0 indicates low ranking of the statement and 5 indicates high ranking.

The following questions were included in the first part of the survey:

(a) Please indicate the level of relevance of the learned industrial design topics, to your future career as engineer in the industry.
(b) Please rank the level of importance of hands-on experience in industrial design.
(c) Please rank the level of satisfaction from the final product your team built.
(d) Please indicate the level of your personal involvement in the industrial design elements of product development.
(e) Would you recommend that your friend take the course?

The responses to these five questions are presented in Fig. 9.

The average scores for all the responses were 4 or higher. The responses to the first two items reveal that the students understand the importance of learning industrial design fundamentals. Of all the items, the average score for the third was lowest, possibly indicating that some of the students were challenged by the artistic aspects of product design. More than any of the other results, the unanimous response that the lab participants would strongly

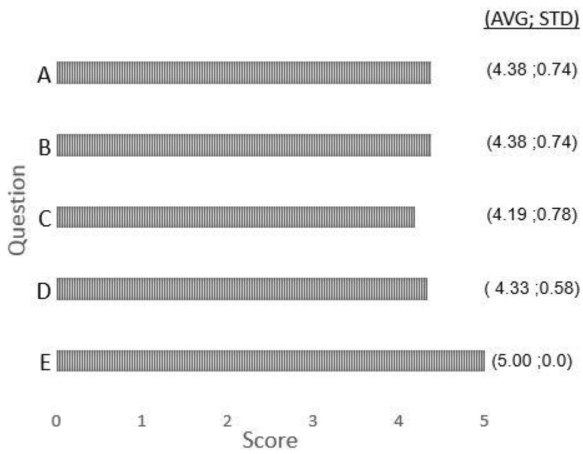

Fig. 9. Average scores and standard deviations for student survey (n = 28).

recommend the course to their friends, demonstrates high overall student satisfaction from the course; despite the heavy demand on students' time and the level of effort required, the waiting list each semester for this course is long.

The second section of the survey comprised three open-ended questions, which we reproduce here together with a few representative responses.

We learned about the visual, marketing, and human aspects related to industrial design. Which one would you like to see expanded on?

A: All aspects are important. I would like to take a full-length industrial design course. I hope one will be added to the ME curriculum.

B: I would like to learn about human factors and ergonomics. It is a developing field in industry and is the most relevant for a mechanical engineer. We learn how to design mechanical parts that will be easy to assemble. It will be useful to learn how to design a product that is user-friendly and intuitive to operate.

C: I am interested in a full-length industrial design (ID) course. One weekly hour does not give us enough background to really understand industrial design.

Please list three advantages to taking this laboratory course.

A: (a) Being introduced to ID, even though it was not thorough enough, gave me a lot to think about. (b) It presented a new point of view of the design process and enriched the practical experience we have in model building. (c) It gives new meaning to all the theoretical courses I have taken so far. It should be an obligatory course for all ME students.

B: (a) I learned how to select materials and make a product out of them. (b) I learned how to develop a product according to customer needs. (c) The artistic elements of design unlocked my creativity. I really enjoyed it!

C: (a) The only course in the ME curriculum that touches on ID topics. (b) It allows us to experience the interaction between mechanical design and industrial design. (c) I learned how to better understand customer expectations and how to design the product to meet them.

Please list three disadvantages to taking this laboratory course.

A: (a) The ID part of the teaching was too brief; one hour a week is not enough. (b) We didn't touch on ergonomics, which is very important for mechanical engineers. (c) The mechanical design activities and the ID activities should correspond to each other better.

B: (a) There is assignment overload in this course. (b) Lots of pressure in order to complete the product. (c) The academic credit for the course does not adequately reflect the investment of effort necessary to build a product.

C: (a) The workload in this course is not proportional to the academic credit it earns. (b) I joined a team in which the members did not contribute fairly, and I found myself doing a lot of work on my own. (c) There should be more freedom given to the students in selecting the final design concept, even if they ultimately fail to develop a product that works. One can learn a lot from a failure.

4. Discussion

The process of product design in industry requires a good understanding of both industrial and engineering design. Yet most academic institutions separate them by teaching each discipline in a different school, thus causing an understanding gap between mechanical engineers and industrial designers. Each interprets the design requirements of a project—the design intent—differently [9].

We introduced the laboratory course in the Technion's ME department in order to teach students good functional mechanical-engineering design that is also client-oriented in that it takes into consideration broader aspects of human and cultural needs. In this laboratory course, we teach engineering students both mechanical engineering practice and fundamental concepts of industrial design. We apply project-based learning methodology [11] and let the students gain hands-on experience in these design projects. The Laboratory for Design and Engineering course evolved from an earlier version of a laboratory course [21] that was solely devoted to teaching mechanical design practice.

Each semester, a small group of 16 students study and apply engineering and design principles in a laboratory course that is supervised by two instructors, one from each discipline. Close rapport between the students and with the instructors is fostered throughout the course, which creates an optimal environment for creativity and innovation. The product development process corresponds with engineering design methodology and incorporates design reviews and engineering analysis. Also used are the traditional design-studio practice of creating "quick models" and the use of paper, wood, and fabric for building intermediate models. The laboratory is housed in the mechanical engineering department and serves engineering students, but in some aspects, it resembles a design studio as described by Ochsner [18].

The laboratory for design and engineering exposed mechanical engineering students to the fundamentals of industrial design and let them apply it in a real project. The feedback from the students who finished the laboratory was excellent, as they understood that this knowledge will help them later in their professional careers. The introduction of industrial design changed the look of the designed and built products to meet not only the functional requirements, but also customer's needs. The advantage of the laboratory is the outstanding "instructor to student" ratio, i.e. two instructors teaching 16 students, four hours each week. It allows personal attention and involvement of the instructors in students' projects. It is also the main limitation of this "studio-like" laboratory that allows us teaching only 16 students each semester.

5. Conclusions

Based on our investigation, we can draw several conclusions which may be applied for improving mechanical engineering design education:

- The introduction of industrial design concepts in an ME-design laboratory improved the design process and, as a result, the final product.

- ME students, who are trained in CAD and are accustomed to using it to create geometric forms, responded naturally to new ID concepts related to visual aspects of form, proportion, material, and color.
- Mechanical engineers and industrial designers may use different languages to describe design and may understand the design intent differently; however, the design process of a new product is quite similar in both disciplines. In both, understanding the client's needs and using creative design thinking are essential to developing new concepts. The most suitable concept can then be selected and drawn using CAD tools, and finally, a model or prototype, built and tested.
- The student feedback that we received confirms that our ME students appreciate learning and implementing the concepts of industrial design.

In response to the positive feedback from our students, the ME department at the Technion is considering an addition to the curriculum of a course called Introduction to Industrial Design. This new course, together with the practice gained in the Laboratory for Design and Engineering course, will give our ME-design students the needed understanding of industrial design and its applications.

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