Sustainability in Engineering Education: A Literature Review of Case Studies and Projects

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Abstract–Sustainability is complex and demanding to teach and learn in engineering. Several learning activities have been reported in the literature to incorporate sustainability in engineering education. This work reports an extensive literature search about learning approaches on sustainability that use case studies and projects. The most significant works were characterized and analyzed to determine trends and opportunities in the development of learning activities that can be used to incorporate sustainability at different levels in the engineering curriculum.

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Abstract–Sustainability is complex and demanding to teach and learn in engineering. Several learning activities have been reported in the literature to incorporate sustainability in engineering education. This work reports an extensive literature search about learning approaches on sustainability that use case studies and projects. The most significant works were characterized and analyzed to determine trends and opportunities in the development of learning activities that can be used to incorporate sustainability at different levels in the engineering curriculum.

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I. INTRODUCTION

Sustainability is a complex term that might have different interpretations depending on the perspective used to define it. The definition of the term using narrow scopes makes difficult to understand it in its whole dimension. The notion of considering the environment, economy and society in the study of sustainability in a holistic form is probably the most comprehensive approach. Nevertheless, the integration of the three pillars mentioned before is still complex and not well balanced where the environment is a predominant factor followed by economic and social factors. As a result, any sustainable development requires not only deep understanding of the effect of decisions on the different pillars but also the knowledge of practical approaches to balance the pillars while looking for sustainable solutions.

In the particular case of engineering, design for sustainability is becoming a critical issue. The development of new products has impacts on the three pillars along the life cycle of the products from material extraction all the way to final disposal. Consequently, engineers must be educated with a solid foundation on sustainability to be able to create new products and systems in a bearable, equitable and viable way. Unfortunately, despite some initiatives around the world, the study of sustainability in engineering is still in the early stages. The scope of sustainability in engineering is predominantly about ecology (eco-design) and energy efficiency [1], and the teaching approaches are mainly limited to a single pillar rather than the integration of the three pillars [2]. The call for sustainability and sustainable development in engineering curricula and other related disciplines is coming from accreditation agencies around the world including ABET in the U.S. [3], the European Network for Accreditation of Engineering Education (ENAEE) [4], Engineers Canada [5], and Engineers Australia [6] among others. This effort is to educate engineers capable of tackling global challenges affecting the ecosystems including climate change, contamination, and the indiscriminate consumption of natural resources by finding solutions and creating new products without compromising resources for future generations while fostering fair economic growth and human wellbeing. Other important drivers for consideration of sustainability in engineering education are international treaties and laws, which are strict in environmental regulations, and in the standards for verification of the impact of industrial activities in the communities. Now industries are looking for engineers with knowledge on sustainability to comply with the normative and avoid sanctions while the governments are looking for engineers to verify compliance and enforce regulations.

It is evident that effective sustainable practices require the collaboration among the industry, government, academia and society. Merely environmental regulations are not enough for fair economic growth and social welfare. This collaboration should contribute to establishing a balance between feasible, viable, legal and desirable factors in the development of products or systems. Likewise, due to its nature, sustainable development requires also an interdisciplinary approach in which technical, economic, regulatory and social aspects are taken into consideration. This is why a holistic approach of the three pillars is more conducive to a better understanding of the sustainability concept rather than consideration of individual separate pillars. One of the main challenges in engineering education has been the emphasis on the technical aspects of problem solving, considering only some economic factors and practically ignoring the social impact of the solution [7]. This requires changes in the engineering education paradigm. However, the rigorous academic plans of engineering do not provide more room for additional courses. Therefore, the idea is to incorporate sustainability in the curriculum interwoven within existing courses using learning modulus and case studies that can be easily adopted by and adapted to different engineering disciplines.

An effective incorporation of sustainability in the curriculum should require taking into consideration three aspects awareness, knowledge and applicability that students should develop in their engineering education following the heart, head and hands learning model [8]. Awareness implies that students should be prepared to be aware of and sensitive to the importance and need of sustainability issues taking into consideration the three pillars. This is important since is related to the interest and motivation of the students in the topic. The next level is knowledge where students should be able to distinguish the different pillars and recognize indicators to be considered in the solution of engineering

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challenges including specifications for decision-making processes. This step is important since allows students to frame and model the problem considering sustainable parameters. Finally, the third constituent is applicability where students should be able to use concepts, principles, methodologies, indicators and tools for sustainable solutions. Currently, there are different approaches that try to add or consider aspects of sustainability in the engineering curricula; however, each approach is unique and the contents and methodologies vary depending on the instructor and the focus of the program. Besides, there is no a unique recognized strategic approach to effectively prepare engineering students to find sustainable solutions. Because of the diverse literature in the topic, it is necessary to establish trends and characterize the existing works to determine trends and patterns that can be eventually use across different disciplines in engineering. Consequently, the aim of this work is to synthesize and classify the works on sustainability in engineering education based on case studies reported in the literature to encourage future use and future research and contributions in this field.

II. LITERATURE REVIEW METHODOLOGY

An extensive literature review was carried out related to sustainability in engineering education in the last 15 years. Peer review articles were reviewed and classified according to specific topics of interest, and taking into account different type of works and approaches developed by different universities around the world.

In order to make a complete characterization of previous works, a systematic method was used as described in Figure 1. This method considered a database revision taking into account key concepts including sustainability, engineering education, design and development of curriculum, and courses focused in sustainable development. International Journals related with engineering education were reviewed and most meaningful works were selected for an in-deep analysis.

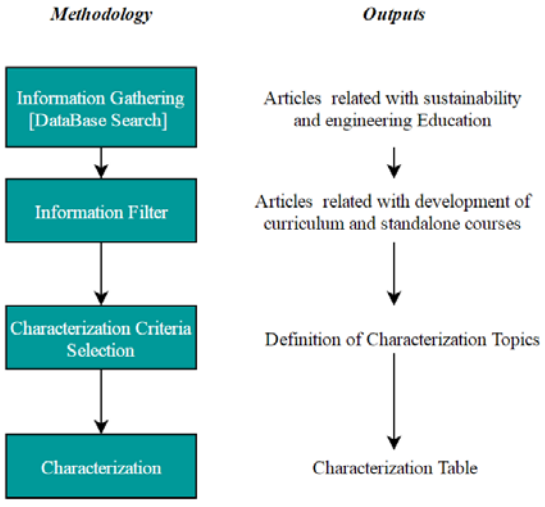

Figure 1: Characterization methodology employed

The works selected in the first step of the characterization methodology employed do not represent the full amount of works developed in engineering education for sustainability; however, they represent the most important contributions published in the topics considered in this study. The work presented here is focused on undergraduate engineering programs; thus, the approaches focused in high school and postgraduate programs are not considered in this analysis. Specific multidisciplinary projects and extemporaneous programs oriented to engineering design in sustainability but not added into curriculum are also excluded in this paper.

Characterization criteria were selected from analysis of previous works [9], [10], [11], and considering the most representative aspects associated with the development and modification of curriculums and courses focused on sustainability. Criteria used for characterization are summarized and explained in Table 1.

Table 1: Characterization Topics established

Topic	Description	Categories
Type of Approach	Type of method in which sustainability is addressed.	*Curriculum Integration:* Sustainability is integrated into the curriculum through topics in existent courses. *Stand-alone Courses:* dedicated courses related with sustainability topics.
Engineering Area	Engineering Discipline in which approach is applied.	*General, Industrial, Mechanical, Civil, others*
Interdisciplinary Scope	Consideration of different disciplines or different from the specific engineering area.	*YES:* The approach considers interdisciplinary. *NO:* The approach does not consider interdisciplinary.
Sustainability Dimension	Consideration of Environmental, Economic and Social aspects.	*Environment* *Economic* *Social*
Region	Region where the approach was developed.	*North America* *Europe* *Australia* *Asia* *Africa*
Case Study / Applications	Tasks or activities for application of sustainability	Various

III. CHARACTERIZATION OF RELATED WORKS

After establishing the characterization criteria, existing literature is reviewed to classify the selected works according to the topics and categories defined. This analysis provides important information about tendencies, lacks and opportunities for future work on sustainability in engineering education. Table 2 summarizes the characterization of 33 selected works from an initial group of 60 papers resulting relevant according to the literature review methodology. These works are listed primarily by author, and sorted according to the publication year from newest to oldest.

Table 2: Characterization of works related with development of curriculum and courses in Engineering Education for Sustainability

Author	Type of Approach		Eng. Area	Region	Case Study and/or Applications	Interdisciplinary Scope		Sustainability Dimension		
	Curriculum Integration	Specific Courses				Yes	No	Env	Econ	Soc
Mueller Price & Robinson 2015 [12]	*		Civil	North America	Progressive Course Projects	*		*	*	*
Pearson Weatherton 2015 [13]	*		General	North America	Multi-disciplinary Senior design Project	*		*	*	*
Nazzal et Al. 2015 [14]		*	Industrial	North America	Senior Design Project	*		*	*	*
DuPont & Wisthoff 2015 [15]		*	Mechanical	North America	Case Study Projects		*	*		
Sieffert et Al 2014 [16]		*	Civil	Europe	Case Study Project	*		*	*	*
Balan & Manickam 2013 [17]		*	Chemical	North America	Case Study Project	*		*	*	*
Lockrey 2013 [18]		*	General	Australia	Case Study Project	*		*	*	*
Enelund et Al. 2012 [19]	*	*	Mechanical	Europe	Progressive Projects		*	*	*	
Nagel et Al 2012 [20]	*		General	North America	Case Study Projects	*		*	*	*
Rydhagen 2011 [21]	*		Sanitary	Europe	Lectures & Projects		*	*	*	*
Filipkowski 2011 [22]		*	General	Europe	Lectures & Exercises	*		*		
Alahmad et Al. 2011 [23]	*		Arch. Eng	North America	Case Study Projects and Workshops	*		*	*	*
Arasat et Al. 2011 [24]		*	General	Europe	Case Study Project	*		*	*	*
Dempere 2010 [25]	*		Materials	North America	Case Study Project		*	*	*	*
Filion 2010 [26]		*	Civil	North America	Projects & Competitions		*	*	*	*
De Vere et Al. 2010 [27]	*		Mechanical & Industrial	Australia	Progressive Course Projects	*		*		*
De Vere 2009 [28]	*		General	Australia	Progressive Course Projects	*		*	*	*
Manoliadis 2009 [29]		*	Civil	Europe	Case Study Project	*		*	*	*
Lehmann et Al. 2008 [30]		*	General	Europe	Project problem-oriented	*		*	*	*
Lundqvist & Svanstrom 2008 [31]	*	*	General	Europe	Case Study Projects		*	*	*	*
McAloone 2007 [32]	*		Mechanical	Europe	Progressive Course Projects	*		*	*	*
Chu 2007 [33]	*		Civil	Asia	Problem-based learning Project		*	*	*	*
Kevern 2007 [34]		*	Civil	North America	Case Study Projects	*		*	*	*
Jerlich et Al. 2007 [35]		*	General	Europe	Research Projects		*	*	*	*
Fox et Al. 2006 [36]		*	General	North America	Research Projects		*	*		
Kamp 2006 [37]		*	General	Europe	Case Study Projects	*		*	*	*
Oakes et Al. 2006 [38]	*		Product/ industrial design	Europe	Case Study Project	*		*	*	*
Mulder 2006 [39]	*	*	General	Europe	Progressive Course Projects	*		*		
Boks & Diehl 2005 [40]		*	Industrial	Europe	Role Game Project		*	*		
Vezzoli 2003 [41]	*		General	Europe	Application of Software Tools in courses	*		*	*	*
Siller 2001 [42]	*		Civil	North America	Design-related Course Projects		*	*		
Coles 2001 [43]	*		General	North America	Project & Competition	*		*		
Quist et Al. 2000 [44]	*		General	Europe	Case Study Projects	*		*	*	*

IV. FINDINGS AND DISCUSSION

Table 2 provides information about the characterization criteria tendencies and motivations since year 2000. As it can be seen from the results, there is a growing tendency in the development of curriculums and courses oriented to sustainability in engineering. After 2005, the efforts and concerns about this topic were taken into account by universities around the world with more emphasis considering the increment in the number of publications in the field (See Figure 2).

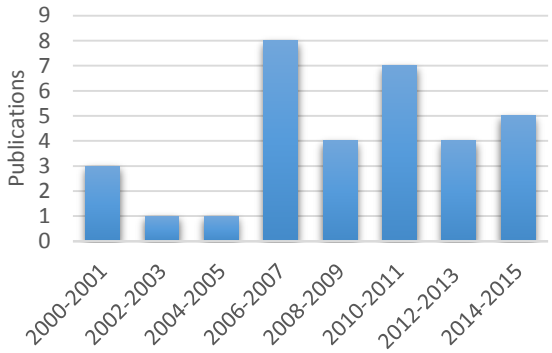

Figure 2: Publications during the last 15 years in the study topic

Following with the analysis of the data founded, the results of each criterion employed are described below.

A. Type of Approach

A review of the literature shows that there are two main approaches to introduce sustainability topics in engineering education. The first approach consists of introducing topics in existing courses through the addition of modules and/or learning activities related to sustainability. This approach is identified in this work as "curriculum integration". The second technique is the development of specific stand-alone courses on sustainability identified here as "course specific".

In this study, 55% of the works reviewed in the literature employ the curriculum integration technique. This approach is considered especially in universities with different engineering programs (Civil, Mechanical, Industrial, and Chemical among others), and is usually used in common engineering basic courses that provide an early perception and global vision of sustainability issues. The other 45% uses stand-alone courses traditionally developed in specific programs; however, in most cases, these courses are not a required course in the curriculum and courses are used as technical electives.

In the category of curriculum integration, it is common to find projects that evolve throughout the program. This is considered a powerful learning approach since students get involved in sustainability in a progressive way from basic concepts to application of principles in the solution of design challenges. This technique also provides opportunities for critical thinking and teamwork in interdisciplinary fields.

B. Engineering Area

An analysis of the literature shows that Civil (21%), Mechanical (12%) and Industrial (9%) engineering are the programs with more sustainability educational initiatives documented. Nevertheless, most of the works founded in the literature corresponds to general engineering programs or transverse courses designed as common requirements for all engineering programs in a university. It is important to highlight the incidence of sustainability in civil and architecture engineering, and other close related programs. This is because the design of buildings is one of the most advanced fields in terms of sustainability in which the use of renewable energy, eco-materials and principles of eco-design are a common denominator. Figure 3 shows a percentage distribution of this criterion in the most important engineering programs.

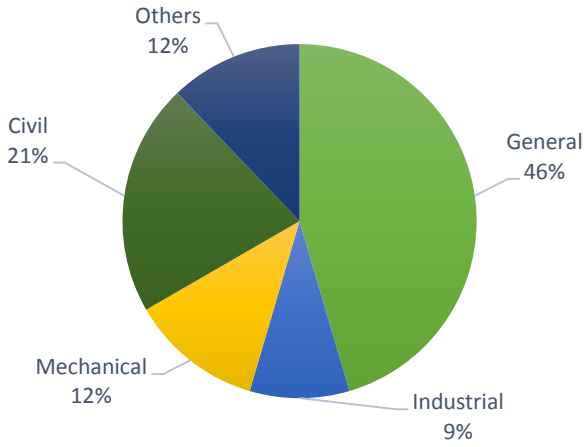

Figure 3: Distribution of sustainability education initiatives by Engineering Fields in 33 works analysed

C. Interdisciplinary Scope

Due to the nature of sustainability, knowledge from a variety of disciplines and aspects from different engineering field should be considered in engineering education for sustainability. In the literature reviewed, 66% of the cases are oriented to interdisciplinary tasks, requiring instructors from other programs and, in some cases, participation of students from other engineering disciplines. This is particularly common in course projects where it is necessary to find a design solution taking into account different engineering and design fields.

Universities with many engineering programs have a great advantage because the availability of instructors and students from different programs that can work together to enrich the learning experiences and projects. Institutions with one or only few engineering programs can develop projects involving other disciplines such as science, business, humanities and social sciences. Participation in open competitions, workshops, or multi-campus projects working

with students from other institutions and fields is another option to provide the diverse knowledge needed for sustainability; however, this approach requires a higher effort from organizers and institutions.

D. Sustainability Dimensions

One of the most challenging issues in sustainability is defining and measuring economic and social indicators in the development of products or systems. Therefore, it is difficult to include those dimensions effectively in learning activities because of the complexity of moving from the theoretical definition of economic and social impact in sustainability to the practical application of those pillars to the solution of engineering challenges. However, an analysis of the literature reveals that most of the works consider the three main pillars of sustainability including concepts related to ethics, cultural analysis, critical thinking, and socio-political issues among others. In this criterion, 75% of the works reviewed consider the three domains of sustainability despite the challenges of dealing with them due to the lack of standards. This holistic consideration has been significant in recent years. The absence of economic and social dimensions was evident in the early 2000s when only the environment was the primary focus of sustainable design.

Some researchers have used surveys in their projects to measure the social impact considered by students in the solution of the projects. The surveys evaluate the level of understanding of the social dimension of sustainability. When students can identify specific social issues, they can consider that dimension in the projects. This practice generates awareness about the need and requirements associated with social issues from early design stages.

E. Region

Europe (UK, Denmark, Spain, Italy, The Netherlands, and Sweden among others) with 49% and North America (USA) with 39% are the regions with leading the publication of initiatives on sustainability in engineering education followed by Australia with a 9% of participation and Asia with a 3% (See Figure 4). It is important the advances of European universities in incorporating sustainability in their curriculum. Even some European engineering programs have alternative degrees and postgraduate opportunities focused specifically in sustainable development. It is important to highlight here that South America, Central America and Africa have not significant participation in publications showing the implementation of sustainability into engineering education tasks.

The literature review suggests that developed countries are more committed to incorporate learning activities on sustainability in their engineering curriculum. However, since sustainability issues are global in nature, there is a need of contribution on this effort from the developing countries for an effective global impact.

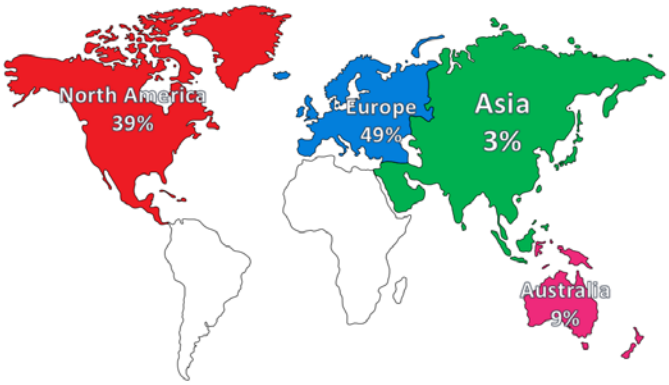

Figure 4: Region distribution of 33 works analysed

D. Case Study / Applications

This aspect refers to the approaches used to introduce the concepts of sustainability and sustainable development in specific learning activities in different engineering programs. After analyzing the 33 works referenced here, the most common approach is the use of case studies, some of them focused in problem-based learning (PBL). Universities with high advanced curriculum integration in sustainability demand many course projects in which students demonstrate the use and application of sustainability topics (mainly in design-oriented projects). Interesting activities such as competitions and interdisciplinary projects are proposed with the aim of motivating students to create multidisciplinary teams from different engineering programs and using sustainability principles for the solution of engineering challenges.

Cases and projects sponsored by the industry have a significant impact in the study of sustainability since students can develop awareness, knowledge and ability to apply sustainability principles in real situations affecting industries and communities. However, this approach requires strong collaboration between industry and academia.

V. FUTURE TRENDS

Even though the literature review reveals the growing efforts to create particular learning approaches and specific learning experiences on sustainability, there is still a need to create methodologies based on the use of standard sustainability indicators in engineering education to meet minimum sustainability requirements in the curriculums. Engineering accreditation agencies around the world are requesting the inclusion of sustainability as students learning outcome; however, engineering accreditation is not mandatory and is not an additional requirement for professional practice in many parts of the world. Therefor this request from accreditation agencies even tough is important, it is not enough. It is necessary to demand the integration of sustainability into engineering curriculum from higher government agencies.

This paper summarizes approaches in engineering education focused on curriculum and course modifications to introduce sustainability. Nevertheless, it is inferred that other experiences and works have not been published. In the next few years, it is expected that more work is done and reported around the world, especially in places such as South and Central America, Africa, and Asia.

Undergraduate programs in United States and Europe show a significant progress in curriculum modifications to introduce sustainability and this tendency is expected to continue growing not only in those regions but also in Australasia and Asia. As many Latin American institutions are looking for international accreditation of their engineering programs, it is expected that this will result in more institutions in that region incorporating sustainability in their curriculums. Additionally, more postgraduate programs on sustainability are expected to arise in response to the need of more specialized workforce in the field.

VI. CONCLUSIONS

Published case studies analyzed in this paper show differences among different undergraduate approaches in engineering education taking into account sustainability. The differences in curricular contents, application methods and dimensions considered are significant and reveal the need of standardization and methodological frameworks for the effective incorporation of learning activities on sustainability.

The literature review also reveals that the use of case studies and projects are common practices to provide learning experiences to engineering students on sustainability. However, it is necessary to integrate interdisciplinary projects in collaboration with the industry in order to develop real problem-based projects. This collaborative approach will facilitate the definition of sustainability indicators and specifications that are necessary for the understanding of this complex topic. Case studies and projects connecting students with real situations trigger student interest in the topic resulting in learning experiences that are more effective. Hence, the active collaboration among academia and industry is seen as a key element for a successful integration of sustainability in engineering education.

The UNESCO Roadmap for Implementing the Global Action Program on Education for Sustainable Development [45] has identified priority areas and strategies for a transformation in education for sustainable development. Some researchers have proposed the formulation of a methodological framework based on the recommendations by UNESCO even though there are no specific learning initiatives stipulated. The roadmap document has a significant value since it contains valuable information that can serve as an adequate complement for learning initiatives on sustainability in engineering education.

The characterization and analysis presented in this paper will be used to determine commonalities in approaches and concepts with the aim of proposing a methodological framework for the incorporation of sustainability in engineering education at the different levels from introductory to advance courses.

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