DESIGNING
A COMPREHENSIVE METHODOLOGY TO INTEGRATE SUSTAINABILITY ISSUES IN CDIO PROJECTS

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ABSTRACT

We present in this study the first steps in the design and implementation of a new methodology that aims to consider systematically the different dimensions of sustainability, including ethical and strategic aspects, attempting to balance all them. The pilot methodology was implemented in the course 2014-15 in the "INGENIA" course, a 12 ECTS compulsory subject taught in the first year of the master in industrial engineering of the Technical University of Madrid. As this is an on-going process, we also introduce some practical guidelines we are currently addressing to the students by means of taking into account various approaches in particular socio-economic contexts or to differentiate specificities by industrial sectors or activity fields. Ultimately, we aim at enabling our INGENIA-CDIO students to raise reflections and assessments about the related impacts of their engineering projects.

KEYWORDS

Sustainability, Social Responsibility, Professional Responsibility, Ethics, Project-based courses. Standards 2, 3, 6, 7, 9, 11

INTRODUCTION

The global agenda of sustainability is increasingly demanding the acquisition of technical skills and the development of specific personal competences of future professionals. Many of the coming new graduates at our Engineering Schools will have to deal to some extent with the recently approved Sustainable Development Goals (United Nations, 2016), which are crucial to transform our world by means of end poverty, protect the planet, and ensure prosperity for all. Everyone has to contribute to reach these goals: governments, the private sector, civil society and, of course, universities.

In this way, the Escuela Técnica Superior de Ingenieros Industriales of the Universidad Politécnica de Madrid (School of Industrial Engineering, Technical University of Madrid. ETSII-UPM hereafter), launched in 2014-15 the new Master's Degree in Industrial

Engineering in which the above outcomes were outlined as one of the main priorities of the overall curricula. Its program includes a new innovative set of project-based courses denominated “INGENIA”, whose name comes from “ingeniar” (to provide ingenious solutions) and “ingeniero” (engineer). All INGENIA courses have an analogous structure; primarily aiming at the acquisition of professional outcomes not only related to sustainability but also with the ability to design, implement and operate engineering systems, as well as creativity, teamwork and communication skills. Every subject is directly linked in essence to the different ETSII-UPM majors.

The teaching-learning strategy adopted fits to CDIO standards, such as the intensive use of supporting software, prototyping technologies and testing facilities at different labs, enabling the instructors to fulfil adequately all the CDIO steps, from the conception and design, to the implementation and operation.

Sustainability is a key aspect that INGENIA students have to carefully take into account throughout the four CDIO steps. In this sense the initiative requires a comprehensive methodology to be systematically used in all the projects, but flexible enough to be adapted and oriented to the specific social, environmental, economic, strategic and ethical aspects of each of them. A literature review shows that these aspects have rarely been integrated in engineering curricula in a holistic and balanced approach. Additionally, the definition of social value and the measurement of social impacts are issues not yet sufficiently clear both in the academic and practical fields.

We therefore present in this study the design and implementation of a new methodology that aims to consider systematically the different dimensions of sustainability, including ethical and strategic aspects, and attempting to balance all them. Ultimately, we aim at enabling our INGENIA-CDIO students to raise reflections and assessments about the related impacts of their engineering projects.

LITERATURE REVIEW

General background

Engineering programs are increasingly recognizing the ability to formulate sustainable solutions as an important goal to ensure in graduate students’ profile. The concept of sustainable development is grounded on the ethical commitment to the wellbeing and enhanced opportunities of contemporary and the future generations (Chua & Cheah, 2013). Therefore, the application of sustainability framework in engineering education requires a better understanding of the ethical concepts and a responsibility approach would ask questions about the “whys” as well as the “hows” (Brodeur, 2013; Chua & Cheah, 2013).

Several authors have discussed the integration of sustainability and ethics in the context of CDIO engineering education (Augusto et al., 2012; Hussmann et al., 2010; Palm & Törnqvist, 2015; Silja et al., 2011; Wedel et al., 2008), and the CDIO Syllabus 2.0 already includes ethical and social responsibility aspects and sustainability criteria for each one of the lifecycle stages (CDIO, 2011). Nevertheless, while many engineering programs state objectives and learning outcomes in these areas, few have developed effective teaching and learning strategies that holistically and systemically address them (Brodeur, 2013).

The most common strategy used is based on the integration of specific sustainable development/ethics (SD/E hereafter) topics in courses whenever it is consider appropriate, or set up separate courses to guarantee that general aspects of SD/E are included (Enelund et al., 2012). However, in order to make the most of the learning of SD/E topics, the context of engineering practices in which the students have to work frequently with open problems in interdisciplinary projects must be prioritized (Chua & Cheah, 2013; Hussmannn et al., 2010; Wedel et al., 2008). In this line, Malheiro et al. (2015) explain an interesting CDIO design-implement experience which includes sustainability and ethical concerns as mandatory topics to be integrated in the project.

This practical approach enables to consider SD/E issues by a systematic exploration of all lifecycle phases. It provides a holistic view needed to avoid environmental bias and to deal with complexity (Cheah, 2014). It also enhances the training of students in other essential skills such as teamwork, communication, creativity and cultural understanding as integral parts of the education (Crawley et al., 2008). Furthermore, several authors point out the fact that integrating ethical assessment, emphatic design, and social and environmental criteria strengthen the final product (Palm & Törnqvist, 2015, Crawley et al., 2008).

Methodologies for integrating SD/E into projects-based courses

The Life Cycle Assessment (LCA) has been found a useful approach to integrate sustainability into CDIO-based engineering courses since it can help to assess environmental issues under a broader scope and substantially minimize environmental impacts (Jeswiet et al., 2005).

LCA is a “cradle-to-grave” approach for assessing industrial systems. “Cradle-to-grave” begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. The life cycle assessment methodology has been vastly used for the design and environmental evaluation of industrial process and products during the last two decades (Curran, 1996) and it is supported by well established procedures and thoroughly documented guidelines such as the standards ISO14040 or ISO14044.

Enelund et al. (2012) present a successful CDIO experience of using LCA in a Sustainable Product Development course. It begins with general treatment of the environment and sustainable development focusing on global issues. Analytical tools such as LCA and multi criterion analysis are introduced to help determine the effect that products and processes have on the environment. In other project courses the students have to consider also social impacts, such as safety concerns, and to apply models that stress the value of all potential customers for the whole lifecycle of the product (Wedel, 2008; Enelund et al., 2012).

The primary focus of LCA methodology was limited to assess the impacts that a product or process will have on the environment. However, since 2006 and after 30 years of development of those methods, the endeavors strove towards expanding the scope of life cycle thinking to become a comprehensive assessment tool for sustainability, which involved incorporating the three dimensions of sustainable development (planet, people, profit), also known as the triple bottom line (Elkington, 1997). Hence, together with the already well-established methods of E-LCA (environmental life cycle assessment) and LCC (life cycle costing), the need emerged for a new commonly accepted methodology for evaluating a product or process from the “people” perspective, using social indicators. The bases for this complementary methodology to E-LCA, the so-called Social Life Cycle Analysis (S-LCA), were recently launched by Benoît & Mazijn (2009) and later on complemented by Benoît-Norris et al. (2013).

In S-LCA, the social impacts of a good, service or process are assessed using a life cycle perspective and in relation to different groups of stakeholders. For each stakeholder category there is a number of associated impact categories intended to identify social "hotspots" in the life cycle of the product, service or process.

S-LCA is not the only methodology for evaluating the social dimension of sustainability. Other methods and approaches have been developed in last few years for this purpose. Most of them include standards and certifications such as SA8000, OSHAS18001 or AA1000 series, or reporting guidelines like the Global Reporting Initiative (GRI) guidelines, which also adopt a stakeholder perspective for evaluating social impacts. Nonetheless, among the wide variety of tools for assessing the social footprint of a product or process, S-LCA is perhaps the methodology that better grasps a systemic life-cycle perspective in the evaluation.

However, it should be noted that the maturity of S-LCA and other social impact assessment tools is still in its infancy when compared with the well-established procedures and thoroughly documented guidelines of E-LCA. There is a long roadmap to be covered for reaching a common ground on the accounting for the social dimension of sustainability.

Finally, some other structured methodologies to incorporate ethics into projects should be mentioned, like the Value-Sensitive Design (Cummings, 2006) or diverse proposals from the ethical assessment of technology (Brey, 2012; Palm & Hansson, 2006; Wright, 2011; Palm & Törnqvist, 2015). All of them provide practical tools to be used in project courses by means of checklists to identify ethical issues, and sets of questions that must be answered when assessing the ethical aspects of the real cases.

We have found in summary a need to develop a holistic, well-established methodology that enables our INGENIA students to properly integrate the environmental, social, economic, strategic and ethical aspects of sustainability into their engineering projects.

DESIGN OF THE EXPERIENCE

INGENIA courses and non-technical skills

INGENIA students experience the complete development and implementation process of a complex product or system (Lumbreras et al., 2015). They choose among different kinds of subjects (and projects), that cover most of the engineering majors at ETSII – UPM, as shown in Table 1.

These subjects are 12 European Credit Transfer System (ECTS) equivalent, which correspond to a student workload between 300 to 360 hours, distributed along two semesters with the following structure: 120 hours of class work plus 180-240 hours of personal student work usually organized in teamwork. Class work of the subjects is structured in three modules:

- Module A (Technical): 30 hours dedicated to adapt basic theoretical knowledge derived from other subjects to those directly related with the project, and a second set of 60 hours is devoted to practical work in the lab, with professor supervised sessions.
- Module B (Transversal skills): 15 hours for workshops on teamwork, communication and creativity skills and techniques.
- Module C (Sustainability): 15h for lectures and workshops about social responsibility issues such as environmental and social impact, ethics and professional responsibility, health & safety, intellectual property, etc.

These lectures, practical sessions, seminars and workshops, are distributed along the 28 weeks of the two semesters of the first year, resulting in 5 hours per week of lectures or practical sessions in the regular schedule of students. The relation of each module with the CDIO Syllabus can be seen in Figure 1.

Table 1. INGENIA subjects' description

Different INGENIA Subjects	Product / system developed & objective
Formula Student	Students take part in the complete development project of a competition car, from the conceptual design, to the final competition.
Machine development projects	Students live the whole process of creating an innovative machine, from the conceptual design stage, to the final trials with real prototypes, searching for design improvements.
Everyday life products / household goods	Students live the whole process of designing innovative products, from the concept step, to final simulations and trials with prototypes.
Smart systems engineering	Students experience the process of designing a smart system, using state-of-the-art engineering resources and taking account of the whole life-cycle. (A set of co-operative drones in current year).
Electronic devices	Students live the whole process of creating a new electronic product, oriented to improving everyday life in our ETSII-UPM, from the concept, to the prototyping stage and trials.
Industrial Construction projects	Students experiment with information management and project planning resources applied to a real industrial construction project (A beer-factory in current academic year).
Electricity supply networks	Students live the development project of an electricity supply network, from an initial renewable energy source to population.
Biomedical engineering design	Students experience the process of creating an innovative medical device, from the conceptual stage, to the final trials with prototypes.

The module C of INGENIA courses focuses on the ABET's learning outcomes (f) - an understanding of professional and ethical responsibility - , (h) - the broad education necessary to understand the impact of engineering solutions in a global, economic, societal and environmental context -, and (c) - an ability to design a system, component, or process to meet desired needs within realistic constraints, such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability -. They are strongly correlated with several items of the CDIO Syllabus, as the Figure 1 shows.

	INGENIA learning outcomes		
CDIO Syllabus 2.0	Module A (Technical) ABET (b) (c)	Module B (Skills) ABET (d) (g) + Creativity	Module C (Sustainability) ABET(c) (f) (h)
2.2 Experimentation, Investigation and Knowledge Discovery	[black]		
2.3 System Thinking	[light grey]		[light grey]
2.4.3 Creative Thinking		[dark grey]	
2.5 Ethics, Equity and Other Responsibilities			[black]
3.1 Teamwork		[black]	
3.2 Communications		[black]	
4.1 External, Societal and Environmental Context	[light grey]		[black]
4.2 Enterprise and Business Context	[light grey]		[black]
4.3 Conceiving, Systems Engineering and Management	[black]		
Environmental needs. Ethical, social, environmental, legal and regulatory influences. Risks and alternatives			[dark grey]
4.4 Designing	[black]		
4.4.6 Design for Sustainability, Safety, Aesthetics, Operability and Other Objectives			[dark grey]
4.5 Implementing	[light grey]		
4.5.1 Designing a Sustainable Implementation Process.			[dark grey]
4.6 Operating	[light grey]		
4.6.1 Designing and Optimizing Sustainable and Safe Operations			[dark grey]

[black]	Strong correlation, according to CDIO-ABET correlation (CDIO, 2011)
[light grey]	Good correlation, according to CDIO-ABET correlation (CDIO, 2011)
[dark grey]	Strong correlation (own criterion)

Figure 1. INGENIA learning outcomes correlated with CDIO Syllabus 2.0.

Conceptual model

In the designing process of our methodology adapted, we have consider first the three classical dimensions of sustainability (economic, environmental and social), emphasizing the essential fact that these dimensions have to be deeply grounded on the ethical and professional responsibility issues that may be relevant to each specific project (Figure 2).

After this, we added in our conceptual model a strategic dimension that must always be considered in every phase of the project, by means of identifying its basic "why", their main differentiation characteristics or how the long-term shared-value creation will be created in its development. These aspects cannot be studied separately, that's why our framework also includes the relationships with the different stakeholders that may be affected by the technology/service/artefact developed in the project. These are in essence the foundations of our methodology, characterised in the next Figure 2.

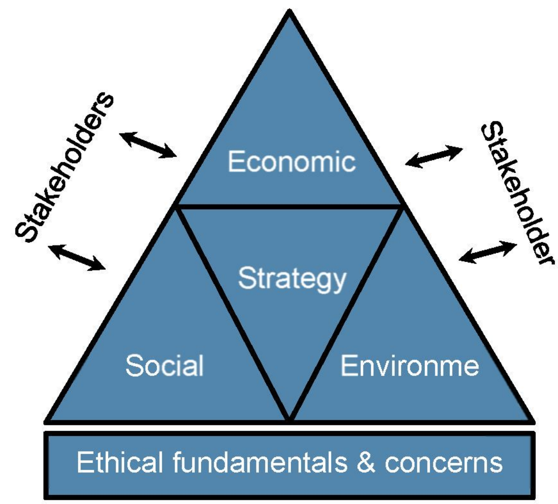

Figure 2. Framework for integrating sustainability and ethics in the INGENIA subjects.

Practical implementation

At the beginning of the course, an opening lecture was given to all the INGENIA courses' students together. We introduced for the first time our conceptual framework (Figure 2), revised the concept of sustainability and the principles of engineering ethics, and presented briefly some categories of both social and environmental impacts. Throughout the two semesters, different workshops and tutorials (12 hours) for each INGENIA course were scheduled. Two faculty members worked closely with the students with the specific objective of integrating all the sustainability aspects into their project.

Key guidelines for dealing with this holistic integration were developed. Inspired by the Value-Sensitive Design method and other experiences mentioned in the literature review, we established four phases to carry out the works: identification of possible impacts, analysis and selection of the relevant issues, the technical phase, and a final reflection.

In the first phase, all the possible ethical, social and environmental issues or impacts related to the project should be identified. Previously, the description of the technological sector in which the project is framed in and its organizational specificities have to be outlined. After this, the students are required to scrutinize the intended and potential unintended social and environmental consequences of the project, and the possible ethical concerns. They have to consider the whole lifecycle and all the stakeholders that could be affected. For supporting impacts' identification, a checklist methodology is proposed and the students are provided with several lists for different dimensions. They have been adapted from several resources from the ethical (Brey, 2012; Wright, 2011), social (GRI; ISO26000; UNEP, 2009) and environmental fields (ISO14000 and LCA). The goal of this first phase is not to make an exhaustive list but to make sure that major impacts will not go unnoticed.

In the second phase, students have to select the most relevant issues to their project from the ones identified in the previous step, and analyze them in depth. Different methodologies are proposed for environmental and social analysis.

For the environmental analysis the general LCA methodology is proposed. However, given the complexity of the projects and the variety of targeted outcomes, the LCA methodology has been simplified and adapted to each specific technical skills on product or system to support a better design building on previous knowledge and specific environmental assessment provided by other subjects within the curricula (Borge et al., 2011). Although the environmental assessment made by the students if far from exhaustive, the setting of system boundaries and reflection on the relevant inputs and outputs supports a systemic and comprehensive analysis of the product, process or service at hand.

In the case of social impact, we proposed a selection of impacts to be analyzed taking into account the consequences of its impact, ease of further analysis or the capacity to influence them. The students are asked to accomplish the following tasks: making a detailed description of the impacts selected; identifying stakeholders and how they are affected; identifying regulations, laws, ethical codes related to them; and pondering on the possibilities of an assessment or quantitative evaluation of the impact.

The third phase is aimed at quantifying and measuring the impacts selected in the previous phase. When possible, the students will test the product, studying the interactions with potential users or affected groups, so as to contrast the expected impacts or to identify new ones. Since this phase depends so much on the nature of the project, and bearing in mind the constraints of the INGENIA courses' academic context, we let this phase as optional.

The last phase is a final reflection. The teams have to produce as deliverable a report which structure is provided beforehand. This report must include the identification, description and analysis of the most significant social, environmental and ethical issues of the project carried out. Two different sections are asked for social impact and environmental impact. Moreover, it has to show how the project has been influenced by this analysis. It should highlight how the risks and negative impacts have been minimized or avoided, how the positive ones have been enhanced, as well as the overall coherence of the project with professional responsibility. This report is evaluated by the instructors and it represents 12,5% of the final score of the INGENIA course.

RESULTS

The experience developed during the course 2014-15 has been analyzed from two perspectives: the overall teaching methodology and the progress of the students in sustainability skills. Qualitative information and quantitative data was gathered not only from the final report described in the last phase of the methodology, but from pre and post questionnaires and specific open questions provided to them.

When asked for the most positive aspects of the experience, students highlighted that they have become more aware about sustainability as an important and key part of the engineering work, expanding their global vision of their future profession. Besides, they emphasized the usefulness of the learning acquired in this module. The questionnaires also showed that the bias towards environmental awareness observed in the initial evaluation had diminished. The greatest improvements were in the knowledge of social impact - particularly negative social impact-, in the self-perceived ability to analyze social impact and the capacity to enhance the positive impacts of an engineering project.

The best valued aspects by the students were the attention given by the C module's teachers and the teaching methodology. However, they also collected interesting suggestions for improvement. As teachers, more support and feedback are requested, as well as more coordination with the technical A module' faculty. The students ask for more clear guidelines and methodologies that allow them to focus on the particular sustainability issues of their project.

Regarding the negative aspects, students considered that the opening lecture is too theoretical and not very useful for the course. The asked also for improving the supporting documentation –providing examples of sustainability analysis of engineering projects – and for reconsidering the workload. All these suggestions have been very helpful to improve the experience during the current 2015-16 academic course.

DISCUSSION, CONCLUSSION AND FURTHER RESEARCH

The conceptual framework we present comes from the need to jointly work with the multi-dimensional, relevant aspects of sustainability. In the learning process it is crucial for example, to remark what is social value and social impact, its dependency on the environmental and socio-economic context and the identification of which are the relevant issues in different domains or activity fields. Alongside, students need support from the instructors in order to strengthen their strategic vision, classify stakeholders' needs or quantify impacts. These tasks are particularly challenging in projects where these aspects don't appear to be very evident (for example software projects, development of domotic gadgets,..).

The analysis of social impacts needs an adaptation of the social footprint methodologies to the CDIO context, as well as designing evaluation criteria and rubrics. We need in this sense a clear but flexible enough framework to integrate this diversity. It is important therefore to minimize the number of key ideas to be transmitted to the students.

In regard with the analysis of environmental impacts, further work is needed to define a more general framework to apply the main principles to any device or system with a similar detail, making it easier to guarantee that environmental issues are intimately integrated in the process and reflected in the prototype design.

After two years of experience in the design of this particular methodology, we can conclude from this on-going process that our conceptual/practical approach is well suited to the teaching and learning requirements that the sustainability agenda demands from the future engineers, obtaining satisfactory results from various perspectives.

Nevertheless, we have some key challenges to address, i.e. to get a common vision of sustainability in the faculty members who teach the subject, and to involve the rest of INGENIA professors by sharing this approach.

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