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APPLICATION OF REVERSE ENGINEERING ACTIVITIES IN THE TEACHING OF ENGINEERING DESIGN

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1. Introduction

Existing studies show that D/A/A (Disassemble, Analyse, Assemble) activities can become a popular pedagogy to provide engineering design students practical experience in the classroom [Lamancusa 1996], however, the information available on how to prepare, conduct and evaluate these activities is abstract, not detailed and dispersed, there are no standardized guidelines on how to make the most out of these activities leaving this task to the experience of the professor at work, which is a particularly important challenge for first time or novice instructors of this type of activities. To address this issue a research project at the Technical University of Catalonia is in progress to develop a guiding manual for the implementation of D/A/A activities adapted to the specific requirements of a curriculum in engineering design considering specific learning objectives, fundamentals, methodologies, tools, test materials and feedback mechanisms for interested professors. This project will require the documentation of the theoretical background behind hands-on activities in education and the technical and methodological knowledge needed to conduct D/A/A activities to test the project hypotheses and answer the research questions.

2. Background for D/A/A activities

Some educators believe that "engineering design students in these times are less prepared to do well in engineering, since they lack the experience and intuition that develops from hands on activities from adolescent years" [Ogot et al. 2008]. At the same time, these educators declare that "It is difficult to transform theoretical knowledge into practice" which is indeed a problem statement often heard not only in Engineering Design Education but also in Engineering Education overall, nevertheless, these two arguments, can be logically related and through the following examples that rephrase these past statements the need to provide high quality hands-on experiences to engineering design students as way to bridge the gap between theory and practice is supported.

1. "Many students report that design methods are typically taught at a high-level and in a compartmentalized fashion. Often, the students' courses do not include opportunities to obtain incremental concrete experiences with the methods. Nor do such courses allow for suitable observation and reflection as the methods are executed." [Otto et al. 1998]
2. "Disassemble/Analyse/Assemble (D/A/A) activities of an artifact pervade many undergraduate engineering courses in the USA as they provide useful 'hands-on' learning components. D/A/A activities are central to product dissection and reverse engineering activities used by many engineering practitioners as part of their industry's benchmarking and competitive analysis processes." [Ogot et al. 2008]

3. "…hands-on experiences through the use of "reverse-engineering" projects. As the fundamentals of design techniques are presented, students immediately apply the methods to actual, existing products. They are able to hold these products physically in their hands, dissect them, perform experiments on their components, and evolve them into new successful creations. Based on this reverse-engineering concept…" [Otto et al. 1998]

From the statements above the terms incremental concrete experience; observation and reflection highlight a suitable way to reduce the gap between theory and practice through D/A/A exercises which imply hands-on activities. There are several theories of learning in design and engineering, classical examples include Piaget's early learning model and Felder-Silverman learning styles but it is Kolb's learning model [Kolb 1984] the one that states that concrete and practical experience can be obtained through product dissection activities which in turn help reduce the gap between theory and practice in experimental learning environments. To teach and study engineering design can be difficult sometimes, especially when transforming theoretical knowledge into practice. The characteristics of D/A/A activities and their integration to an engineering design curriculum are presented as it is suggested that these activities can be used as a support tool in engineering design education. This statement is evaluated throughout this paper by presenting a theoretical background of these activities, including descriptions, steps, encompassed tools as well as possible lines for future research. The experiences and findings about this topic at the Polytechnic University of Catalonia are presented for further use by interested researchers.

3. Research topic

The analysis of existing consumer products as a means to provide students with hands-on activities during their engineering design studies is concerned with the attempt to discover the technological and non-technological principles of a device, object or system in the areas of interest of an engineering design educational program, through an analysis of its structure, function and operation, taking it apart and analyzing its workings in detail to try to recapture the abstract and functional top level specifications envisioned by the original designers during the product design specification (PDS) stage to help the students understand the design rationale and tradeoffs from the multiple solutions originally available that led to the delimited solution boundaries embedded in the final product as a way to assess the fulfillment of customer requirements and its eventual market success or failure. This process is generically called "Reverse Engineering" which is a concept spanning several disciplines, but for a specific engineering design context it is theoretically founded on the product tear down analyses conducted in 1972 by Yoshihiko Sato [Sato et al. 2005], the reverse engineering for product design methodology proposed by authors Otto and Woods [Otto et al. 2001] and Kolb's model of learning [Kolb 1984]. Other common names for "Reverse Engineering" in the engineering design education context include "Mechanical Dissection", "Product Dissection" or D/A/A (Disassemble, Analyse, Assemble) Activities which is the term used throughout this paper. Related activities in areas of engineering other than educational engineering design that share the same concept of disassembling a product to further analyze it have been know and practiced for a long time and are called depending on their ultimate purpose "Tear Down Analyses", "Analysis of Known Solutions", "Weak Points Analysis", "Value Engineering", "Forensic Engineering" or the German term "Konstruktionskritik – roughly translated as - Analysis of Designs" among others, all of them traditionally associated to formal studies of the design itself, typically oriented to system analysis or industrial applications but neither fully focusing on the pedagogical value of the hands-on activities themselves nor on the non-technical aspects of a product. D/A/A activities in an engineering design education context thus should be considered a derivative modern effort that is pedagogically oriented and benefits from modern media technologies not available before to provide engineering design students with practical hands-on experiences that help them understand and catch up with the ever changing design and manufacturing technologies relevant to an engineering design curriculum. Reverse engineering exercises though, are suitable only for a subset of the total expected competences of an engineering design graduate that's why they are a tool in the teaching of engineering design as a whole and should not be seen as a substitute for traditional (forward) engineering exercises which in turn are also suitable only for a subset of the total expected competences.

4. The different contexts of reverse engineering:

The generic term "Reverse Engineering" can be found in different areas but in all of them "Reverse" implies starting backwards from something existing and then finding the way back to the initial conceptual stages through a combination of cognitive processes, technical tests and calculations to try to recover the initial specifications of a product, some of the contexts where the term "Reverse Engineering" is used - few of them actually related to engineering design – are shown next along with typical activities related to them.

Table 1. Contexts of reverse engineering

CONTEXT	RELATED ACTIVITIES
ACADEMICAL	D/A/A Activities used to teach engineering principles, mainly mechanical, physical, hydraulic; Legal side of Public policy and Information Management
INDUSTRIAL MANUFACTURING	Competitive Intelligence, Benchmarking of products and processes
GEOMETRICAL FEATURES EXTRACTION	CAx scanning systems, Land surveying
HOBBY	Hardware hacks a.k.a "Mods"
INTELLECTUAL PROPERTY ENFORCEMENT	Patent or copyright infringement
SEMICONDUCTORS INDUSTRY	Topologies
COMPUTER SOFTWARE INDUSTRY	Legacy software, Interoperability, Security
TECHNICALLY PROTECTED DIGITAL CONTENT	Circumvention and anti-circumvention measures
MILITARY	Foreign technology acquisition, Military advantage pursuit
FORGERY	Electromechanical products of significant market value
FICTIONAL	The term is often mentioned in Movies, TV Series and Documentaries

The broad scope of areas where the term "Reverse Engineering" is used creates misunderstandings with related disciplines (i.e. Forensic Engineering, Value Engineering, Safety Engineering) and sometimes the differences are not easy to discern since these disciplines share common analysis tools.
The following table summarizes the milestones of reverse engineering in education and includes a brief description of the associated accomplishments.

Table 2. Milestones of reverse engineering in education

MILESTONE	YEAR	DESCRIPTION
Value Engineering	1947	Product value improvement through examination of functions
Konstruktionskritik "Analysis of Designs"	1956	Search for errors in manufacturing or constructions, design, through use, repair, etc.
Product Tear Down Analyses by Yoshihiko Sato	1972	Fundamentals and methods of Tear Down Analyses for use in automotive manufacturing
Kolb's Model of Learning	1984	Educational psychology and foundations of hands on activities
Mechanical Dissection at Stanford University	1991	Well regarded courses by engineering students, Development of educational materials
The Learning Factory at	1995	Continuous development of the theoretical

Pennsylvania State University		foundations of hands on activities
Otto and Woods at MIT and UoT at Austin	2001	Dedicated book for reverse engineering and encompassed analyses
Ciber-U WikiMedia	2006	development of an internet based platform to collect and browse reverse engineering examples

5. From analysis to synthesis through reverse engineering activities

Kolb's model considers four extremes of learning represented by two lines. The horizontal one represents how individuals transform experience into internalized knowledge while the vertical one represents how individuals take in information. In this regard, education is often considered to be concentrated towards abstract conceptualization. By following Kolb's recommendation the use of hands-on activities in engineering education helps students spend equal time on each of the four extremes so they can benefit from an integral learning.

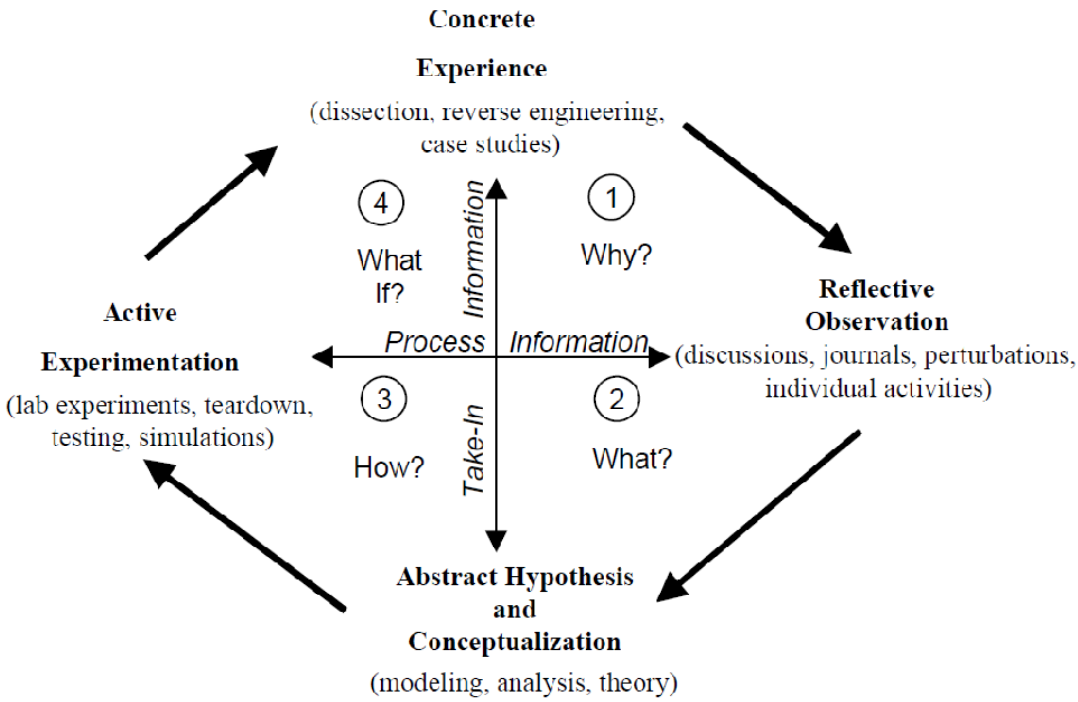

Figure 1. Annotated Kolb's model of learning [Wood 2005]

An integral part of reverse engineering is knowledge acquisition because it requires design information that is not usually available through standard design documentation so it must be solicited from the user or inferred by the system. The design information solicited from the user may be conjectured knowledge because it cannot be confirmed to be true or simply because they are hypothetical assumptions. Interestingly Ullman studied the types and nature of information solicited by designers during redesign and reported that a relatively high percentage (90 %) of conjectures made during redesign proved to be actually valid. [Jounghyun 1994]

6. Detection of need

As promising as D/A/A activities may seem in helping students keep up to date with the requirements of the engineering design praxis and its interdisciplinary nature, their integration into engineering design curricula has been unequal, previous exploratory studies conducted as part of this research showed that they can be perceived as interesting and favorable by some professors but also as complex, unappealing, unlawful and unnecessary by others. This research projects aims at improving their credibility as a teaching tool and easing the entry barriers and learning curve for those interested in integrating them into their teaching.

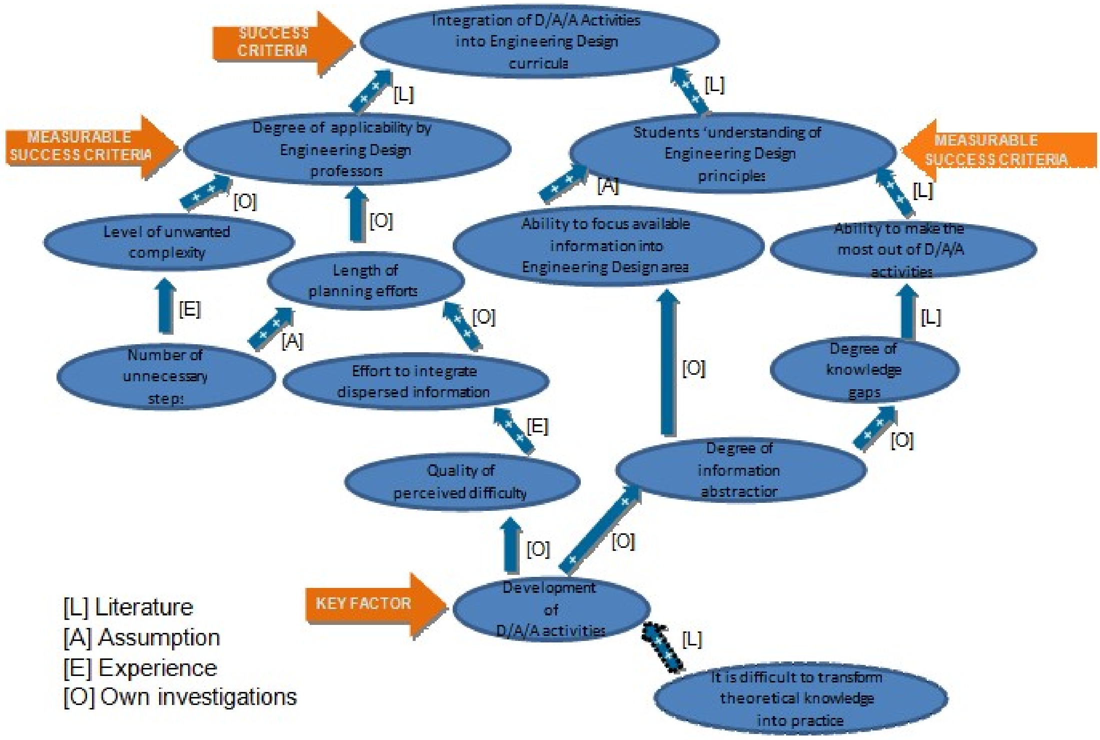

Figure 2. Graphical representation of understanding of existing situation

6.1 Expected students competences from engineering design education

Part of the added value that hands-on activities bring to engineering design education is that they help exercise most of the expected competences of an engineering design curriculum while at the same time keep students interested in the activities. The following table shows the expected competences of an engineering design graduate.

Table 3. Expected Competences in Engineering Design

COMPETENCES	LEARNING OBJECTIVES
Teamwork	Participate effectively in groups or teams
Information Gathering	Gather Information, using various sources and techniques, Including analysis
Problem Definition	Define problem, including specific goal statement, criteria and constraints
Idea Generation	Utilize effective techniques for idea generation
Evaluation and Decision Making	Utilize critical evaluation and decision making skills and techniques, including testing
Synthesis	Combine information together from pre-existing elements in a different way in a new pattern or proposing alternative solutions
Implementation	Implement the design to a stage of usefulness to prospective clientele
Communication	Communicate at all stages of development and implementation of design solutions

Table 4. Example of a (forward) engineering design exercise and practiced competences

EVENTS	COMPETENCES REQUIRED	LEADING TO…
1. Define a need; express as a goal	Problem Definition Teamwork Communication	Definition of the Problem, Including Specific Goal Statements

2. Establish design criteria and constraints	Problem Definition Information Gathering Teamwork Evaluation and Decision Making Communication	Acknowledgement and delimitation of constraints, Understanding of the open ended nature of problems, Recognize importance of problem definition
3. Evaluate alternative designs	Evaluation and Decision Making Idea Generation	An iterative approach that employs evaluation of proposed solutions repeatedly in the design process
4. Build a prototype of best design	Implementation Teamwork	Achieve familiarity with the design
5. Test and evaluate the prototype using the design criteria	Evaluation and Decision Making Teamwork Implementation	Management of time and other resources as required to complete the project
6. Analyze test results, make design changes, and retest	Synthesis Evaluation and Decision Making Teamwork	Self- assessment of design proposals and also learning to follow instructions provided by others in implementation
7. Communicate the design	Communication Teamwork	Presentation of a the development and implementation of a solution

Table 5. Example of a reverse engineering exercise and practiced competences

EVENTS	COMPETENCES REQUIRED	LEADING TO…
1. Plan Reverse Engineering Exercise	Problem Definition Information Gathering Idea Generation	Specify Goals and span of the exercise
2. Collect Samples (Products)	Information Gathering	Selection of products to cover expected theory principles and effects, Acknowledgement of the positioning of your product
3. Disassemble	Teamwork Idea Generation	Achieve familiarity with the product and its design
4. Perform Analysis	Information Gathering Idea Generation Teamwork Evaluation and Decision Making	Understanding of inner workings as well as external factors influencing design of products, Understanding of the positioning of your product
5. Evaluate Advantages and Disadvantages	Evaluation and Decision Making Information Gathering Idea Generation Teamwork	Acknowledgement of design “suitability”, assessment of design proposals
6. Assemble the Product	Teamwork Implementation	Increase of awareness of product (i.e. DFM) and hands-on experience

7. Recognize Status Quo	Information Gathering Evaluation and Decision Making Teamwork	Situational awareness of the product (historical timing, design productions), Understanding of the open ended nature of problems in design
8. Suggest Immediate Improvements	Synthesis Implementation Teamwork Idea Generation	Presentation of immediate improvements and rational behind them, Acknowledgement of current design constraints
9. Suggest Future Improvements	Synthesis Implementation Teamwork Idea Generation	Presentation and theoretical foundation of future solutions or redesign, Acknowledgement of current design constraints
10. Communicate the Findings	Communication Teamwork	Presentation of the findings

The tables above show that reverse engineering exercises can be seen as a complement not a substitute of traditional design engineering projects and that they enhances student learning and reinforce engineering concepts through hands-on experience through the practice of the competences considered important for an engineering design graduate.

7. Framework for research

A design research methodology is an approach and a set of supporting methods and guidelines to be used as a framework for doing design research, the design research methodology by authors Blessing and Chakrabarti called DRM [Blessing et al. 2009] has been chosen as the supporting framework for this research project since "its methods are intended to support a more rigorous research approach by helping to plan and implement design research". If used flexibly as the authors suggest, this methodology should help make design research more effective and efficient. The methodology framework proposed by Blessing and Chakrabarti consists of four stages, namely: Research Clarification, DS I, Prescriptive Study (PS) and Descriptive Study II. As stated by the authors The RC stage helps clarify the current understanding and the overall research aim, develop a research plan and provide a focus for the subsequent stages. The DS-I stage aims at increasing the understanding of design and the factors that influence its success by investigating the phenomenon of design, to inform the development of support. Where the term support is used to cover the possible means, aids and measures that can be used to improve the current situation and that enable the evaluation of the core contribution of the researcher. The PS stage aims at developing support in a systematic way, taking into account the results of DS-I. And finally the DS-II stage focuses on evaluating the usability and applicability of the Actual Support and its usefulness.

7.1 Research project goal

To develop an assimilable and readily applicable manual for the systematic and effective development, execution and evaluation of D/A/A (Disassemble, Analysis, Assembly) activities to support the teaching of Engineering Design.

7.2 Research Questions

The research questions that initially sparked the interest in this project are listed here though it is important to note that they have changed through time as more and more is known about the research topic.

1. What are the major challenges Engineering Design professors perceive in order to implement D/A/A (Disassemble, Analyse, Assemble) activities?
2. How can D/A/A -based educational materials be developed in a systematic way?
3. How can D/A/A activities' effectiveness as an educational tool be measured?
4. What are the characteristics of D/A/A -based educational materials that are favored by Engineering Design students?

5. What are the tradeoffs and added value in Engineering Design education between Reverse Engineering exercises and Forward Engineering exercises?
6. Are there any legal boundaries to the dissemination in academical environments of results obtained through the use of Reverse Engineering in education?

7.3 Hypotheses

These are the hypotheses the project aims to test which will help to see if the proposed solution is indeed suitable for the problem detected

H1: The development, conduction and evaluation of reverse engineering exercises to support the teaching of engineering design can be systematized through a guiding manual that takes into account documented experiences, conclusions and best practices in reverse engineering praxis as well as relevant learning topics on the teaching of engineering design.

H2: Increased awareness of a reverse engineering methodology as a tool to teach engineering design through the presentation of a guiding manual will increase professors' eagerness to use it and include it in an engineering design curriculum.

H3: The analysis and explanation of a reverse engineering exercise to teach engineering design presented in a guiding manual will provide professors with ideas on how to teach engineering design topics and increase their competence to develop examples of their own.

The following figure shows the global areas relevant to this research project, they are color coded to indicate the research topic itself, the areas essential to the research project in this case analysis and synthesis, the educational areas of expected contribution of the research results and finally the areas useful for the execution and completion of this project.

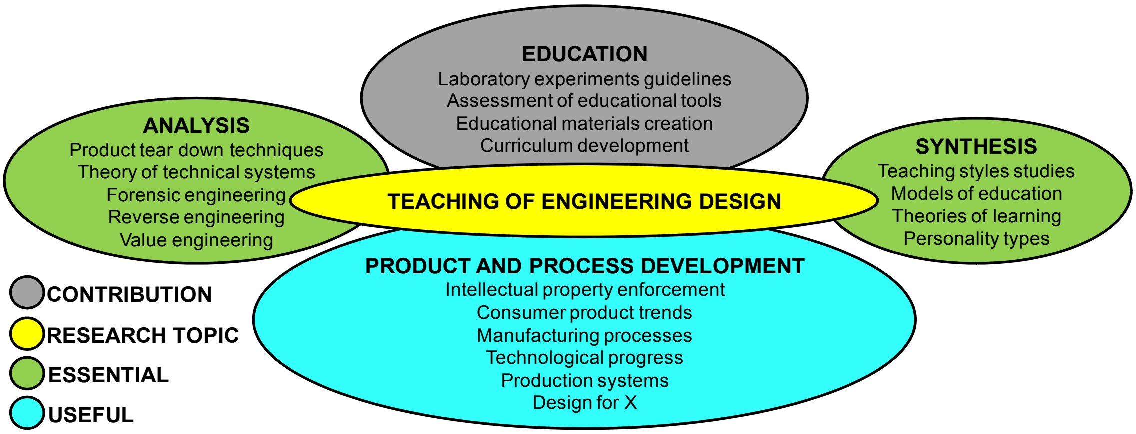

Figure 3. Diagram of areas of relevance and contribution

7.4 Research approach

According to the DRM methodology by authors Blessing and Chakrabarti this is a Type 3 research project "Development of support" type meaning that the understanding of the existing situation obtained from the literature review and reasoning is enough to start the development of a support tool, in this case being the manual for the development, execution and evaluation of D/A/A (Disassemble, Analyse, Assemble) activities.

8. EXPECTED RESULTS

To document scientifically the practical knowledge across dispersed disciplines needed to develop a manual that helps professors to integrate educational D/A/A activities into their engineering design curriculum, easing the learning curve for the preparation, execution and evaluation tasks by reducing knowledge gaps, unwanted complexity and unnecessary steps.

8.1 Expected deliverables from the research project

1. A Doctoral Thesis: Documenting the rigorous research studies needed to test the hypotheses and answer the research questions as well as the theoretical background behind hands-on activities in education and the technical and methodological knowledge needed to conduct reverse engineering exercises.
2. A Guiding Manual: For the implementation of reverse engineering exercises adapted to the specific requirements of a curriculum in engineering design considering specific learning objectives, fundamentals, methodologies, tools, test materials and feedback mechanisms for interested professors and students.
3. Academic Papers: To be presented at congresses or journals on relevant topics to the research project.

9. Preliminary results

- Categorization of desirable competences In an engineering design student and their links to the specific steps of a reverse engineering methodology
- Comparison of a reverse engineering exercise vs. a conventional engineering design exercise by showing events, competences and results to provide a solid argument for the added benefit that reverse engineering exercises can bring to engineering design education
- Effort to link reverse engineering activities with existing courses and projects on product and process engineering, environmental impact analyses, DFMA in the engineering design curriculum at the Polytechnic University of Catalonia

10. Current and future research lines

The current integration of computational techniques in the analysis, tracking and support of a reverse engineering project is limited and it still offers opportunities for a broader use and strengthening of this methodology thus keeping pace with new technologies and developments in the engineering design area. Efforts like the Cyber-Infrastructure-Based Engineering Repositories for Undergraduates [CIBER-U. 2008], provide online case studies and digital product models for instructors and students. On the theoretical side a recently proposed framework for dissection activities classifies them on four stages based on the desired educational goal and the amount of guidance provided by the instructor through either oral or written instructions, the stages of proficiency growth are called Expose, Inspire, Inquire and Explore [Ogot et al. 2008].

11. Conclusions

Existing studies show that D/A/A (Disassemble, Analysis, Assembly) activities can become a popular pedagogy to provide students practical experience in the classroom since they benefit from increased students interest and engagement with the tasks, though there are still many areas to explore since suitable methodologies which allow for teachers guidance and students freedom are required to make the most out of these activities. deep knowledge of multiple science and engineering disciplines already exists and it is not the intention of the reverse engineering student to be an expert in all of them just to be aware of their existence and understand their potential use and applications as resourcefulness is an expected and desired competence of an engineering design student , reverse engineering projects helps foster cooperation from companies and research groups at partner universities since the study of the design principles materialized into existing products and the ability to produce improved derivative products are an important part of a competitive market where on one hand the authors or inventor's innovation deserves to be rewarded and protected by intellectual property and on the other hand innovation is encouraged in order to ensure fair and competitive markets for everyone, reverse engineering activities can in this way open venues for industrial collaboration and applications where existing industrial requirements can be handed to students to find a suitable solution. Last but not least, It is also necessary to spread knowledge among students and the general society and try to bring to everyday's life the benefits obtained from all areas of knowledge from anywhere in the world. While reverse engineering might be a common term now in an industrial environment, its use in education still offers interesting areas for research and development in education.

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