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INNOVATIVE ENGINEERING DESIGN EDUCATION

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1 Introduction

Innovation is not new [1, 2]. What is new here is the idea that some innovation may be driven through the use of innovative engineering design methods that can be systematically studied, advanced, and taught in engineering education. Since innovation is also important for remaining globally competitive, we have established a course on innovative engineering design methods. The objectives of the course are for students to be exposed to and to learn many different methods of innovative engineering design, test them with examples, and apply them in projects. Through the course they also understand the context of innovative engineering design in industry and the public sector. Hence, the students who take this course will have a set of methods that they can use to infuse innovation into their design efforts, and should recognize which are appropriate in which cases. In this paper, we begin by defining innovative engineering design through an overview existing definitions in the literature, and show that innovation is a learnable process. We then present our case for why students should learn innovation engineering design methods. An overview of the course we have developed is presented, as well as some observations on results from the course. The paper also discusses a new Student Workshop for Innovative Engineering Design (SWIED) that will take the knowledge accumulated by the course and seek projects for application of innovative design methods.

2 What is innovative engineering design?

Defining "innovation," "invention," and "innovative design" is a popular activity and there is no shortage of quite varied definitions given in the literature. We examine here several of the definitions given, with specific interest in those applicable *to an engineering design context*. Innovation, as defined by Sternberg *et al.*, is "the channeling of creativity so as to produce a creative idea and/or product that people can and wish to use." [3] In a seminal work, Myers and Marquis state that "innovations are the units of technological change." They go on to state that "innovation is not just a single action but a process of interrelated subprocesses. It is not just the conception of a new idea, nor the invention of a new device, nor the development of a new market. The process is all of these things acting in an integrated fashion toward a common objective." [4]

In technology fields, innovation is often defined as "the use of new knowledge to offer a new product or service that customers want. It is invention + commercialization." [5] Although success in the marketplace is important, this last definition trends towards entrepreneurship, with which we wish to make a distinction. One such distinction is [6]: "innovation is the act of creating something new and worthwhile, entrepreneurship is the act of carrying an innovation to market in a commercial manner." Innovation and innovative design play a major role within entrepreneurship, but it is upstream from the commercialization stage, which is a major component of entrepreneurship. It is also true that innovation takes place in the public sector, such as the mission agencies of defense and space in the U.S.

Often, when "innovation" is considered, it is the artifact, i.e., the end result, and not the process that is examined. Innovation, however, is a socio-technical process, and attempts to define innovation in purely technical terms misleads in that it is divorced from human influence [7]. Innovative engineering design methods apply to new processes, systems, and services, as well as to new products. Engineering design is a social process that begins with an opportunity (a problem) that is resolved though a question-driven divergent process [8] that develops knowledge about clients, stakeholders, users, needs, specifications, market assessments, and current technology that is used to contextualize the innovative processes for concept generation [9]. Some proponents argue that group dynamics is the key to innovation and hence advocate methods such as synectics ("the bringing together of diversity"), mind mapping, and brainstorming.

Diversity of participants within a design environment is one of methods for ensuring an innovative design solution. That is, the stronger a specific culture, the less likely innovative thinking leading to innovative products can flourish. Conversely, a heterogeneous culture is more likely to breed innovation because the actors look at things from different viewpoints.

Innovative designs owe their origins to many sources—the chance intersection of knowledge and circumstances, necessity, dictate, genius, unique childhood experiences [10]. But innovations may also come from methods that are learnable [11, 12]. Because of this view and the need presented in Section 3, we have established a course on innovative design methods that we discuss further in Section 4.

Many researchers have examined people who are considered creative to determine attributes necessary and the conditions that foster creative thinking. Although a number of different theories have been developed (see, for example, the review in Richards, [13]), we may consider three basic ingredients necessary for creativity or innovation: acquisition of domain skills, developing creative thinking skills, and intrinsic motivation [14]. With exception of the last ingredient, the first two are things we can teach—and the third we can try to affect as well!

As a learnable process, innovative engineering design fits within the larger framework of engineering design. In his proposed framework for order in design research, Horváth [15] places design innovation within the broader research into design methodologies. With this placement, it is implicit that design innovation is a methodology and, as such, can be studied, analyzed, and ultimately learned. In this context, design innovation research is concerned with both innovative products and innovative processes.

3 Why teach innovative engineering design?

There are many signs that the engineering education community in the United States is becoming alarmed about the growing strengths of the global economy, particularly in Asia. For example, a recent report by the National Academy of Engineering, *The Engineer of 2020*, stresses the impact of globalization on the practice of engineering and the necessity for U.S. engineers to focus on innovative and creative aspects of the profession to be globally competitive [16].

Design must play a key role in responding to global competition, and there is evidence to support this view. A study by the Design Council in the U.K. found that companies good at design outperformed the average company listed on the FTSE by 200% over a 10-year period, 1994–2003 [17]. A recent study in the U.S. by CHI Research found that the "top twenty-five S&P companies with patents that are most highly cited by papers and other patents" far outperformed the S&P 500 over 1990–2003 [18]. In addition, cross-national studies show a very high correlation between patents per million and a nation's standard of living [19].

Many managers view innovation as inefficient because they see it as undisciplined, contrarian, and iconoclastic [20]. They would, of course, prefer that innovation occurred according to a preplanned schedule. Pugh [21] claims that "what is required is a process of disciplined creativity rather than innovation." This is his primary argument for companies to employ a "Total Design" process, one in which the design process "connects the selling function (output) back to the market or user need (input)—and links together all the other activities, including specifications of the need, concept design, and manufacture." Hence, engineers that know innovative design methods and techniques for fostering innovation should be of great value to companies.

Brainstorming is preferred by many companies, often exclusively, to foster creativity. Osborne [22] coined the term "brainstorming" to promote his view that creative ideas were locked up in people's minds but were not released for fear of rejection. Hence, in a judgment-free environment, the ideas should be released in a torrent. Although brainstorming certainly has its place, the reliance of engineering designers on this technique—e.g., a survey of 400 Japanese companies in 1989 showed 87% using this technique, well above all other techniques [23]—even though it was developed for marketing, not engineering. Another recent study by Simón [24] examined the use of creativity methods within Swiss companies and found that over 90% use brainstorming (or its variants) and a few other techniques. It seems that no companies employed more than a handful of different methods.

With this as background, it is clear that there is a large benefit to be gained from learning innovative design techniques beyond the ubiquitous brainstorming. But how do we as educators teach these methods?

4 How should we teach innovative engineering design?

4.1 Innovative engineering design course

A course on innovative design methods was developed as an investigation into the various factors that influence innovative design. We are interested in students learning the context surrounding innovation and innovative design. As specific course objectives, the students should 1) learn the many methods of innovative engineering design, test them with examples, and apply them in projects; and 2) understand the context of innovative engineering design in industry and the public sector. As part of the course, we were not able to evaluate the student's use of these methods in other design courses, although this is a possibility in the future. It would also be of interest to compare the cohort of students who have taken the course on innovative design methods with those who have not, as well as to perform a longitudinal study as the students enter the workforce. This research is yet to be performed and of significant interest.

Carayannis *et al.* [7] provide a useful approach to classifying innovation concepts along four dimensions:

- Process—how an innovation is developed, diffused, and adopted
- Content—the specific technical or social nature of the innovation
- Context—environment in which the innovation emerges
- Impact—technological and social change that results

Hence, the course contained modules on

- Innovation, invention and diffusion
- Inventions: social and environmental impact from ancient Mesopotamia to air conditioning and genetic engineering
- Individual genius: da Vinci, Tesla, Edison, Carver, Mary Walton
- Culture: individualism as an economic factor
- Structural factors. team size, team culture, participative decision making
- Role of incentives: intellectual property rights, material benefits, recognition
- A survey of innovative engineering design companies and the methods that they use
- An examination of innovation that takes place in the public sector such as NASA centers and government labs such as Lawrence Berkeley National Laboratory

A major emphasis of the course is on the research pertaining to which methods work and which do not within a design environment. In the course, we examine the many variants of brainstorming; analogous methods such as biomimicry and synectics; checklisting; technology transfer; inversion; idea diagrams; morphological methods; axiomatic design; TRIZ; memory banks of ideas; stimulation techniques; social process methods; innovation in organizations; question driven design—there are well over 100 known creativity and problem solving tools. Table 1 provides a listing of many of the methods explored as well as a proposed categorization of the methods. It should be noted that several of the methods are generally applicable, whereas others are much more engineering focused.

Table 1. A categorization of innovative methods (methods with an engineering focus denoted by *)

Individual Methods 1. Problem conceptualization; raising the level of generality may be helpful in seeing new solution sets and in cross cultural contexts. 2. Mind mapping 3. Morphological analysis* 4. Technology transfer* 5. TRIZ*
Group Process *More Rational* 1. Check list 2. Design for X*

3. Analogies 4. Biomimicry *Less Rational* 1. Brainstorming 2. Word association 3. Synectics
External Inquiry 1. Lead user observation and dialogue 2. UCID (User-Centered Innovative Design) 3. Customer needs assessment: survey, focus groups, user observation 4. Asking around: "does anyone know anything about this?" 5. Benchmarking
Stimulation by Existing Technology* 1. Technology transfer 2. Knowledge brokering using idea lists 3. Tech boxes of embodied ideas 4. Exploration of current technology—new technology teardown 5. Visits to hardware stores, toy stores, exploratoriums, etc 6. Experimentation
Designing Innovating Contexts *Corporate Strategies* 1. Incentive schemes from immediate rewards to IP % 2. Constructing environments that support the innovative process 3. Letting others innovative and then buying them 4. Searching for new market "spaces" and better differentiation 5. Experimenting from prototypes to pilot trials (skunk works, etc.) 6. Disciplined focused culture of innovation 7. Flatter less bureaucratic organizations 8. More R&D (U.S. companies have been shrinking it while Japan, Korea, and now China are stressing it.) *Entrepreneurship* 1. Many ideas, lots of motivation, no bureaucracies, no money, and sometimes no sense 2. Obstacles include tax system, IP hard to defend against corporate lawyers, and cost of venture capital 3. Incentives include SBIR program, bankruptcy laws 4. Value in the culture and as a job creation system (also a job loss system)
Other Categorizations of Creativity/Innovation 1. Higgins: Product Innovation, Process innovation, Marketing Innovation, Management Innovation

Much of the research into the methods was performed by the students in the class, rather than the professors. When researching innovative design methods, the students were asked to

1. Provide the context and characteristics of the method;
2. Give at least one illustration of the method;
3. State where it is being used;
4. Provide evidence that it works; and
5. Describe the method clearly.

This information was then documented via the form shown in Table 2, which is completed for the method of classic brainstorming. When completing the form, the students were also to propose a sample problem that the class would use the technique on to develop a list of concepts. This problem is also documented in Table 2, as is a brief summary of results.

Table 2. Example of the form used to document innovative methods; this is the form completed for classic brainstorming.

Method name	Classic brainstorming
Context and characteristics	A general creativity tool best applied in small groups when idea generation is important rather than technical problem solving. It produces results quickly, inexpensively, and in-house, which maintains secrecy.
Sources	Original: Osborn, Alex F. *Applied Imagination: Principles and Procedures of Creative Problem-Solving,* 3rd revised ed. New York: Charles Scribner's Sons, 1963. Current: many texts
Professional use	Many extant variations on the original exist although the original is still widely used and the most popular innovative method. Some variations derive from cultural differences when used overseas such as in Japan where it is very popular.
Evidence that it works	This is not provided in this example but it is very important. [Brainstorming is the most widely used innovative technique that implies it is at least somewhat effective.]
Method description	1. Arrange a meeting for a group of the right size and makeup (typically 4–8 people). 2. Write the initial topic on a flipboard, whiteboard, or other system where everyone can see it. The better defined—and more clearly stated the problem—the better the session tends to be. 3. Make sure that everyone understands the problem or issue. 4. Review the ground rules. o Avoid criticizing ideas/suspend judgment. All ideas are as valid as each other. o Lots, Lots & Lots—a large number of ideas is the aim, if you limit the number of ideas people will start to judge the ideas and only put in their "best" or, more often than not, the least radical and new. o Free-wheeling. Don't censor any ideas, keep the meeting flow going. o Listen to other ideas, and try to piggy back on them to other ideas. o Avoid any discussion of ideas or questions, as these stop the flow of ideas. 5. Have someone facilitating to enforce the rules and write down all the ideas as they occur (the scribe can be a second person). 6. Generate ideas—either in an unstructured way (anyone can say an idea at any time) or structured (going round the table, allowing people to pass if they have no new ideas). 7. Clarify and conclude the session. Ideas that are identical can be combined, all others should be kept. It is useful to get a consensus of which ideas should be looked at further or what the next action and timescale is. From Mycoted: http://www.mycoted.com/creativity/techniques/classic.php
Sample problem	A new solution for access (door) designs for consumer refrigerators
Group process	8 people engaged in the process for 10 minutes
Group solutions	A. Main parameters developed were 1. Number of doors : one, two, and three door designs 2. Symmetry or asymmetry of doors 3. Super-positioning of freezer and refrigerator doors 4. Opening doors vs. pullout drawers: either or both B. Number of solutions ~ 30 C. Group response to the methods favorable overall, but comments and critiques noted in the feedback file.

We note that some methods focus on problem recognition (e.g., checklists), some on problem identification (e.g., fishbone), and most on generating alternatives. Most individual and group processes can cross over (i.e., an individual method may be performed by a group); however, their efficacy greatly diminished and usually less effective.

The design process itself is a variable and best designed for a specific design problem in a specific context from a larger set of different tools and procedures. To the extent that a certain minimal structure occurs in almost all such processes, this structure may be relatively mundane in importance, being present tacitly almost everywhere a process is invoked. Process issues, then, may have more to do with a failure to adequately contextualize the problem than with the failure to adhere to some abstract concept of the process.

One of the important tasks of the educator is to teach students how to define a problem properly. Root–Bernstein, for example, argues that creativity and innovation consist of effective "problem-raising", not "problem-solving". [25] Formulating the problems in a manner so as to allow their solution is as important as finding solutions: poorly posed questions divert energy, resources, and ideas.

Similarly, innovative methods are not equally useful and applicable in all contexts; rather, they require careful selection based on the problem being addressed and its context. In addition, innovative methods should not exist as choices (i.e., one versus another), but as a series of strategies taken to generate a very large idea base from which to select options. It is quite likely that a given number of very similar ideas could be generated by many different approaches, each of which entailed a series of innovative methods. Although at some point enough is enough in terms of quantity, one question will always be whether certain methods tend to have qualitatively unique outcomes. Thus, trying to rank all methods by their relative effectiveness may neither be feasible nor particularly meaningful.

Further, we have found it relatively straightforward to generate new innovative methods. For example, customer needs assessment (CNA) focuses on increasing market share by finding what most customers want most of the time. We have used a similar process to document unique ideas rather than repeat ideas and thus turned CNA into a user-centered innovative design process [26] we call UCID (user-centered innovative design). On another occasion, we used geometrical variations to generate design options using refrigerator doors as an example (see Table 2): one, two, or three doors? freezer above or below? why not four doors, or five? This creative process then triggers proximal creativity: why not drawers instead of doors? why not glass doors so people could gaze without opening and wasting energy? Maybe we could even develop "meta-methods" which create sets of methods in given contexts.

Another observation we had was that students had a difficult time fully surrendering control and allowing the methods to take their course. Hence, one of our tasks was to make the engineering students more flexible, as becoming an innovator requires flexibility to identify new problems and to get away from the traditional ways of solving them [27].

4.2 SWIED

We have just established a Student Workshop for Innovative Engineering Design (SWIED). The idea is to develop a cadre of student experts in innovative design methods. SWIED will be a home for small groups of students researching innovative design methods and doing on-going innovative design projects, some of which will be for small businesses and industries and some may lead to start-up companies. One concept we want to deploy is that of a rapid response team that could provide timely service for small companies facing problems. We are certain of one thing: students can generate a lot of ideas and resources very quickly to inform decision making, even when not yet expert in all areas of analysis and detail design. Innovative methods have broad application from products to services even of a non technical nature. SWIED will also allow us to build our own experiential base.

5 Conclusion

The innovative engineering design course we have developed is inquiry driven and we expect to achieve an understanding of innovative design that synthesizes what is known in ways better than we have been able to find to date. For example, such a synthesis must describe the intersections between creativity tools and innovative engineering design and between innovative engineering design and innovation in the organizational context. We would also like to see better analytical categorizations of innovative methods, where and how they are used, and when and why they work—if they do. In addition, while we have found many good sources, we do not see obvious texts for a first (survey) course on innovative engineering design. Given a history of lauding the economic power of innovation and invention in U.S. culture, this may seem curious, but there are actually extensive literatures lauding both inventors and innovation as a valued business practice. Apparently it is something of an unquestioned cultural icon that we, and others, are beginning to see as researchable and learnable knowledge. As with engineering design education generally, we badly need a developmental model of learning innovative engineering design from novice to expert.

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