A COMPARISON OF COMPETENCES REQUIRED IN REVERSE ENGINEERING EXERCISES VERSUS CONVENTIONAL ENGINEERING EXERCISES AND ITS RELATIONSHIP TO IPMA'S COMPETENCE BASELINE

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Abstract

The International Project Management Association (IPMA) through its IPMA – ICB Competence Baseline Version 3.0 provides the official definition of the competences expected from project management practitioners and describes the competence elements necessary to develop and realize good project plans and results. In this document, professional project management is broken down into 46 competence elements that cover three ranges: Technical competences for project management; Behavioral competences of project personnel and Contextual competences of projects. As these competences are expected from project management practitioners, it is important to discover how students from related fields start acquiring and developing these competence elements; for example through D/A/A activities (Disassemble, Analysis, Assembly) also known as Reverse Engineering activities which provide useful 'hands-on' learning experiences and are used as a complement to conventional engineering design exercises in an educational context and require the use of several of the competences mentioned in the baseline document. A methodological comparison of the activities involved during a forward engineering exercise versus a reverse engineering exercise is presented, expecting to understand the links between the competences exercised at an educational stage and those expected later during the project engineering practice and how to reflect these findings in improved educational curricula.

Keywords*: engineering design education; competences; reverse engineering*

Resumen

La Asociación Internacional para la Promoción de la Dirección de Proyectos (IPMA) a través de su Documento de Referencia (ICB Competence Baseline Version 3.0) proporciona la definición oficial de las competencias esperadas en los profesionales de la dirección de proyectos y describe las competencias necesarias para alcanzar buenos resultados. Este documento divide la dirección de proyectos en 46 elementos de competencia que cubren áreas técnicas, contextuales y de conducta. Debido a que se espera encontrar estas competencias en los profesionales de la dirección de proyectos, es importante descubrir cómo se adquieren y desarrollan estos elementos de competencia durante la etapa formativa universitaria, por ejemplo, a través de Actividades D/A/A (Desensamble, Análisis, Ensamble) también conocidas como actividades de Ingeniería Inversa las cuales proporcionan experiencias de aprendizaje practico y se utilizan como complemento a los ejercicios convencionales de ingeniería de diseño en un contexto educativo. Este artículo presenta una comparación metodológica entre las actividades involucradas durante un ejercicio convencional de ingeniería de diseño y un ejercicio de ingeniería inversa, esperando entender los vínculos entre las competencias utilizadas durante la etapa formativa y las utilizadas durante la práctica de la dirección de proyectos para reflejar estos resultados en mejores programas de estudio.

Palabras clave: *ingeniería de diseño; competencias; ingeniería Inversa*

1. Introduction

Many 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. At the same time, other educators declare that “To teach and study Engineering Design can be difficult sometimes, especially when transforming theoretical knowledge into practice”, these two arguments can be logically related and support the need to provide high quality hands-on experiences to students. Kolb’s model of learning (Kolb, 1984) states that concrete and practical experience can be obtained through product dissection activities also known as D/A/A activities (Disassemble, Analysis, Assembly) or more generally as Reverse Engineering activities since they help reduce the gap between theory and practice in experimental learning environments.

To address this need, a research project at the Technical University of Catalonia is in progress to develop a guiding manual for the implementation of Reverse Engineering 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 and students. 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 reverse engineering exercises so the project hypothesis can be tested and the research questions answered.

2. Objective

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, a good level of integration of reverse engineering activities has been noticed in engineering design programs in the United States of America, Canada, Germany or the United Kingdom but in other countries their integration has been irregular -with some notable exceptions in universities and countries, as expected-, while this situation is not necessarily bad, previous exploratory studies conducted as part of this research showed that reverse engineering activities can be perceived as interesting and favorable by some professors but also as complex, unappealing, unlawful and unnecessary by others, which might explain why these activities have not been fully adopted by engineering design professors everywhere. This paper aims at improving the credibility of reverse engineering activities as a teaching tool by evaluating the correlation degree between the properties of these activities against the desired learning outcomes from engineering design programs and the competences expected from graduates of these same programs, hoping that a clear view of the suitability of these activities to reach the desired goals of engineering design professors can help them better justify their inclusion into their teaching curricula.

3. Methodology

A number of studies have been conducted already to highlight the most important student competences expected in engineering education, the knowledge obtained from these studies helps plan better engineering curricula where the benefits to the students can be maximized so they can achieve what is expected from them during their future professional praxis. It is important to note that this paper focuses on engineering design education rather than engineering education overall since the results from this study will be part of a larger research project whose goal is to create a guiding manual for the planning , execution and evaluation of reverse engineering activities for the teaching of Engineering Design. However as engineering design is multidisciplinary and draws heavily from other areas of engineering, the results from this paper can be easily placed in proper context for the different areas of engineering education. This paper then, illustrates a comparison of a reverse engineering exercise against a conventional engineering design exercise by showing events, competences and results and comments on how this illustration might be used to evaluate the correlation of these competences to those outlined in the IPMA – ICB Competence Baseline Version 3.0 as well as other significant studies on the desired competences of design engineers. The generic term “reverse engineering activities” as used in this paper refers to the broad variety of standardized laboratory tests and morphological analysis tools available for the analysis of technical systems common to the teaching of engineering design, where the “reverse engineering exercise” term refers only to one specific test among the available selection of tools for the execution of reverse engineering analyses. The following list shows an example of some of the typical reverse engineering activities as outlined by authors Otto and Woods. (Otto, 2001)

1. Identifying components of a product and determining how a product accomplishes its function
2. Black box model creation
3. Establishment of customer needs
4. Functional design analyses; function structure and activity diagrams for each component
5. Product teardown, assembly and disassembly plans creation
6. Identify differences (if comparing similar products)
7. Create a tree structure to show the relationships between components and subassemblies
8. Create a bill of materials for the entire product including function, mass, material, manufacturing process identified, dimensions, and cost
9. Subtract and Operate procedures for product analysis
10. Validation and verification analyses
11. Force flow diagrams creation
12. Function sharing and compatibility analyses
13. Morphological matrix analyses (constraints and solutions)
14. Create sketches, pictures or CAD diagrams of components
15. Identify user requirements and formulate engineering specification sheets
16. Determine and apply appropriate analyses to measure engineering specifications, be it for example, hand calculations or dynamic simulations of CAD components like (MSC.ADAMS, Working Model)
17. Comment on the product’s ability to address user requirements based on measured engineering specifications
18. House of quality creation for a given project

19. Performance tests and energy analyses
20. Calculate economic/environmental impact of the product analyzed
21. Understand the situational characteristics of the product, i.e.: why was the product produced and at what historical timing

3.1 Existing Studies on the Competences of Design Engineers

It is important to know about the expected and desired competences of engineering design students for the purpose of preparing better curricula and learning activities during their college years. This type of research involves not only interacting with students but also including practicing engineers, professors, cognitive psychologists and representatives from industry, it requires as well, the definition and agreement of the involved parties on a variety of concepts such as competence, knowledge and skills. The different definitions available for the existing studies can sometimes be confusing but they all aim to bring a point of view where whatever students can learn and practice during college years will have an effect during their professional practice, for this paper a number of representative studies listed in Table 1 were identified and analyzed and the results for four of them considering their items , learning objectives and competences were listed and presented in tables in a condensed form from the original studies with the intention to find the correlation degree and suitability of reverse engineering activities to achieve the desired goals mentioned for every item of the studies analyzed. The Likert-like suitability scale in Table 2 was developed and every item was evaluated against this scale to evaluate through an analysis of existing literature and exploratory discussions with professors and students at the Technical University of Catalonia in Barcelona, Spain; the Technical University of Ilmenau in Germany ,and the participants of the 2009 Summer School on Engineering Design Research in Croatia and Finland to find the suitability of reverse engineering activities and their potential to achieve the expected competences of engineering design students and graduates. For purposes of space and clarity only the final suitability values for every study are shown

Table 1: Representative Studies on Engineering Design Competences

Study	Reference in This Paper
ABET's engineering program outcomes	ABET, 2009
Expected qualities in a design engineer	Sheppard, 1996
Taxonomy of engineering competencies	Woollacott, 2009
CDIO syllabus	CDIO Council, 2010
TIDEE's design process competencies	Calkins et al; 1996
Desired attributes of an engineer	Boeing university relations, 2010
Saeema's categorization of knowledge-process	Saeema, 2007
ICB – IPMA competence baseline version 3.0	IPMA, 2006

Table 2: Seven Point Likert Suitability Scale

Scale	Value
Strongly suitable	1
Suitable	2
Somewhat suitable	3
Neutrally suitable	4
Somewhat unsuitable	5
Unsuitable	6
Strongly unsuitable	7

3.2 Study on the Qualities Expected in a Design Engineer

Sheppard and Jenison in their study about the qualities expected in a design engineer and that engineering courses should be helping engineering students to develop state that qualities can be viewed as being comprised of competency and attitudes (not shown here for reasons of space and readability) and one of engineering education's major challenges is to help students develop these qualities during their stay at a University. How to integrate these experiences that help students develop the qualities listed by them in Table 3 can take a number of very different forms, it is the intention of this paper just to compare the suitability of reverse engineering exercises to help engineering design professors develop these qualities in their students.

Table 3: Qualities Expected in a Design Engineer

Quality	Competency	Reverse Engineering Activities' Suitability to Achieve Desired Goal
Communicate, negotiate and Persuade	Skills in oral presentation, report writing, formulating persuasive arguments, effective communications	Suitable
Work effectively in a team	Skills in team organization, setting meeting agendas, meeting facilitation, taking on leadership role	Somewhat suitable
Engage in self-evaluation and reflection	e.g., skills in journaling, matching local problem to big picture	Strongly suitable
Utilize graphical and visual representations and thinking	Skills in the appropriate use of sketching, geometric and physical modeling and CAD at various stages of design process	Suitable
Exercise creative and intuitive instincts	Skills in both right-brain and left-brain thinking.	Strongly suitable
Find information and use a variety of resources (i.e., resourcefulness)	e.g., skills in database searches, interviewing potential customers	Strongly suitable
Identify critical technology and approaches, stay abreast of change in professional practice	Skills in project definition and planning, knowing "hot" publications in a given field, awareness of Professional Society activities	Suitable
Use of analysis in support of synthesis	Skill in identifying when analysis will provide insight into the quantification of a design or into strengths/weaknesses of a design. What type of analysis is appropriate?	Strongly suitable
Appropriately model the physical world with mathematics	Idealization of complex geometries/loads into simple components that can be analyzed, but realization that the map is not the	Suitable

	territory (per Prof. Rolf Faste, Stanford University)	
Consider economic, social, and environmental aspects of a problem	Understanding of basic issues in these domains	Strongly suitable
Think with a systems orientation, considering the integration and needs of various facets of the problem	Understanding issues of importance to product success, including other engineering fields, psychology, aesthetics, etc.	Strongly suitable
Define and formulate an open-ended and/or under-defined problem, including specifications	Gantt charts, QFD, need finding, etc.	Suitable
Generate and evaluate alternative solutions	e.g., brainstorming, mind-mapping, visual thinking, kinesthetic thinking	Strongly suitable
Use a systematic, modern, step-by-step problem solving approach. Recognize the need for and implement iteration.	Skills in project definition and planning, mind-mapping. Ability to use or formulate an appropriate problem solving procedure.	Suitable
Build up real hardware to prototype ideas	Basic machining and laboratory skills, understanding of time and cost issues related to prototyping, and knowledge of rapid prototyping skills.	Strongly suitable
Trouble-shoot and test hardware	e.g., design of experiments, data analysis, diagnostic skills.	Suitable

The amount of reverse engineering exercises is so broad that is difficult to find a competence that a given reverse engineering exercise can not address, but perhaps more important than this “good-for-all” effect is to start discerning the real competences that reverse engineering exercises can better match to maximize their related benefits through the creation of better study curricula and activities for the students and leave the other items that are not so comprehensively covered to other tools and activities in the teaching of engineering design.

3.3 The CDIO Syllabus

The CDIO (Conceive–Design–Implement–Operate) syllabus is the most detailed statement on the goals of engineering education currently found in the literature it focuses on the knowledge, skills and attributes needed to perform the various engineering processes associated with the life-cycle of an engineering system or product.

Table 4: Condensed CDIO Syllabus Items

Topic	Overall Suitability to Reverse Engineering Activities
Technical knowledge and reasoning	Suitable
- Knowledge of underlying sciences	Suitable
- Core engineering fundamental knowledge	Suitable
- Advanced engineering fundamental knowledge	Suitable
Personal and professional skills and attributes	Somewhat suitable

- Engineering reasoning and problem solving	Strongly suitable
- Experimentation and knowledge discovery	Strongly suitable
- System thinking	Strongly suitable
- Personal skills and attitudes	Somewhat suitable
- Professional skills and attitudes	Somewhat suitable
Interpersonal skills: teamwork and communication	Suitable
- Teamwork	Strongly suitable
- Communication	Suitable
- Communication in foreign languages	Strongly suitable
Conceiving, designing, implementing and operating systems in the enterprise and societal context	Strongly suitable
- External and societal context	Strongly suitable
- Enterprise and business context	Suitable
- Conceiving and engineering systems	Strongly suitable
- Designing	Strongly suitable
- Implementing	Suitable
- Operating	Strongly suitable

On its evaluation against the CDIO Syllabus, the reverse engineering activities rank well in the technical areas mentioned but on the personal skills area it would be wise to look for more efficient alternatives to promote the developments of them in the engineering design students.

3.4 Saeema's Categorization of Knowledge-Process

Saeema's study describes the findings carried out with engineers in senior roles within a large company manufacturing complex products. The research aimed to identify the types of knowledge that are important for design engineers since design engineers have different combinations of competencies, and any industry, company, or project requires design engineers with differing competencies for a number of reasons like industry trends or specific geographically or natural resources-based industries.

Table 5: Saeema's Categorization of Knowledge-Process

Type of Knowledge	Definition Process Knowledge	Overall Suitability to Reverse Engineering Activities
Conceptual design	The designer is dealing with the whole product or whole assemblies and works from a blank sheet of paper, generating and evaluating several ideas.	Strongly suitable
Detailed design	The knowledge required to define specific components including technical drawings and specifying manufacturing requirements.	Strongly suitable

Analyze and verify	The knowledge required to analyze and verify a design; this may be conducted by the designer. Sufficient knowledge is required to be able to set up any necessary tests and to be able to challenge results from a formal analysis.	Strongly suitable
Compliance with standards	Knowledge to ensure design complies with standards and legislation.	Strongly suitable
Value improvement	Knowledge to improve a design from a particular perspective, e.g., cost or quality, not necessarily employing a formal design for the x method or tool.	Strongly suitable
Knowledge of assembly	Knowledge of how the product will be assembled and of assembly plans.	Strongly suitable
Design for service	Considering the product through its service, i.e., once released, for example, inspection or monitoring components for wear limits, etc.	Strongly suitable
Managing requirements	Managing requirements and assessing the risk of these requirements not being achieved for each component.	Strongly suitable
Physical integration	Ensuring that interfacing components physically fit together.	Strongly suitable
Functional integration	Knowledge required to integrate the function of a component with other component or assemblies that share the function.	Strongly suitable
Investigating and identifying the problem	Investigative and diagnostic work to identify the problem and may be applied to major quality failures.	Strongly suitable
Engineering processes and methods and tools	Knowledge of the impact of engineering processes, methods and tools.	Strongly suitable
Managing time and cost requirements	Management knowledge, The ability of a designer to deliver a design to schedule and cost.	Neutrally suitable
Managing resources	Knowledge of line management, e.g., setting objectives, training, etc.	Somewhat unsuitable

It was important to include this study in this article since the research from author Saeema focused on the knowledge of design engineers not during their university years but during their professional practice where the author also investigated how long it takes practicing engineers to become proficient in these areas , nevertheless it is important to notice that reverse engineering still rank well in this study and that an effort to help students develop the aforementioned competences during their university years is important. This is the study where reverse engineering activities rank the higher since most of the items deal with technical topics, showing once more that while reverse engineering activities are not bad for learning managerial topics there are much better ways to exercise these capabilities with the students.

3.5 ICB – IPMA Competence Baseline Version 3.0

The final study considered for this paper is the Competence Baseline Version 3.0 International Project Management Association that represents the integration of all the competence elements of project management as seen through the eyes of the project manager when evaluating a specific situation.

Table 6: IPMA's Competence Elements

Topic	Subdivisions	Overall Suitability to Reverse Engineering Activities
Technical Competences		Suitable
	Project management success	Neutrally suitable
	Interested parties	Neutrally suitable
	Project requirements & objectives	Suitable
	Risk & opportunity	Neutrally suitable
	Quality	Somewhat suitable
	Project organization	Suitable
	Teamwork	Strongly suitable
	Problem resolution	Strongly suitable
	Project structures	Somewhat suitable
	Scope & deliverables	Suitable
	Time & project phases	Suitable
	Resources	Suitable
	Cost & finance	Somewhat unsuitable
	Procurement & contract	Somewhat unsuitable
	Changes	Neutrally suitable
	Control & reports	Neutrally suitable
	Information & documentation	Neutrally suitable
	Communication	Somewhat suitable
	Start-up	Unsuitable
	Close-out	Unsuitable
Behavioral Competences		Neutrally suitable
	Leadership	Neutrally suitable
	Engagement	Suitable
	Self-control	Somewhat suitable
	Assertiveness	Somewhat suitable
	Relaxation	Neutrally suitable
	Openness	Suitable
	Creativity	Strongly suitable

	Results orientation	Somewhat suitable
	Efficiency	Suitable
	Consultation	Somewhat suitable
	Negotiation	Neutrally suitable
	Conflict & crisis	Unsuitable
	Reliability	Suitable
	Values appreciation	Suitable
	Ethics	Suitable
Contextual Competences		
	Project orientation	Neutrally suitable
	Program orientation	Neutrally suitable
	Portfolio orientation	Unsuitable
	Project, program & portfolio implementation (PPP implementation)	Unsuitable
	Permanent organization	Neutrally suitable
	Business	Neutrally suitable
	Systems, products & technology	Strongly suitable
	Personnel management	Neutrally suitable
	Health, security, safety & environment	Suitable
	Finance	Somewhat unsuitable
	Legal	Somewhat suitable

As an important responsibility of practicing design engineers is to oversee the completion of design projects by integrating people and knowledge from different fields, the study of the competence elements from IPMA's study with a natural focus on project management and their correlation to reverse engineering activities can guide professors and curriculum developers to better plan the activities and exercises necessary to familiarize students at an early stage with the responsibilities and peculiarities of project management practice. In general reverse engineering activities rank well for this purpose but it is the responsibility of engineering design professors to complement their teaching strategies with the available tools and methods that cover the areas that reverse engineering activities cannot properly cover so they can help their students maximize their learning experience during their university studies.

4. Results

To take into consideration such large number of studies on the competences, skills, qualities and characteristics of studying and practicing design engineers is not an easy task due to the varied number of definitions; criteria, underlying assumptions and contexts considered for the different studies. However it can be seen that reverse engineering activities in their technical nature tend to rank better on those items dealing with technical aspects of engineering design. While those competences related to behavior and management don't rank well enough as to be considered the only alternative to teach and exercise this capabilities in students. The information obtained from this research will help to create a guiding manual for the preparation, execution and evaluation of reverse engineering activities for engineering design studies that will try to maximize the benefits on the technical aspects of design that reverse engineering activities bring, while on those items related to the "soft skills" better strategies to dealt with through the different kinds of exercises and activities that can be found in a engineering design curriculum will be suggested.

5. 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 help 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. Reverse engineering exercises provide realistic, complex experiences that can be safely repeated to provide reinforcement and repetition of key information until the desired goal is attained which helps equalize the differences in status, experience and knowledge among students. Hence, the design and delivery of effective reverse engineering activities should be based on a variety of learning theories and stimulate as many modalities and senses as possible. Reverse engineering exercises can be seen from an industrial and an academic perspective, very often the same type of analysis is performed depending only on the desired level of detail and information required from them so it can be seen from the results before that the reverse engineering activities tend to favor the product related goals stated throughout the different studies while those related to behavioral "soft skills" such as career development or selling skills tend to be less favored by the reverse engineering activities, this can be considered "normal" to a certain extent since reverse engineering activities involve a strong interaction with the product, its structure, materials and manufacturing technologies, but also because reverse engineering activities are just one more of the multiple tools available to engineering design professors to use in their teaching, and as such, reverse engineering activities will favor just a part of the total expected and desired competences of a design engineer, just as much as other different tools in the teaching of engineering design will tend to favor a different set of the competences desired. Last but not least the challenge in planning engineering design education is to provide an appropriate balance between social and technical issues with didactic and experiential activities considering the main learning theories and their implications as well as a wide range of strategies that consider the influences on students such as differences in gender; intellect, emotions, health and socio-cultural backgrounds.

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