122nd ASEE Annual Conference & Exposition
June 14 - 17, 2015
Seattle, WA
Making Value for Society
Paper ID #12760

Systems Engineering Entrepreneurship Modules Across Aerospace Engineering Curriculum

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Abstract

"Systems engineering" is concerned with the effective management of complex systems over the entire product lifecycle. Good systems engineering practice is essential for the effective design, fabrication, testing and operation of complex systems, such as spacecraft and aircraft.
However, teaching good systems engineering to undergraduates is often viewed as either impossible (because "true" systems engineering capabilities must be developed in real, professional settings) or impractical (because it requires sophisticated tools that are best covered at the Masters level). While we do not dispute that years of practical experience and solid technical fundamentals are necessary to master the concepts and application of systems engineering, we believe that undergraduates are capable of learning some of the fundamental tools, and applying them to relevant projects.
We modified a five-course focus area in the Department of Aerospace and Mechanical Engineering of Saint Louis University to introduce systems-engineering modules with an entrepreneurship mindset. The sequence spans the first three years of undergraduate studies in the department, and the students' learning will be further demonstrated in the capstone design course sequence. And while these modules will be tailored to space-systems applications, we will show that these systems engineering modules can be beneficial to a wider range of engineering majors.
We created ten modules that introduce the field of systems engineering as it applies to space missions. Students learned key topics related to spacecraft and mission design, including requirements development, trade studies, the project life cycle, system hierarchy, risk analysis, and cost analysis. The concepts presented in this course were demonstrated with examples from recent space missions. The students were exposed to concepts regarding team organization, design fundamentals, and work ethics. These topics are in preparation for the capstone design course experience. They learn that systems engineering is iterative and develop judgment that will allow them to compare and evaluate engineering alternatives. They learn to discuss systems engineering methods and processes as well as engage in systems thinking. Material covered in lectures and tutorials is complemented by hands-on laboratory exercises and real-world examples of space missions, which will be used to illustrate the use of the analytical techniques and demonstrate the relevance of the material.

Introduction

Faculty members across the engineering disciplines are aware of the importance of Systems Thinking capability of engineering students, yet find it very hard to implement the same concepts in a meaningful way in the curriculum. There are enough literature published in this and other conferences highlighting the fact that Systems engineering educators are struggling to address workforce development needs required to meet the emerging challenges posed by increasing systems complexity[1] and the widening gap in systems engineering expertise in the workforce. There is a parallel need to develop "entrepreneurally-minded" engineers (i.e., those who can identify opportunities to create or improve products, and to implement plans to capture such opportunities). Engineering graduates need the capability and competency to *efficiently* and *effectively* engineer innovative systems that satisfy customer and user operational needs, within budget, schedule, technology, and risk constraints. The solutions developed must incorporate societal impacts as well as regulatory constraints. As evidenced by our definitions, there are strong overlap between entrepreneurially-minded engineering and sound systems engineering practice. Systems Engineering

principles and practices are getting more critical in current global business environment since engineering and business projects and works require the collaboration with global implications. Universities, colleges, government, and industry often create or procure Systems Engineering courses that may provide necessary but insufficient content for educating and training engineers in concepts, principles, and practices required to achieve system, product, or service development success. At the same time there has been much discussion in recent years about the contents of Systems Engineering curriculum with particular emphasis to the question of how to introduce young or inexperienced students to Systems Engineering concepts[2, 3, 4, 5, 6, 7]. The overall consensus is to introduce students to these concepts through hands-on experiential learning experience. Several innovative pedagogical approaches have been presented to develop systems engineering curriculum[8], introducing fundamentals of systems engineering principles to freshmen engineering students through group activities[9], embedding systems engineering practices into courses that are systems engineering oriented[10], as well as a non-academic perspective of the importance in systems engineering competency for future engineering students[11], and the importance of teaching innovation and entrepreneurship through specific courses and/or changes to the curriculum including more team based and problem based activities to instill entrepreneurial mindset[12, 13]. However, teaching good systems engineering to undergraduates is often viewed as either impossible (because "true" systems engineering capabilities must be developed in real, professional settings) or impractical (because it requires sophisticated tools that are best covered at the Masters level). While there is no dispute that years of practical experience and solid technical fundamentals are necessary to master the concepts and application of systems engineering, the authors believe that undergraduate students are capable of learning and practicing some of the fundamental tools, and applying them to relevant projects. To this end, students in many of the traditional engineering curriculum experience applying systems engineering concepts in a two sequence senior capstone design course. Even though some programs have introduced systems engineering concepts in freshman or sophomore courses, there is no evidence of continuity in multiple courses in every year across the curriculum, with students getting seldom systems engineering exposure in course during the first three years of their curriculum.
The paper discusses the developed modules that will give students an initial exposure to the field of systems engineering as it applies to aerospace vehicles, while students in freshman year experience non-aerospace engineering projects as well. Students will learn key topics related to aircraft design, spacecraft and mission design, including requirements development, trade studies, the project life cycle, system hierarchy, risk analysis, and cost analysis. The concepts presented in this course will be demonstrated with examples from recent aircraft and spacecraft missions. The students will also be exposed to concepts regarding team organization, design fundamentals, and work ethics. These topics help students prepare for the capstone design course experience. They will learn that systems engineering is iterative and will develop judgment that will allow them to compare and evaluate engineering alternatives. They will learn to discuss systems engineering methods and processes as well as engage in systems thinking. Material covered in lectures and tutorials will be complemented by hands-on laboratory exercises and real-world examples of aircraft and space missions, which will be used to illustrate the use of the analytical techniques and demonstrate the relevance of the material.

Entrepreneurial Mindset

In terms of student learning outcomes, the term "Entrepreneurial Mindset" goes beyond someone becoming an entrepreneur and creating or starting a business venture. This is also reflected in what industry needs as skillset in future workforce. Thought sound technical background and understanding is essential to having a successful engineering career, engineers find remarkable success when they couple technical understanding and skills with a mindset to create extraordinary value.

Entrepreneurial Mindset, as defined by Kern Engineering Entrepreneurship Network (KEEN), is three C's: **C**uriosity, **C**onnections and **C**reating value. It is the ability to exercise curiosity about the surrounding world; identify opportunities with market potential; developing solutions in terms of value creation; assess risk and learn how to mitigate them; persist through and learn through failure; identify opportunities to create extraordinary values.

Skills associated with the entrepreneurial mindset that attributes student learning experience are ability for effective communication, teamwork, awareness and thorough understanding of customer needs and requirements, persistence through failure, systems thinking with creativity and innovation, project and personnel management skills[14].

The qualities or attributes of "entrepreneurial mindset" described above are very well aligned with systems thinking and practicing systems engineering principles as shown in the Table 1 below.

Curriculum Modules

The curriculum modules were developed without eliminating or reducing the actual course content, rather the concepts of systems engineering principles were introduced to the existing projects with minor modifications, like; team based hands-on exercises, discussions concerning the system engineering implications for each project and experiencing entrepreneurial thinking. In addition, by improving some of the project methods using a system engineering approach, the instructors have observed reductions in time previously spent in frustration by students approaching projects in a non-systematic way, while improving the quality of their work.

Modules were developed to introduce systems-engineering-focused entrepreneurship modules across five courses in our aerospace engineering program and selected technical electives.

1. AENG/MENG 101 – Introduction to Aerospace and Mechanical Engineering (required)
2. AENG/MENG 102 – Introduction to Computer Aided Design (required)

} Freshman Year

3. AENG 200 – Introduction to Aeronautics and Astronautics (required)

} Sophomore Year

4. AENG 322 – Astrodynamics (required)
5. AENG 498 – Space Mission Analysis and Design (elective)

} Junior Year

These undergraduate modules will introduce key concepts through hands on-experiences, culminating in a dedicated 3-credit-hour course in the second semester of junior year. The project outcomes are listed in Table 1, along with their corresponding KEEN "Entrepreneurial Mindset" Learning Objectives.

Table 1. Outcomes

Systems Engineering Outcome	Corresponding KEEN Program Learning Objective
S1: Students will be able to develop mission or needs statements	**K1:** Construct and effectively communicate a customer-appropriate value proposition Identify opportunities to **create value**
S2: Students will perform requirements flowdown, converting mission statements to goals, and allocating requirements to systems and subsystems	**K2:** Apply critical and creative thinking to ambiguous problems Integrate information from many sources to gain insight (Curiosity, Connections)
S3: Students will create a validation & verification process for a given set of requirements	**K3:** Effectively manage projects and apply the commercialization process Apply systems thinking to complex problems (Connections – assess and manage risk)
S4: Students will articulate how the competing factors of cost, schedule, performance and risk are manifested in the development of space missions	**K4:** Construct and effectively communicate a customer-appropriate value proposition Convey engineering/technical solutions in economic terms (Creating Value)
S5: Students will be able to identify mission design drivers, and their impact on cost, schedule, performance and risk	**K5:** Evaluate technical feasibility and economic drivers Examine societal and environmental needs (Connection)
S6: Students will perform trade studies to identify mission concepts that best satisfy the functional and program constraints	**K6:** Persist through and learn from failure Team work and effective communications (Curiosity)
S7: Students will demonstrate the ability to use modern systems-engineering tools to complete a project within the constraints	**K7:** Project management – completing commitments in timely manner Apply and pursue ethical practices (Connection)

Example Modules
AENG/MENG 101/102: Introduction to Aerospace and Mechanical Engineering and Computer Aided Design (Freshman year)

- **Importance of Specifications** (Hands-on): The class is divided into teams of four to six; half the teams are designate Group A and the rest is Group B. Each team is tasked with building a functional object (tower, bridge, mechanism). However, Group A designs one object and creates the instructions for Group B, and vice versa. Other than the written instructions, no communication is allowed between the teams. (The directions will not explain what is being built, only how to build it.) Each object is evaluated based on performance, and the teams report on the limitations and benefits of having clear specifications.
- **Importance of Clear Mission Objectives** (Group design): The class is divided into (different) teams of four to six. Each team is given the same general objective, and asked to design a concept for a system, part or process to meet that objective. However, each team is given slightly different

wording of the objective. For example, one team could be tasked with designing a "pen that will work in zero gravity" and another with designing a "writing implement" (i.e., a pencil). The results of each design are compared against the wording of the objective, and the class will identify which wording was best, and why.

• **Systems Engineering Video: Joint Strike Fighter Program – Boeing vs Lockheed Martin:** The class watches the video of the JSF competition between The Boeing Company and Lockheed Martin to learn the systems engineering approaches and process followed by the two competitors. They assess and learn why one of the competitors won the competition and the other did not. A classroom discussion of the importance of systems engineering process in the competition to pursue the contract from DoD.

This activity leads the students to understand the systems engineering issues from a company/organization perspective leading them to consider the issues of business case, market competition and technical problems in systems design as well as the value creation for systems design and implementation.

Systems Engineering Outcome: S1, S2, S5, and S7
KEEN Student Outcome: K1, K2, K5, and K7

Example Modules for AENG 200: Introduction to Aeronautics & Astronautics (Sophomore year)

• **Rocket Building under Constraints** (Hands-on): Student teams are given a model rocket kit and additional kit parts, and tasked with modifying the rocket to meet a performance object (e.g., maximizing the payload, maximizing height, closest touchdown to target). The teams compete and a nominal prize awarded. The next week, the teams repeat the project, but with a new program-level constraint. For example, the teams could be given half the allotted time, or their score is reduced by the cost of the supplies used, or they are forced to use nonstandard parts because the "supplier" has gone out of business. In the debriefing, the class will discuss the effects of real-world program constraints on mission performance, and identify strategies for mitigating their effects.

- **Objective:** Launch a light-bulb "astronaut" to a height of more than 50 feet and safely recover them. ("Safe" means that the light bulb lights up after landing)
- **Constraints**: The two main constraints in engineering are time and money. Use your time wisely, because you only have this class period to submit a budget, design/build the rocket, and fly. You will be making your own budget for the project with the allotted $100. Cost is an important aspect for projects throughout all of engineering.

• **Failure** (Case study): Students perform a case study in aircraft or space mission failure, identifying systems engineering challenges (or mistakes) that contributed (or caused) the spacecraft mission to fail and/or aircrafts

Objective: Recognize and understand the trade-offs between budget, schedule, performance and risk, including the consequences of these trades.
Examples:

- Boeing 787 Dreamliner production delay due to project management
- Boeing 787 Dreamliner Battery Failure Case and it's implications
- X-33 Reusable Launch Vehicle
- NASA Dart Mission

• **Civilian Unmanned Aerial Systems:** This activity challenges the students to explore critical, crosscutting issues of civilian (urban) UAS systems performing at high level of safety and reliability.

Investigate specific market opportunities, identify technological challenges, regulatory issues and other barriers (such as social issues, legal hurdles etc.) that must be overcome.

- **Speculative Case Study: Boeing Vs Airbus:** In the early part of the 21st century, there was a heated competition between Airbus and Boeing about the future of commercial air travel. Each company held a very different vision for the future of air travel (broadly speaking: hub-and-spoke vs. point-to-point), and each company designed an all-new aircraft to secure that vision. In this Speculative case study, students learn about the original design decisions leading to the A380 and the 787, and then perform their own research to assess the relative merits of each business approach (and technical implementation).

Objective:

- Investigate the market
- Evaluate technical feasibility, customer value, societal benefits and economic viability
- Communicate engineering solution in economic terms
- Validate market interest
- Technical: Identify the effect of basic aircraft design parameters (e.g. aspect ratio, Mach number) on the size/shape/performance of these large commercial aircraft.

Systems Engineering Outcome: S3, S4, S5, and S6
KEEN Student Outcome: **K3, K4, K5, and K6**

Example Modules for AENG 322: Astrodynamics (Junior year)

Design for Operability (Hands-on). The purpose of this module is to show that the customer value proposition is important even in space systems. This is accomplished by contrasting the typical design approach (optimizing a spacecraft for launch) and a customer-focused approach (optimizing for operation of the spacecraft after launch). Student teams will operate a robotic device across a radio link (e.g., drive a rover through an obstacle course), but with a very limited set of sensors. It is expected that the performance will be poor and the experience frustrating. Next, they are given the opportunity to perform the same task with an expanded set of sensors. As the last part of the exercise, students assess the costs and benefits of the added sensors; the sensors added weight, complexity and schedule to the rover; they will need to create the customer value proposition that validates (or invalidate) the design choices.

- **Creating the Value Proposition** (Group presentation):

The purpose of this module is to give students experience in creating innovative value proposition. Using SMART (Specific, Measurable, Attainable, Realistic, Time-bound) strategy, student teams are given a challenge to design a mission idea that would enhance their organization (whether federal or private industry). Specifically, three components are addressed:

- Technical Fundamentals: Student teams will research the current TRL levels of various technical projects relevant to their project; combine them to suit their mission. They should identify "who is the customer" and what specific "customer requirements" that their project is addressing
- Business Plan: Develop a business plan addressing how their project would increase the value of their organization. The team should present management infrastructure, detailed project timeline and the projected outcomes of their project.
- Societal Values: Teams will address the societal impact of their project

The student teams will create posters and give a "3 minute" elevator pitch to potential investors at the end of the semester.

- **Systems Engineering Example "Spider":** The "Spider" episode from HBO's *From the Earth to the Moon* is shown in class. This episode dramatizes the process by which Grumman designed, built, tested and operated the Lunar Module in support of the Apollo program. Using a guided assignment, students identify examples of the spacecraft design process; identify technical/program challenges that occurred and the chosen solutions. They assess the impact of the decisions made under schedule and budget constraints. o Example question: The NASA people spent a lot of time talking about how to organize the moon landing (think "Lunar Orbit Rendezvous"). Very briefly, what were the design drivers for Lunar Orbit Rendezvous, and what were the risks related to this approach? Why did it win out over the alternatives?

    - Example question: When the landing strut failed in testing, how did they address the problem. [Hint: which of the "manager's tools" did they use – more time, more money, changed objectives or increased risk?]

Systems Engineering Outcome: S1, S2, S5, and S7
KEEN Student Outcome: **K1, K2, and K5**

Example Modules for AENG 493: (Junior/Senior Year year):

• **Roving Mars** (Case Study). As a semester-long evaluation, the students read the "Roving Mars" book (by Mars Exploration Rover Principal Investigator, Steve Squyres). The book outlines the process by which the science team, science instruments were selected, and then how the rovers were designed, built, tested and operated. Every homework assignment through the semester includes a few questions about the book. o Example question: What are the Fundamental Questions about Mars that the author is trying to answer? What measurements are needed to answer those questions? What instruments are needed to capture those measurements?

- Example question: What is the difference between a flight spare and a flight component? How does that difference play into the saga of the APXS instrument?
- Example question: The second rover cost approximately $300 million. In hindsight, was the second rover worth the cost? Consider not only the science return of the second rover, but the fact that spending $300 million on the second rover meant that some other space mission was never flown at all. Under what circumstances is it beneficial for NASA to build two copies of a space vehicle?

• **Design Sheet** (Project). Students are giving an instructor-supplied spreadsheet that links basic sizing analysis for space missions (e.g., link budget, solar panel sizing, moment of inertia calculation, battery discharge, propellant consumption). Using the spreadsheets, students are guided through a series of exercises to design/size a communications satellite. As the last step, students are tasked to choose a set of components/design points to maximize revenue of the spacecraft; to first order, that means maximizing the number of transmitters that the spacecraft can carry, while reducing development/launch costs. Though it is a simplistic model, students independently identify the key drivers in communication design, namely, that the long-term revenue from adding another transmitter more than offsets any initial expenses. It is almost always financially beneficial to use the most advanced sensors and propulsion systems, despite the cost to add them to the system. This matches reality, whereas communication satellites are bigger and more expensive to build every year.

Systems Engineering Outcome: S1, S2, S5, and S7
KEEN Student Outcome: **K1, K2, and K5**

Implementation and Assessment

Courses AENG/MENG 101 and 102 sequences are offered in both fall and spring semesters. Modules specifically developed for these two courses were implemented in Fall 2014 and assessment data and student feedback that were collected are currently being analyzed. This data will be presented during the conference presentation. Modules developed for AENG 200 course will be implemented in Fall 2015 as this course is offered only once an year.

The evaluation metrics and the assessment data for one of the modules (The SMART assignment) for AENG 322 course is shown in Table 2, that was evaluated by all the student teams and an external evaluator (faculty member from the department) and the instructor.

Table 2: SMART Assignment: On a scale of 1 -5, with the scale designated as 5 for strongly agree (SA), 4 agree (A), 3 for Neutral (N), 2 for disagree (D), and 1 for strongly disagree (SD), please rate the following questions:

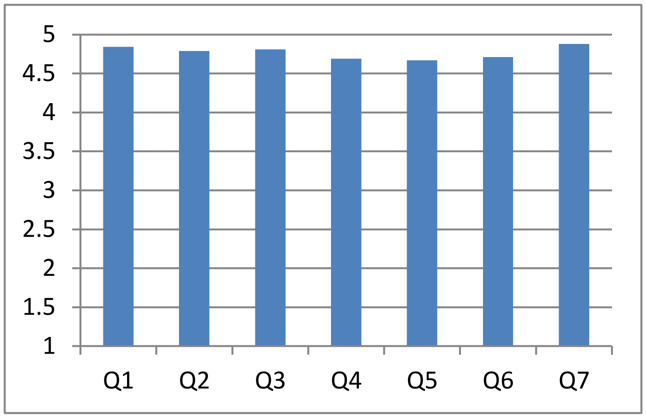
MISSION EVALUATION

	Question	Points (1 – 5)
Q1	The proposed mission adheres to the 5 core elements of SMART strategy	
Q2	The proposed mission demonstrates how NASA will benefit	
Q3	Clearly identifies the area of research or other exploration that the mission will be fulfilling	
Q4	Suggests how the mission will be a booster for NASA as a whole	
Q5	The proposed mission is novel and innovative	
Q6	Is the mission realistic and marketable to the public	
Q7	The mission idea has sound scientific/engineering backgrounds.	

TEAM EVALUATION

	Question	Points (1 – 5)
Q1	Demonstrated effectiveness of pitch, given short time frame	
Q2	Was able to present mission statement and mission idea clearly	
Q3	Poster is neat and well organized	
Q4	Clear demonstration of team effort, evidence that every team member has contributed	

Figure 1 and 2 shows the SMART assignment evaluation for the mission idea and team evaluation respectively.



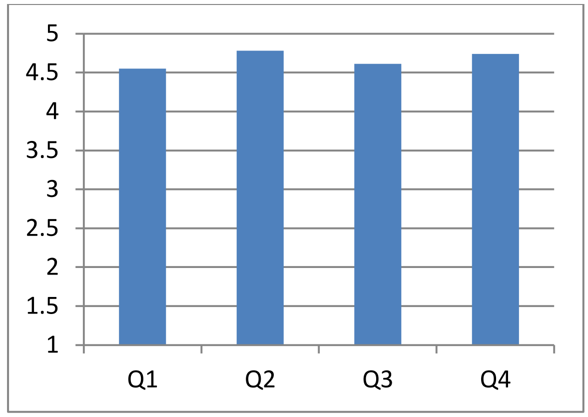


Figure 1: Survey Results for SMART Assignment Mission Evaluation

Figure 2: Survey Results for SMART Assignment – Team Evaluation

Evaluation and assessment outcomes from modules implemented in all the courses in future semesters will be collected and made available to the faculty members.

Summary

Today's engineers must think differently, be curious about the changing world, create extraordinary value by integrating information, apply creative thinking to assess technical feasibility that has meaningful societal impact. Systems engineering principles/practices and entrepreneurial thinking have emerged as vehicles to innovate and solve complex problems.

Teaching the systems engineering principles in a way that would facilitate entrepreneurial mindset is a challenge. In this paper, different types of modules have been developed and implemented in courses spanning from freshmen year to senior year preparing students in systems engineering concepts as applied to creating value and think innovatively. Over the last year, some of these modules have been implemented in several courses in our curriculum with overall positive feedback from the students. The implementation of specific activities through several courses resulted in significant improvement in the students' understanding of systems engineering concepts related to entrepreneurial mindset. However, these modules are work in progress and it will be improved based on the students' feedback and instructor's evaluation.

It is worth noticing that the integration of systems thinking coupled with entrepreneurial thinking is particularly powerful and can accelerate the creation of immense value.

Acknowledgements

The authors would like to thank the Kern Engineering Entrepreneurship Network (KEEN) for supporting this work through their Topical Grant Program.

References

1. Bagg, T. C., Granata, R. L., Brumfield, M. D., Casey, C. A., & Jamison, D. E. (2003). "Systems engineering education development (SEED) case study." In *Proceedings of the 13th annual international symposium, INCOSE 2003, crystal city, Virginia, USA, june 29 - july 3, 2003.*

2. W. Bauer, W. Biedermann, B. Helms, and M. Maurer, Student laboratory for Systems Engineering: teaching Systems Engineering to students without previous SE knowledge based on an industry-oriented example, 2012 International Systems Conference, IEEE Society, 2012, pp. 1-6.
3. C. Chittister and Y. Haimes, Harmonizing ABET Accreditation and the Certification of Systems Engineers, Systems Engineering, Vol. 14, No. 3, 2011, pp. 341-348.
4. International Council on Systems Engineering, INCOSE List of SE Programs July 2013, https://www.incose.org/educationcareers/academicprogramdirectory.aspx.
5. National Aeronautics and Space Administration, Systems Engineering Handbook, December 2007, http://foiaelibrary.gsfc.nasa.gov/_assets/doclibBidder/tech_docs/5.%20NASA%20SP-6105%20Rev%201%20%28Sys%20Eng%20Handbook%29.pdf.
6. Sage, Systems Engineering education, IEEE Transaction on Systems, Man, and Cybernetics Part C: Applications and Review, Vol. 30, No. 2, 2000, 164-174.
7. K. Shimazu and Y. Ohkami, Systems Engineering education for inexperienced students by providing hands-on practices, 2011 International Systems Conference, IEEE Society, 2011, pp. 367-370.
8. F. Squires, etal, “Investigating an Innovative Approach for Developing Systems Engineering Curriculum: The Systems Engineering Experience Accelerator”, ASEE Annual Conference, 2011.
9. M.C. Brannon, T.A. Mazzuchi, “Introducing the Fundamentals of Systems Engineering to Freshman through Various Interactive Group Activities”, ASEE Annual Conference, 2014.
10. S. G. Teng, “Embedding Systems Engineering Practices into Systems Engineering Classes”, ASEE Annual Conference, 2014.
11. C.S. Wasson, “Systems Engineering Competency: The missing course in engineering education”, ASEE Annual Conference, 2012.
12. M.D. Wilson, etal, “Entrepreneurship Education: Engineering a Pracademic Approach”, ASEE North Midwest Section Conference, 2014.
13. C.D. Carpenter, etal,” Assessment and Evaluation of a Comprehensive Course Modification Plan”, Journal of Engineering Entrepreneurship, Volume 2, Number 2, pp. 15 – 34, 2011.
14. KEEN Framework http://www.kffdn.org/files/keenzine-2-framework.pdf.