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Spurring Innovation in a Sustainable Manufacturing Course

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Abstract: A course on sustainable manufacturing has been developed and offered since 2010 at XYZ University. In the course, a comprehensive definition of manufacturing is adopted, covering not only material transformation processes but also any activities that are needed to support manufacturing such as product development and design, manufacturing systems design and operation, and supply chain systems design and operation. With such a comprehensive definition of manufacturing along with the comprehensive nature of sustainability, a radically different approach was necessary in order to effectively educate students on sustainable manufacturing. Innovation is emphasized and promoted throughout the course, as Albert Einstein succinctly put, "we can't solve problems by using the same kind of thinking we used when we created them."

Students have numerous opportunities to devise their innovative solutions while they develop new sustainable products, starting from ideation, to concept generation, to product design, to selection of manufacturing processes, and ultimately to fabrication of physical prototypes. Therefore, how to spur innovative minds among students has been the main challenge of the course. Four main methods have been devised and adopted to spur innovation: (i) by explaining the criticality of sustainability issues, (ii) by sharing existing and conceived examples and solutions, (iii) by providing practical methods, and (iv) by imposing thoughtful constraints.

This paper presents the learning objectives, contents and approaches of the course, how those four methods have been implemented in the course, and the preliminary analyses of the effectiveness of those methods in spurring students' innovation potential as exhibited in their learning.

1. Introduction

Sustainability is one of the most pressing issues that the present generation beings need to address[1] Since the problem is global, complex, and comprehensive, all the members and communities in the world must be engaged in and contribute to addressing the issue. The engineering community, particularly manufacturing engineering community has important roles to play[2,3,4]. However, the challenge of educating engineering students to effectively addressing the grand sustainability issues requires truly innovate pedagogy. As Albert Einstein succinctly put, "we can't solve problems by using the same kind of thinking we used when we created them."

A course on sustainable manufacturing has been developed and offered since 2010 at XYZ University. In the course, a comprehensive definition of manufacturing is adopted, covering not only material transformation processes but also any activities that are needed to support manufacturing such as product development and design, manufacturing systems design and operation, and supply chain systems design and operation. With such a comprehensive definition of manufacturing along with the comprehensive nature of sustainability, a radically different approach was necessary in order to effectively educate students on sustainable manufacturing.

Innovation is the key that has been emphasized and promoted throughout the course. Students have numerous opportunities to devise their innovative solutions while they develop new sustainable

products, starting from ideation, to concept generation, to product design, to selection of manufacturing processes, and ultimately to fabrication of physical prototypes. How to spur innovative minds among students has been the main challenge of the course. Four main methods have been adopted to spur innovation:

(i) by explaining the criticality of sustainability issues,
(ii) by sharing existing and conceived examples and solutions,
(iii) by providing practical methods, and
(iv) by imposing thoughtful constraints.

When students are educated about the severity of issues surrounding sustainability, they become motivated to come up with innovative ideas and solutions. Real product examples provide students with a sense of achievability and in turn trigger additional product ideas. Practical methods to become more innovative and creative enable students to start generating solutions immediately. As numerous innovative companies testify in recent years, imposing certain types of constraints can be an effective strategy to nurture an innovative culture.

2. Course content

New course on sustainable manufacturing has been developed as a part of campus-wide sustainability initiative at XYZ University. It is an elective course that upper level undergraduate students as well as graduate students can take, although the majority of students who have taken this course have been graduate students. The course is offered through the Department of Mechanical and Aerospace Engineering, but open to any student from any engineering discipline. It is a 3-credit course (three hours per week for 14 weeks) offered once a year. The schedule of the current course offering is shown in Figure 1.

In the course, students learn

(i) the vision of sustainable manufacturing and product development, and its relation to larger societal issues,
(ii) processes, techniques and tools for developing sustainable products,
(iii) sustainable manufacturing processes and systems,
(iv) how to measure sustainable manufacturing practices, and
(v) effective strategies for deploying sustainable manufacturing.

The course consists of four components that are interrelated:

(i) lectures on sustainability and sustainable manufacturing,
(ii) lectures on new product development,
(iii) discussion on case studies and
(iv) students' semester-long project on developing new sustainable products.

	Lectures	*Cases*	*NPD Projects*
Session 1	Introduction		Identification of New Product Opportunities
Session 2	Sustainability in Business	Sustainability at Millipore	Presentation: Opportunities
Session 3		SweetWater	Presentation: Product Ideas Customer Needs
Session 4			Presentation: Needs Analysis Product Specifications Concept Generation
Session 5	LCA (i)		Presentation: Product Concepts Concept Selection
Session 6	Product Design for Sustainability	Cradle-to-Cradle Design at Herman Miller	*Project Consulting*
Session 7	LCA (ii)		*Project Consulting*
Session 8		Team New Zealand	Concept Testing & Prototyping
Session 9			Presentation: Project Progresses *Project Consulting*
Session 10	LCA (iii)		*Project Consulting*
Session 11	Sustainable Manufacturing Processes		*Project Consulting*
Session 12	Lean Manufacturing		Presentation: Prototypes
Session 13	Social Entrepreneurship	Ashoka: Innovators for the Public	*Project Consulting*
Session 14	Conclusion		Final Presentations

Figure 1. The course schedule

The lectures are scheduled so that knowledge and skills on sustainable manufacturing and new product development can be built progressively and timely for students' projects. For example, background and motivations for study are given in the first lecture, followed by a lecture on generating opportunity ideas for new products. Then, an assignment due the following week is given out for students to generate sustainable new product ideas. Real-life cases provide a context for class and online discussions as well as corresponding assignments.

The semester-long projects on developing new sustainable products are the most important part of students' learning. In carrying out the projects, students are required to apply sustainable practices as much as possible in every step of the product development process, including but not limited to:

- solicitation and interpretation of customer needs;

- design for sustainability, recycle, reuse;
- adoption of sustainable materials;
- adoption of sustainable manufacturing processes;
- design of sustainable manufacturing systems and sustainable supply chains;
- adoption of alternative energy sources;
- justification of lifecycle costs;
- use of LCA to systematically understand the impact of each decision or trade-off decisions.

Regarding learning outcomes, students are expected to do the followings at the end of the course.

- compare and evaluate alternative manufacturing processes in terms of energy and materials consumption;
- develop a new product addressing sustainability issues;
- describe pros and cons of alternative manufacturing systems and supply chains on sustainability;
- compare and evaluate alternative energy sources to manufacture a product;
- conduct a life cycle assessment (LCA) on a product;
- function better in a multi-disciplinary team;
- adopt a new behavior to address sustainability issues.

The course has been received very well by students and is one of the most subscribed elective courses in the department. Numerous students won campus-wide innovation competitions using the products they developed in the course. At least one team was on route to establishing a start-up company using their product.

One observation over the years that might contribute to hampering students' becoming more innovative is the course offer timing. This course has been offered in Spring semester when cold weather dominates the region. Influenced by the weather, significant number of initial ideas have been related to winter weather. It would be interesting to see any changes if the course is offered in Fall semester in future.

3. Ways to spur innovation and creativity

In order to simulate and foster students' ability to become more innovative and creative, numerous methods to spur innovation have been attempted and tested. Four main methods proven to be effective are:

(i) by explaining the criticality of sustainability issues,
(ii) by sharing existing and conceived examples and solutions,
(iii) by providing practical methods, and
(iv) by imposing thoughtful constraints.

Figure 2 summarily presents how these four methods are adopted in various stages of students' product development projects.

Figure 2. Use of the four methods in the course

3.1. By the criticality of the issues

As the course begins, a succinct definition of sustainability, "to meet the present needs without compromising the ability of future generations to meet their own needs" is given. As most of students are young, this definition is eye-opening by triggering thoughts beyond their own existence and plans. The critical nature of and pressing needs for addressing sustainability issues are then gradually explained to students. Lectures include various statistics, findings, declarations, and examples illustrating critical sustainability issues that we face and solve immediately. The lectures are presented along with the four dimensions of the problems: (i) finite supply of key natural resources, (ii) environment and climate change, (iii) increasing world population, and (iv) cultural and political factors. Students learn that many of natural resources are not as abundant as they used to think and human beings now have to come up with solutions for rapidly depleting critical resources. Students also discuss and understand that although there are still debates going on regarding details, impacts of recently accelerated changes in environment and climate are real and urgent. Students are typically alarmed by the dramatic increase of world population during the recent years and start pondering the real issues with sustainability. Discussions also occur regarding the global nature of sustainability that leads to indifference and blind-sightedness for those who do not experience immediate consequences yet. Once students understand the criticality and urgency of sustainability issues, they are usually more than eager to do something about the sustainability.

Students then are engaged in case discussion for real companies which have actually implemented numerous changes to address the sustainability issues. In addition, students are provided with trend

and results from the industry that proactive firms indeed consider addressing sustainability as their new business strategy. Changes happening in industry toward sustainability are then discussed. Typical responses toward sustainability from the industry leaders used to be from negative to reluctance, citing additionally needed expenses and becoming less competitiveness. However, recent studies and interviews from the industry clearly demonstrate the change in the sea toward embracing sustainability as one of their important business strategies. After presenting these findings, students are told that the course will focus on what they can actually do rather than just discussing sustainability issues.

New product development for sustainability is then introduced as the main activity of the course. Although most of the lectures throughout the semester are covering various aspects of new product development, a wide range of areas that new product development affects are explained in the beginning. As students develop the understanding of the notion of lifecycle, the concept of lifecycle assessment (LCA) is also introduced. In the end, students appreciate the need for innovation throughout the entire lifecycle of product development processes.

3.2. By providing examples

One of the myths that students have regarding new products is that any new product must be completely different from what exists and the complexity and scale of developing it must be extraordinary. This notion tends to discourage them from actually developing new products. In order to correct this misnomer and encourage students to excel in their projects, many real product examples are shown to students in the first class.

Some of the example products are simple and derivatives of products with which students are familiar. Seeing such examples are also important since students need to come up with new product ideas that can be accomplished within a semester's time frame. Some of the promising product ideas have been suggested as concepts but not yet realized. However, these concepts are realistic so can stimulate students' imagination.

Over years, students' projects have accumulated. With the permission of the students who developed the projects, some of them are also shown to students. It turned out that showing these past projects is a very effective way to stimulate students' innovative minds. First, students are convinced that they can also accomplish something significant during the semester. Second, some students who are especially motivated, competitive, and ambitious wish to raise the bar even higher. In other words, the standard set by the past projects becomes a minimum level of expectation for the current cohort of students. Third, the past projects can play a guideline for overly ambitious ideas. Students learn what kinds of projects ideas didn't end up for various reasons.

At the same time, students are given with failed product examples in which noble idea of sustainability is upheld. Yet they failed because fundamentals of product development efforts have been ignored such as understanding customer needs. In this way, students are able to develop balanced view on meeting future generations' needs as well as still satisfying present needs.

3.3. By providing practical methods

Researchers report that being creative is not necessarily limited to genius or those who can get

inspirations. Practical ways to become creative and innovative are presented so that students can adopt and exercise them in their projects.

They include systematic ways of documenting users' needs and complaints, interviewing lead users, and understanding trends in lifestyles, demographics and technology, among others. Some general principles such as "increasing variance" and "generating large quantity of ideas" are also presented. In addition, appropriate real examples are shown to illustrate how to use practical tips that scholars have suggested. Those tips include 'suspend judgment,' 'generate many ideas,' 'welcome infeasible ideas,' 'make analogies,' 'wish and wonder,' 'use related as well as unrelated stimuli,' 'set quantitative goas,' 'use the galley method,' 'bring old ideas to those who have never seen them before,' 'find new uses for old ideas,' and 'invent new combinations of existing ideas.'

After getting lectures of the practical methods with real examples with stories, students are able to build their confidence in creating innovative solutions at various stages of their product development processes.

3.4. By imposing constraints

Casual understanding of desirable environments where innovation and creativity can thrive is those that are open-ended, unstructured, and free from limitations such as unlimited resources, unlimited time, and unlimited freedom. However, the theme that "innovation thrives under constraints" has been increasingly adopted and practiced in corporations known for their innovation. This theme has also been researched in some disciplines and the results are in supportive of it[5,6,7,8].

Numerous constraints are imposed in the course with the intention of spurring innovation in students' projects. They include selling price of their new products ($50), limited complexity of product, specific deliverables in each week, month and semester, and most importantly the constraint of addressing sustainability. As students' understanding of sustainability grows and deepens, the sustainability become major constraints under which students exhibit their innovation.

Contrary to initial concern that such sustainability constraints may become a hindrance to innovation, assessment results presented in the next section suggest that they play a stimulus.

4. Learning outcomes assessment

The learning outcomes are assessed throughout the progress of student projects. Every week, students submit assignments on their projects, case studies, or problems. Student progresses on the expected learning outcomes are being monitored each week and feedbacks are provided to students. In addition, quality of student works and presentation skills are assessed. Individual contributions to teamwork are also evaluated through self-evaluation, peer-evaluation and instructor-evaluation.

A comprehensive rubric has been developed to assess creativity as shown in Table 1. The rubric assessment results from the past years' student projects suggest that students' abilities to becoming innovative and creative are enhancing as the course progresses.

	Not yet evident	Emerging	Expressing	Excelling
Score	1	2	3	4
Generating Ideas				
Fluency	have no ability to generate and explain the idea easily and accurately	starting or trying to generate and explain the idea easily and accurately	basically have the ability to generate and explain the idea easily and accurately	have excellent ability to generate and explain the idea easily and accurately
Originality	idea is a popular/common existing product	idea is existing in as concepts or unpopular yet	idea is solving problems in an innovative way but not really practical	idea is totally novel and make sense
Elaboration	don't know how improve ideas	have rough feeling on improving idea but don't know how to	have guidelines in mind to refine and improve on idea in some ways	improve the idea in clear aspects
Digging Deeper Into Ideas				
Analyzing	don't know how to analyze the function, customer and design of idea	try to roughly analyze the function, customer and design of idea	analyze the function, customer and design of idea in clear structure with different aspects	analyze the function, customer and design of idea in clear structure with different aspects, with clear aim
Synthesizing	fail to combine a number of ideas/customer needs/technology into one product/idea	attempt to combine a number of ideas/customer needs/technology into one product/idea but not yet succeed	able to combine a number of ideas/customer needs/technology into one product/idea	excellent to combine a number of ideas/customer needs/technology into one product/idea
Reorganizing or redefining	unable to improve the way idea/design/concept is organize or defined along project progress	attempt to improve the way idea/design/concept is organize or defined but hardly worked along project progress	able to improve the way idea/design/concept is organize or defined along project progress	excellent to improve the way idea/design/concept is organize or defined along project progress
Evaluating	unable to expect the potential use/cost/market, etc. of idea/concept	aware of assessing the potential use/cost/market, etc. of idea/concept but hardly worked	able to assess the potential use/cost/market, etc. of idea/concept	assess the potential use/cost/market, etc. of idea/concept and improve the performance
Seeing relationships	unable to see relationships among customer needs, market, design feature, cost, etc.	aware of seeing relationships among customer needs, market, design feature, cost, etc. but not logical	able to define relationships among customer needs, market, design feature, cost, etc.	see relationships among customer needs, market, design feature, cost etc., and improve design from it
Openness and Courage to Explore Ideas				
High levels of curiosity	show no evidence of curiosity	have curiosity in limited aspects	have high levels of curiosity in multiple aspects	excellent to maintain high levels of curiosity in developing, marketing, technology and research
Capacity for fantasy and imagination	show no evidence of fantasy or imagination	attempt to have fantasy or imagination for innovation	have fantasy or imagination for innovation in multiple aspects	have excellent capacity for fantasy and imagination
Tolerance for ambiguity	unable to tolerant uncertainty or inexactness in idea/design/concept	attempt to tolerant uncertainty or inexactness in idea/design/concept	staying in uncertainty, or staying with the question, despite the discomfort of not knowing the answer	staying in uncertainty, or staying with the question, and later come up with innovative ideas
Openness to experience and ideas and not frightened by the unknown	Unwilling to open to experience and ideas, stay out of unknown areas	attempt to open to experience and ideas along with unknown areas	open to some aspects of experience, ideas or other unknown areas	Open to experience and ideas, willing to dig into unknown areas
Listening to One's "Inner Voice"				
Awareness of creativeness	unaware of keep being creative in project	roughly aware of being creative in project	attempt to be creative in project in research methods, result analysis, design and more	creative in research methods, result analysis, design and more
Independence of thought	cannot keep independent thinking	attempt to keep independent in thinking	keep independent in thinking in most aspects of project development	keep independent thinking with innovative outcome

Table 1. A rubric for assessing innovativeness and creativity

A quantitative analysis has been devised to measure students' achievements related to the research theme. The past six year's student projects have been evaluated using the developed rubrics (Table 1). Some results are shown in Figures 3-10. These data clearly demonstrate positive trends in students' innovativeness and creativity over three stages in the course.

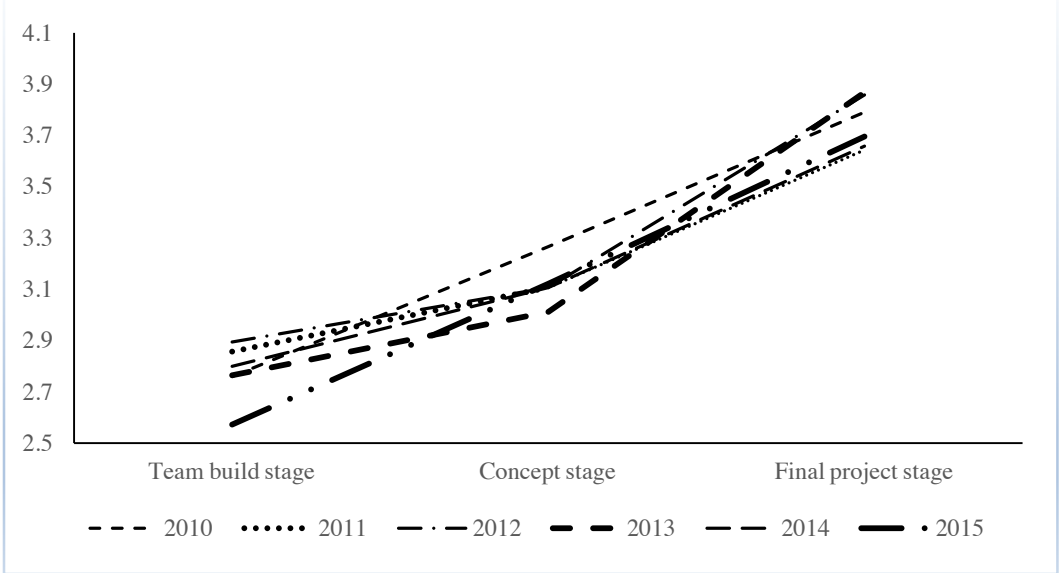

Figure 3. Overall creativity evaluation, 2010-2015

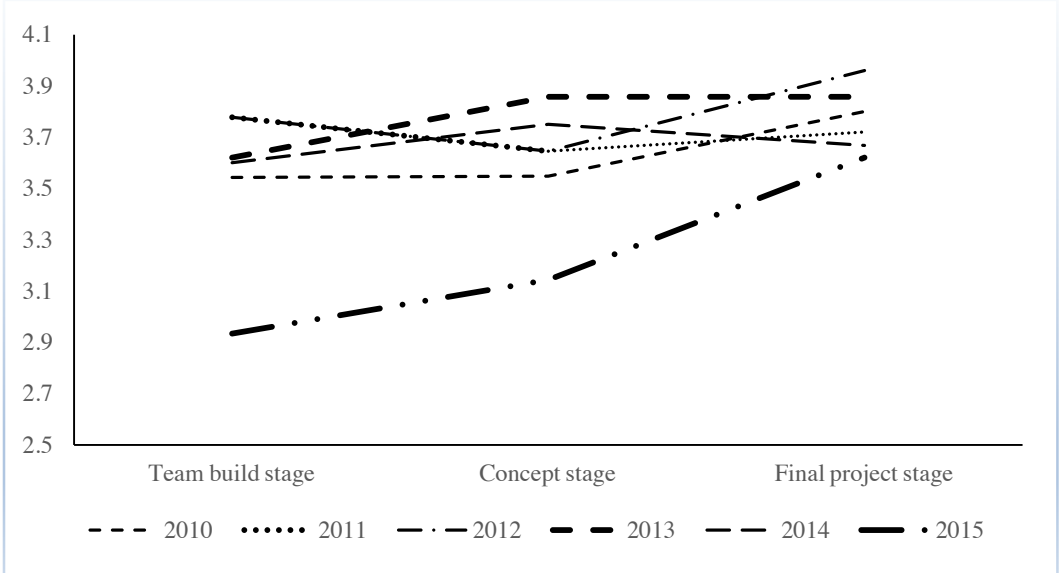

Figure 4. Generating Ideas, 2010-2015

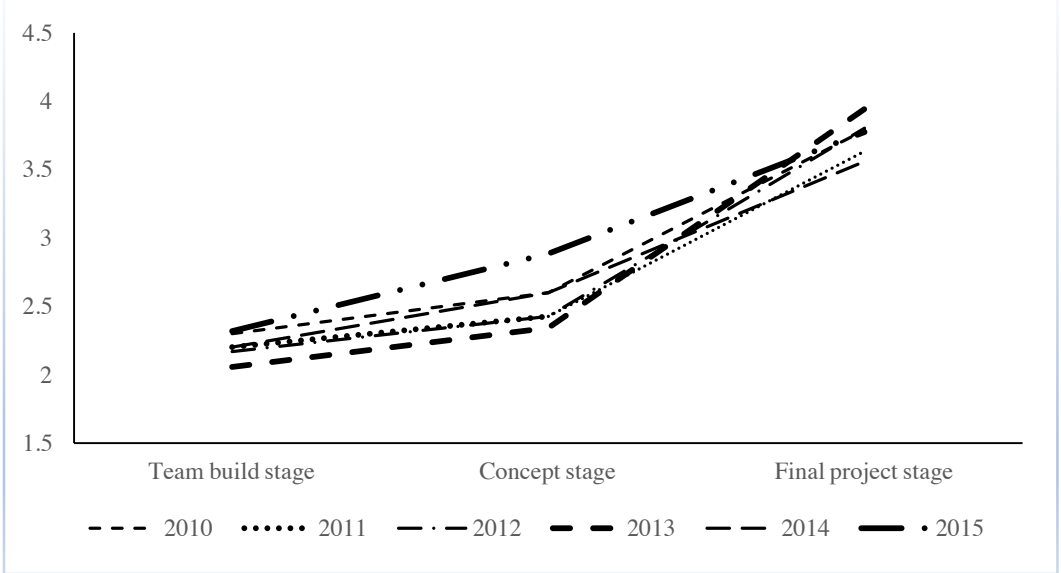

Figure 5. Digging Deeper into Ideas, 2010-2015

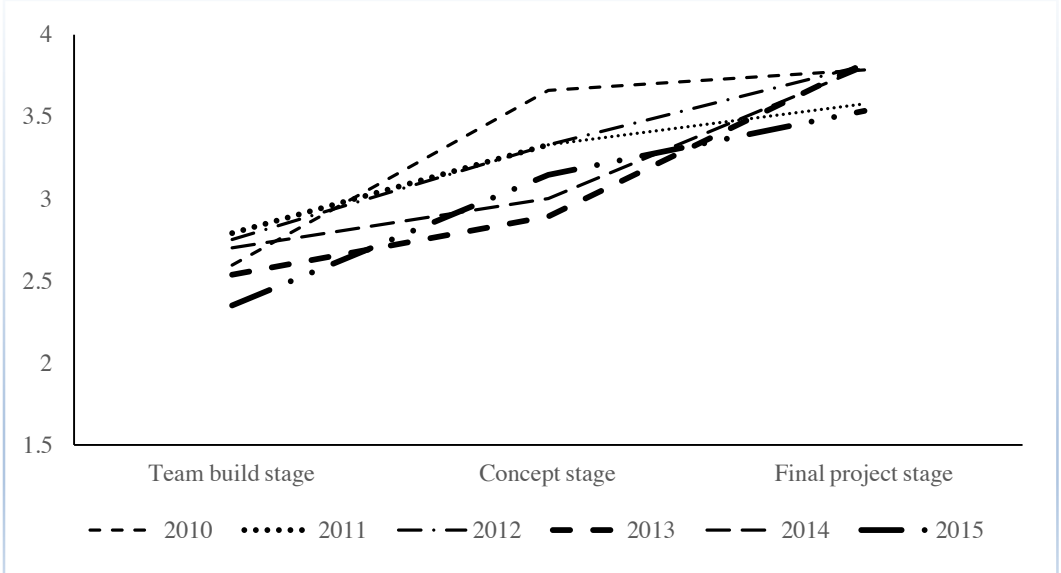

Figure 6. Openness and Courage to Explore Ideas, 2010-2015

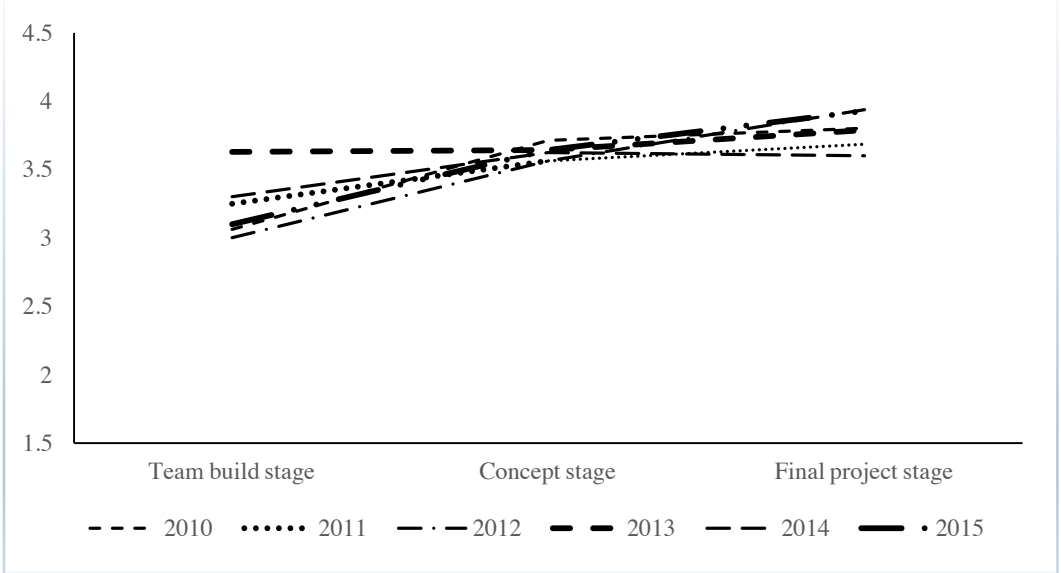

Figure 7. Listening to One's "Inner Voice", 2010-2015

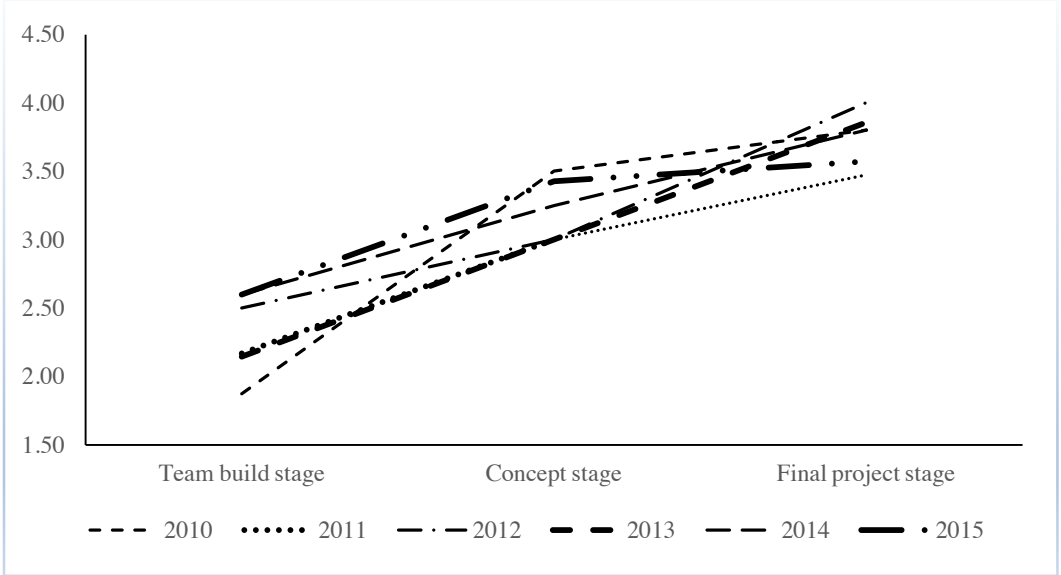

Figure 8. Capacity for Fantasy and Imagination, 2010-2015

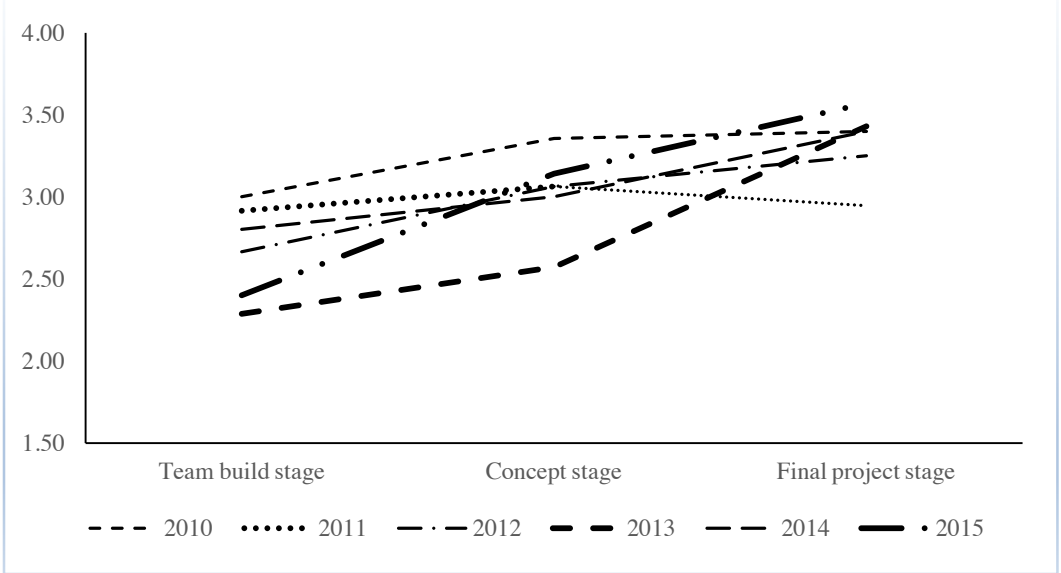

Figure 9. High Levels of Curiosity, 2010-2015

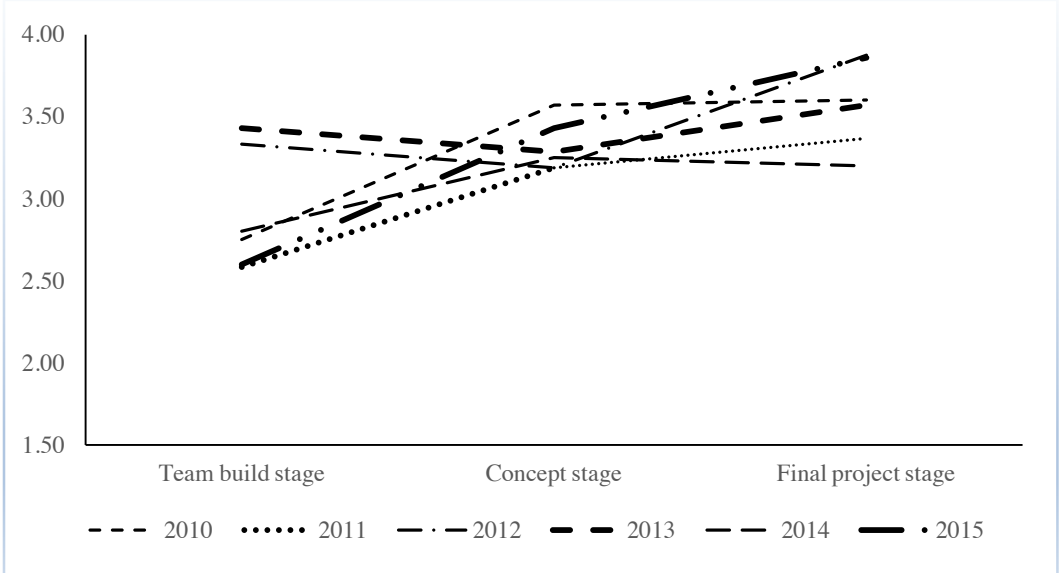

Figure 10. Awareness of Creativeness, 2010-2015

5. Discussion and conclusion

Engineering projects are typically thought-provoking, enjoyable and interesting, while being practical, challenging and educational[9]. By carrying out new sustainable product development projects in a sustainable manufacturing course, students cultivate understanding of sustainability issues, knowledge of sustainable manufacturing and design, and skills for product development. Therefore, the key success factor in the course is innovation skills[10]. In order to spur innovation in

students' projects, the four methods presented in this paper have proved to be effective as observed by the instructor, assessment results, and by the fact that some projects won innovation competitions.

To assess some aspects of innovation and creativity, a comprehensive rubric was developed. Results from the past student projects show improvement of creativity in generating ideas, digging deeper into ideas, openness and courage to explore ideas and listening to one's "inner voice". The abilities of analyzing, synthesizing, reorganizing or redefining, evaluating, and seeing relationships have effectively improved, indicating the effectiveness of the four methods employed in the course.

For future work, additional assessment methods are being devised and will be used in future courses. Another related yet different research topic is to investigate factors hampering innovation in student projects. While this paper focuses on positive factors for becoming innovation, better understanding of negative factors will shed additional light on this critical issue.

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