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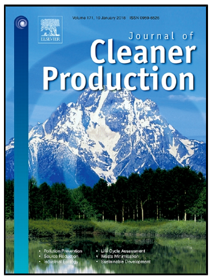

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A Systematic Review of the Literature on Integrating Sustainability into Engineering Curricula

Abstract

Higher education plays an important role in furthering the sustainability agenda, as reflected in a growing body of literature. While there have been several recent reviews of this work, these have been limited in scope and do not explicitly discuss implementations of sustainability in higher education curricula. In response, this paper presents a comprehensive, systematic review of the literature on integrating sustainability into curricula at both an undergraduate and postgraduate level of study in one particular subject area – engineering. A total of 247 articles, of which 70 were case reports, have been analyzed. Twelve future research questions emerged from the analysis, including: the exploration of the knowledge and value frameworks of students and teachers; the exploration of stakeholder influence, including by accreditation institutions, industry partners, parents, and society; and, the use of competencies to evaluate implementations. It is hoped that answering these questions will help to enhance education such that engineers are prepared, engaged, and empowered to confront the environmental, social, and economic challenges of the 21st century.

Keywords: *Sustainability; Education for Sustainable Development; Engineering Education.*

1. Introduction

For several decades, there has been a strong political will and commitment towards sustainability and sustainable development. An important means of furthering the sustainable development agenda is via education, including higher education. Following the launch of the 1983 World Commission on the Environment and Development (WCED) report, various scattered initiatives were implemented to integrate sustainable development concepts and approaches into higher education. Chapter 36 of Agenda 21, the outcome of the 1992 United Nations Conference on the Environment and Development in Rio de Janeiro, later highlighted the important role that education can play in realizing sustainable development; but a further push to stimulate its introduction was needed. Thus, the United Nations Decade for Education for Sustainable Development was initiated from 2005 to 2014, which provided an impetus for integrating sustainability into education, including higher education. This important catalyst awakened and motivated some (but far from all) educators in many curricula to integrate sustainability into their courses, curricula, research, outreach, and on-campus greening activities. A detailed history of the initiatives taken in society, education, and higher education to foster sustainable development is now available in Lozano *et al*. (2013, 2015a).

A survey by Murphy *et al*. (2009) found that more than 80% of US universities have some level of course activity related to sustainability and sustainable development, but the extent of this activity varies. In general, initiatives can be divided into two different strands: (i) initiatives that aim to put sustainability into the curriculum; and, (ii) initiatives aimed at making universities themselves more sustainable, e.g. in the form of sustainable procurement, sustainable campuses, etc. The focus of this study is on the curriculum. It presents a systematic review of the literature on the integration of sustainability and sustainable development into engineering curricula. The focus is upon engineering curricula in particular because of the crucial role it plays in the development of countries (Lucena & Schneider, 2008), such as through the provision of critical infrastructure services and the creation of essential goods and products.

Engineering educators were not the leaders in making curricula changes to incorporate sustainability into their educational work (Mulder *et al*. 2012). They began to integrate environmental engineering into education around 1994 based upon dialogue and papers that were presented at several conferences focused on environmental efficiency issues for engineers. The scope of these conferences was later broadened out to sustainable development with the first Engineering Education in Sustainable Development Conference held in 2002 (Mulder *et al*., 2010). Since then, there has been an increasing effort to integrate sustainability and sustainable development issues into engineering curricula, and this is reflected in an increasing body of literature on the topic. But it is unclear where we are on our journey towards introducing and applying sustainability concepts, approaches, tools and paradigms within engineering education. This paper takes stock of the field.

While there have been several recent literature reviews on sustainability and sustainable development in higher education, these have not typically been in the context of engineering education. These reviews are also restricted to a relatively small sample of papers (Figueiró & Raufflet, 2015; Blanco-Portela *et al*., 2017) or to a focus on descriptive measures (e.g. Karatzoglou, 2013). For example, Figueiró & Raufflet (2015) reviewed 63 papers from 12 journals (from 2003 to 2013) to identify challenges, teaching techniques, and curriculum orientation in management education while Blanco-Portela *et al*. (2017) reviewed 35 papers (from 2000 to 2016) to identify the drivers and barriers to change. It is argued here that a broader, less myopic view is required to adequately take stock of what has been achieved to date. Moreover, there is no review that isolates articles on case implementations to explore what has actually been done in practice. In response, this study started by asking: What is the current state-of-the-art on integrating sustainability and sustainable development into engineering curricula? A comprehensive, systematic review of the literature was conducted to answer this question in terms of: (i) research; and, (ii) practice. Based on this review, the study outlines important future research questions. It is hoped that answering these broad research questions will contribute to providing engineering education with the means to help engineers confront the environmental, social, and economic challenges of the 21st century.

The remainder of this paper is organized as follows. The method followed to conduct the systematic literature review is outlined next in Section 2. Section 3 then presents the results before an overall discussion is provided in Section 4. Final conclusions are then summarized in Section 5.

2. Method – Systematic Review of the Literature

This paper starts by asking:

What is the current state-of-the-art on integrating sustainability and sustainable development into engineering curricula?

The focus is on how sustainability has been integrated into higher education (at the undergraduate and postgraduate level) rather than on what aspects of sustainability have been incorporated. This largely relies on case reports of the process of integration or implementation rather than on cataloguing what material, modules, or programs have been developed. Consequently, this study uses a systematic review of the literature rather than secondary data from university websites to answer this question. We also do not assess the contribution of existing curriculum to sustainability and sustainable development; for this, the reader is referred to Lozano (2010) and Lozano & Young (2013).

A systematic procedure for retrieving and selecting the articles (following Tranfield *et al.* (2003)) was used. Subsections 2.1 to 2.3 outline the approach adopted for sourcing, screening, and analyzing the articles, respectively.

2.1 Sourcing the Articles

The bibliographic database used for sourcing the articles was Scopus – due to its large coverage, e.g. compared to Web of Science, and its accuracy in terms of citation counts, e.g. compared to Google Scholar. It is recognized that there is an extensive literature in the form of books and white papers, but it was not possible to have access to all relevant books for a systematic review. In order to keep the number of articles reasonable and to ensure the quality of the sources, the search was further restricted to peer-reviewed articles. Scopus was queried in April 2017 using the terms: 'Sustainable AND Engineering AND Education'; 'Green AND Engineering AND Education'; 'Sustainable AND Engineering AND Curriculum'; and 'Green AND Engineering AND Curriculum'. While the keyword 'Green' may introduce a bias towards one dimension of sustainability (i.e. environmental), it is included since it is often applied in engineering. To keep results to a manageable number, the search was restricted to the title, abstract, and keywords of papers. No limit on the subject area was applied to reflect the multidisciplinary nature of engineering education. Document type was limited to 'articles' and 'reviews'. There was no restriction on the year of publication or the journals considered (beyond being peer-reviewed). For the four search terms, 1,046, 203, 307, and 66 articles were retrieved, which makes a total of 1,622 articles.

2.2 Screening the Articles

The original sample of 1,622 articles was reduced to 1,230 by removing duplicates. This was further reduced to 408 articles by excluding apparently unrelated articles, i.e. articles not concerned with higher education and engineering. The high number of unrelated articles is justified since no limitations on the subject area were applied. The sample of 408 articles was further reduced based on citation counts. This approach was chosen since it is arguably more objective than using a time limit or putting a limit on the journals that are considered or requiring explicit discussion of the concepts of interest, as used in previous studies (e.g. Figueiró & Raufflet, 2015; Blanco-Portela *et al*., 2017).

It was decided that the final sample would be limited to papers that had been cited at least two times, with the cut-off point of two citations set arbitrarily. Since this cut-off point would be unfair for recently published articles, articles with less than two citations were included if they were published in 2015 or 2016. Thus, all articles with less than two citations and published in 2014 or earlier were removed from the sample. This includes articles for which no citation count could be obtained (112 articles). The resulting sample was comprised of 299 articles. Using several channels for retrieving the full articles, i.e. the different university systems available to the authors, a total of 232 articles were obtained.

To ensure that relevant articles were not missed, the references in the 232 articles were cross-checked. From this process 15 additional relevant articles were retrieved. This approach of supplementing the set of articles that had been mechanically retrieved helped to ensure that the list of articles was complete, but the number of articles added (15) was insufficient to suggest that the original search process was inadequate. The final sample of analyzed full papers was 247 articles from which 70 were case reports on the integration of sustainability and sustainable development into engineering curricula. The screening process is summarized in Table 1.

[Take in Table 1]

Finally, the distribution of articles by year of publication is shown in Figure 1. A steep increase in the number of articles can be observed after 2005, i.e. from the beginning of the United Nations Decade for Education for Sustainable Development. Other measures, such as the distribution of articles per journal, author, etc. were obtained but did not provide any revealing insights and therefore are not presented here.

[Take in Figure 1]

2.3 Analyzing the Articles

This stage involved extracting and documenting information from each of the 247 sources. To minimize subjectivity, the authors: (i) cross-checked results; and, (ii) conducted regular meetings to resolve any emerging inconsistencies in interpreting the results. The major research vehicle was content analysis (see, e.g. Krippendorff, 2003).

This study acknowledges the difficulty in seeking to define ‘sustainability’ or ‘sustainable development’ so that it is applicable to all curricula. Rather, the integration of sustainability and sustainable development can be seen as the result of a set of practices in which various aspects are continuously recombined and expressed in varying degrees of intensity. It follows that to understand the nature, strengths, and flaws of the practices reported in the literature, it is necessary to investigate the concepts and theories underlying the practices and procedures rather than to search for overarching definitions that aim to establish a global reference framework for curriculum transformation. What matters is how practices are conceptualized by the educators and how they are implemented in the curricula in the 'real' world. As a template for data collection, a simple matrix was used where, for each paper (row), the following questions (columns) were asked:

- What were the new practices?
- Who were the subjects and objects of the practices?
- What was the influence of other (internal and external) stakeholders?
- What were the results of the application of the new practices?

3. Results

This section discusses the results of the analysis for each of the above four questions – What were the new practices? Who were the subjects and objects of the practices? What was the influence of other (internal and external) stakeholders? And, what were the results of the application of the new practices? – in Section 3.1 to Section 3.4, respectively. Each section begins with a presentation of the findings based on an evaluation of the 70 papers that presented case reports on the integration of sustainability and sustainable development. This is followed by a discussion informed by the broader literature, leading to our future research questions.

Table 2 to Table 4 summarize the universities where the implementations occurred, the corresponding reference, the study level (undergraduate or postgraduate), and the engineering discipline according to geographical region. Table 2 presents implementations in Europe, Table 3 in North America, and Table 4 in the remaining regions (and contributions that could not be classified by location). Within each table, contributions are sorted by country (wherever possible) and then by engineering discipline. Note that the number of implementations is higher than the number of papers since some studies report on multiple implementations. From Table 2 to Table 4, a dominance of contributions from Europe (34 out of 82) and the US (30 out of 82) can be observed. In general, there is a clear dominance of contributions from highly developed countries with similar higher education systems. Cases should therefore be fairly comparable. Of course, there are always regional differences, but no clear pattern could be identified in this study. Meanwhile, most cases report on implementations at the undergraduate level and on a diverse set of engineering disciplines.

[Take in Table 2, Table 3 & Table 4]

3.1 What Were the New Practices?

Mulder *et al*. (2010) criticized that the first sustainable development courses were often a series of lectures that were added on to existing programs. Meanwhile, Kamp (2006), in their report on Delft University's journey towards sustainable education, presented three approaches to integrating sustainable development into the curriculum:

1. Embedding the concept of sustainable development into regular disciplinary courses;
2. The design of a new elementary course; and,
3. Providing the option to graduate in a sustainable development specialization.

These three approaches summarize what in general has been reported in the literature. The introduction of new courses is by far the most frequently followed path in our sample (31 studies). Authors of 15 studies reported on course adaptation. Another important approach is the introduction of sustainability related topics via project work (10 studies). This typically went hand-in-hand with a discussion on the importance of active learning where project-based learning was generally the preferred method.

3.1.1 Discussion of the Broader Literature

The extent of the change made to the curriculum to integrate sustainability may range from new material in an existing module to a new module in an existing program to an entirely new program of study on sustainability. However, there is little research on which approach is better placed to deliver the competencies and understanding required for sustainability issues. While it may appear that programs that engage in continuous thematic development of the concepts are better placed, this view is questioned by Lozano & Young (2013) who measured the sustainability exposure of students across undergraduate and postgraduate courses at the University of Leeds. The authors found that sustainability related courses do not provide the highest exposure and may even be ranked towards the lower end of the distribution. Moreover, the process of developing a new degree poses a number of challenges, such as regarding the connectivity of courses and the curricula contribution to sustainability (Lozano & Lozano, 2014). This leads to a first important research question:

FRQ1: Which approach to integrating sustainability into the engineering curricula is best suited to expose students to sustainability issues?

In general, there appears to be an agreement on the importance of active learning (e.g. Gutierrez-Martin & Hüttenhain, 2006), which has the potential to increase a student's retention level compared with 'traditional' educational approaches that see learning and teaching as a purely cognitive process of 'to think', 'to analyze', and 'to comprehend' (Dieleman & Huisingh, 2006). However, active learning (e.g. in the form of project based learning) requires significant effort and often good contacts with external stakeholders while it also creates problems in the evaluation of individual learning accomplishments (Mulder *et al*., 2012). An alternative that overcomes at least the problem of requiring external stakeholders is the use of games, simulations, or role plays. However, while platforms that provide information, support material, and case studies to facilitate integrating sustainability into the curriculum were presented, e.g. in Perdan *et al*. (2000), Fletcher & Dewberry (2002), and Verhulst & Doorselaer (2015), these contributions did not provide games. Dieleman & Huisingh (2006) discussed some games that can be used to engage and empower students to think and act in new, more sustainable ways; but more needs to be done, potentially including virtual reality – see, e.g. Tarng (2015) in the context of an elementary school. This leads to a second future research question:

FRQ2: What tools should (and could) be developed and used to support active learning on sustainability and sustainable development in engineering curricula?

3.2 Who Were the Subjects and Objects of the Practices?

The term 'subject' refers to the implementer of a practice while the term 'object' refers to the objective of the practice (what is to be transformed). In terms of subjects and objects, two classes of papers were found:

1. *Subjects of practices are the faculty and objects are the students*: This was the clear majority class, incorporating 67 of the studies. There were two studies (out of the 67) where the objects were PhD students – Baas *et al*. (2000) and Bergea *et al*. (2006).
2. *Subjects of the practice are institutions and the objects are faculty and students*: There were only three studies that fall under this class. Barnes & Jerman (2002) discussed the Sustainable University Initiative, Kagawa (2007) discussed the Center for Sustainable Futures, and the Ecodesign Center was discussed in O'Rafferty *et al*. (2014).

3.2.1 Discussion of the Broader Literature

Sustainability is a concept with both factual and value-based components (Carew & Mitchell 2008). This suggests that, rather than only focusing on course content, academics should develop approaches to teaching and learning that consider the role of values and assumptions in sustainable decision-making. For example, Pellicer *et al*. (2016) found that the degree of sustainability in the decisions of graduate students enrolled in the Project Feasibility course at the Polytechnic University of Valencia depended on the background of the students. However, the values and assumptions of teachers are also important. For example, Brown *et al*. (2015) reported that the incorporation of sustainability issues depends on a teacher's attitude towards sustainability. While there are studies that assess the main effect of values and attitudes, more needs to be done to explore the interaction effects of different value and knowledge frameworks. The third future research question therefore asks:

FRQ3: How does the interaction between a teacher's and student's knowledge and value frameworks influence the integration of sustainability into the curricula?

There are also differences in the knowledge (and potentially value) frameworks between undergraduate and postgraduate students. For example, Boyle (2004) and Biswas (2012) reported on the immaturity of undergraduate students. Postgraduate students were found to be more mature because of their greater work experience and social interactions (Biswas, 2012), and this meant that they were, in general, more interested in developing their knowledge including how to apply sustainability principles in organizations. However, both studies provided rather cursory evidence. The fourth future research question therefore asks:

FRQ4: How does the knowledge framework and value framework differ between undergraduate and postgraduate students?

In a recent survey from Shandong University, Yuan *et al*. (2013) found that alumni shown much higher levels of awareness of local and global environmental issues than faculty and parents. Similarly, 90% of the students in Kagawa's (2007) survey at Plymouth University had a positive attitude towards sustainability. Unfortunately, neither study indicated whether the sample consisted of undergraduate or postgraduate students (or alumnus). If the sample is representative of undergraduate students, then there exists a contrast between the knowledge framework – which should still be ill developed at this stage according to, e.g. Boyle (2004) and Biswas (2012) – and the value framework. This leads to a fifth future research question:

FRQ5: What is the relationship between students' knowledge framework and value framework in the context of sustainability and sustainable development?

The lower awareness of local and global environmental issues (intrinsic motivation) observed for faculty when compared to students is further amplified by a lack of extrinsic motivation. In fact, in the study by Yuan *et al*. (2013), faculty, alumni, and students ranked factors related to faculty and staff development and rewards as least important. Similarly, Lozano *et al*. (2015a) reported that there is limited focus on staff training programs. This leads to the sixth future research question:

FRQ6: How can faculty be motivated to integrate sustainability into the curricula?

3.3. What Was the Influence of Other (Internal and External) Stakeholders?

Almost none of the authors of the 70 case reports discussed the roles of stakeholders and most researchers did not report on possible stakeholders (apart from the subjects and objects of the practices). An exception was Costa & Scoble (2006) who listed collaborators, sponsors, and associates, including funding institutions, companies and governmental agencies as stakeholders.

3.3.1 Discussion of the Broader Literature

Under the seven points for student outcomes (often referred to as professional skills) listed in the Accreditation Board for Engineering and Technology (ABET, 2017) criteria for accrediting engineering programs in the 2019-2020 accreditation cycle, two criteria strongly related to sustainability and sustainable development can be found: (i) an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors; and, (ii) an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts. Unfortunately, the teaching of these professional skills can be particularly difficult for engineering faculty who must balance this against the need for increasing technical curriculum content (Siller *et al*., 2009). So a seventh future research question asks:

FRQ 7: How are accreditation requirements related to sustainability realized in practice?

If sustainability is to be included in university curricula, the relevant professional body for the particular discipline needs to be one of the driving forces (Van Berkel, 2000; Paten *et al*.

2005). However, there is often not a direct link between what industry wants and what universities provide. For example, Desha *et al*. (2009) found that there is a time lag between a shift in needs in terms of, for example, industry requirements, governmental regulations or academic program accreditation, and when University leadership responds. On the other hand, it often appears that industry is not sure what it actually wants. While there have been some attempts to capture industry needs (e.g. Lang *et al*., 1999), there has not been a focus on sustainability issues. This leads to the eighth future research question:

FRQ8: What sustainability related hard and professional (soft) skills does industry require from engineering students?

While the influence of industry on curricula design is widely recognized, an important stakeholder in the context of education has been neglected: the student's parent. Yuan *et al*. (2013) assessed the different views of alumni, faculty, and parents in a random sample study conducted at Shandong University. The alumni showed a much higher awareness of local and global environmental issues than faculty and parents. Faculty and parents also rank the importance of sustainability issues in the curricula much lower than students. But parents ranked job opportunities opened by the green university as second most important among seven factors while students only ranked it sixth out of seven. This raises the ninth future research question, which builds on question eight above:

FRQ9: How do parents (and their view of their child's future) impact the integration of sustainability and sustainable development into engineering curricula?

Finally, the 21st century is deeply influenced by the advancement of information and communication technology. However, none of the authors in the sample have investigated the impact of, for example, social media on curricula development. Information and communication technology deeply influences the creation of knowledge and value frameworks, as discussed in Section 3.3, and creates social pressure in the form of public opinion, which may affect decisions at all level of higher education. This leads to the tenth future research question:

FRQ10: How does society (e.g. in the form of social media) impact the integration of sustainability and sustainable development into engineering curricula?

3.4 What Were the Results of the Application of the New Practices?

In terms of actual results of implementations, most studies rely on *ad-hoc* interviews (Mihelcic *et al*., 2006; Johnston *et al*. 2007) or surveys (Chau, 2007; Bielefeldt, 2011; Wolcott *et al*. 2011; Bhandari *et al*. 2011; Biswas, 2012; Riley *et al*. 2006; Kagawa, 2007) with students (i.e. the objects of the practices). These authors reported an increased awareness of sustainability issues/solutions. However, surveys were (i) not comparable; and, (ii) rather subjective. They were not comparable since different authors used different measures and methodologies. They were rather subjective since no specific cumulative/reflective measures were applied. Rather, students were asked whether they agreed with statements such as "*The earth has plenty of natural resources for future generations*" to assess attitudes (Bielefeldt, 2011; Kagawa, 2007) or self-assessment questions were used, such as "*This course significantly improved my knowledge of sustainability, sustainable development and sustainable engineering*" (Bhandari *et al*., 2011) and "*How could you translate the lessons you've learned about sustainability in this class into your career and your lifestyle?*" (Riley *et al*., 2006).

3.4.1 Discussion of the Broader Literature

On the other hand, a set of mostly agreed upon key competencies and/or learning outcomes exists in the literature (see, e.g. Svanström *et al*., 2008; Lambrechts *et al*., 2013; Lozano *et al*., 2017) that promote the development and evaluation of curricula (Batterman *et al*. 2011). We argue that measures should be developed to capture these competencies. These measures can then be used to evaluate whether or not the objective of implementing sustainability issues into engineering curricula has been met or not. The eleventh future research question therefore asks:

FRQ11: What are appropriate measures to capture the competencies and learning outcomes associated with integrating sustainability into engineering curricula?

Most studies focus on assessing the achievement of learning outcomes at one point in time, thereby neglecting the actual learning process. Exceptions are the studies by Segalas *et al*. (2010 and 2012), which used conceptual maps to capture the result of integrating sustainability and sustainable development into the curriculum. They showed that student perceptions of sustainability approach teacher perceptions along the learning experience. But this may just be a sign of conformance, e.g. to obtain good grades. Kennedy *et al*. (2002) surveyed 102 students at the University of Toronto twice – at the beginning of their 2nd year of undergraduate study and towards the end of their 3rd year – using identical questions. Although students' answers to technical and attitudinal questions exhibited significant changes over the study period, none of the changes could, according to the authors, really be described as dramatic. The students did synthesize new knowledge over the 18 months of study, but their prior knowledge was still discernible in the later set of results. So it remains unclear whether and how students acquire knowledge over time. This leads to the twelfth and final future research question:

FRQ12: How does student acquisition of competencies and learning outcomes evolve over time?

4. Discussion

Sustainability is a contested concept (Carew & Mitchell, 2008), and Fisk & Ahearn (2006) anticipated that postgraduates would be impatient with the confusion of definitions often associated with 'sustainable development'. But, in general, most academics are likely to agree that sustainability and sustainable development are composed of three broad elements: the social, economic, and environmental dimensions. Segalas *et al*. (2010) added a fourth dimension, the institutional, which is comprised of the roles of education and external stakeholders such as governmental agencies, non-governmental organizations, etc. Segalas *et al*. (2012) further reported that experts in engineering education for sustainable development consider that institutional and social aspects are more relevant to sustainability than environmental aspects. This is in clear contrast to students (and probably the wider public), which mostly perceive the environmental aspect to be at the center of sustainability and sustainable development. For example, Kagawa's (2007) survey among students at Plymouth University found that almost half of the respondents related sustainability and sustainable development primarily with the environment while social, economic, political, and cultural dimensions of sustainability were less represented and remained marginal in the understanding of most students. Redressing this balance in the favor of social and institutional aspects is consequently seen by many researchers as a key task of education for sustainable development (Boks & Diehl 2006; Kagawa, 2007; Segalas *et al*. 2010, 2012).

Watson *et al*. (2013) argued that there has been a rapid increase in the number of engineering schools in higher education institutions that have incorporated sustainability into their curricula. Yet, although some advances have been made, Lambrechts *et al*. (2013) argued that higher education institutions are far from reorienting themselves towards sustainability; rather, sustainability appears to be integrated in a peace-meal fashion. Similarly, in a survey among 43 participants of the International Engineering Academic Workshop held during the 2010 International Symposium on Engineering Education, Byrne *et al*. (2013) found that none of the delegates agreed that sustainability knowledge and skills are thoroughly embedded within the engineering curricula at their university. Additionally, based on a survey of final year engineering students across a range of engineering disciplines in several Irish higher education institutions, Nicolaou & Conlon (2012) found that engineering students' knowledge of sustainable development is between 'heard but could not explain' and 'have some knowledge'.

To the question – What should engineers learn on sustainable development? – Mulder *et al*.'s (2012) answer was: (i) what are the problems; and (ii) how should they be solved. During this review, it was felt that most of the cases focused on creating environmental awareness and system thinking when identifying problems and solving them. For example, Gutierrez-Martin & Hüttenhain (2003) argued that there is no lack of expertise in either environmental or conventional technology, rather what is limited is a holistic approach to engineering that incorporates the environment into the mainstream of technological application and thought. However, this misses the important fact that many of the challenges of the 21st century do not have solutions in the traditional sense – they probably cannot be solved, but only managed (Siller *et al*. 2016). Siller *et al*. (2016) highlighted the similarities with developments in medical education where the realization that many illnesses are impossible to cure (so-called chronic illnesses) led to a change in how medicine was taught. Siller *et al*. (2016) argued that creating awareness during the problem definition process, that not all problems can be solved and that some need to be managed, allows for better, more integrated holistic/system thinking.

Finally, this study understands learning as an activity. This activity takes place in an activity system that is constituted of different parts. Figure 2 illustrates Engeström's general model of an activity system (e.g. Engeström & Sannino, 2010). Each of the 12 future research questions that emerged during our literature review is positioned in this activity system to allow for a better contextualization of the questions. These questions are also summarized in Table 5. The set of questions is not exhaustive nor does this represent a comprehensive investigation program. Rather, the questions summarize a series of research gaps that were identified during the review process. It is believed that addressing these questions is a first important step towards the urgently needed curricula and research transformation that would actively accelerate the transition to equitable, sustainable, livable, post-fossil carbon societies.

[Take in Table 5 & Figure 2]

5. Conclusions

There is no doubt that there is a strong political will and commitment towards sustainability and sustainable development. This has had an impact on education, including higher education. As a result, more and more university leaders and faculty members have begun to recognize the importance of sustainability and sustainable development. Consequently, there is an increasing body of literature on the integration of sustainability and sustainable development into engineering curricula at universities around the globe. But while there have been several recent literature reviews, these reviews did not focus on engineering, have been limited in scope and did not explicitly discuss implementations. In response, this study asked: what is the current state-of-the-art on integrating sustainability and sustainable development into engineering curricula? Focusing on the implemented practices, a comprehensive, systematic review of the literature was used to answer this question. The findings can be summarized as follows. The degree of change in the curricula ranges from new material on sustainability in an existing module, to a new module on sustainability in an existing program, to an entirely new program of study on sustainability. Subjects of the implemented practices are mostly teachers while the objects are the students. Finally, the importance of external stakeholders is seldom discussed and the evaluation of results of the integration of sustainability into curricula in practice is rather cursory. Based upon this systematic review, twelve important future research questions have emerged. This includes the exploration of the knowledge and value frameworks of students and teachers, the exploration of stakeholder influences, including accreditation institutions, industry partners, parents and society, and the use of competencies for the evaluation of implementations.

A major limitation of this paper is its focus on the scientific literature. Future research could extend this study and include books, white papers, university program outlines, etc. Another important extension would be to focus on other disciplines than engineering or to focus on different learning contexts such as non-formal or informal education. Finally, this systematic review of the literature encountered 70 case reports from 82 universities. The majority of these universities are located in Europe and the USA. There appears to be a lack of studies or implementations in developing economies. This is in the authors' opinion a major shortcoming given the important role that developing economies play in the context of sustainable development. This study therefore calls for more studies from these geographical regions of the world.

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Highlights

- Presents a systematic literature review on sustainability in engineering curricula
- Provides an important reference guide for the research community
- Outlines twelve future research areas to further develop the field

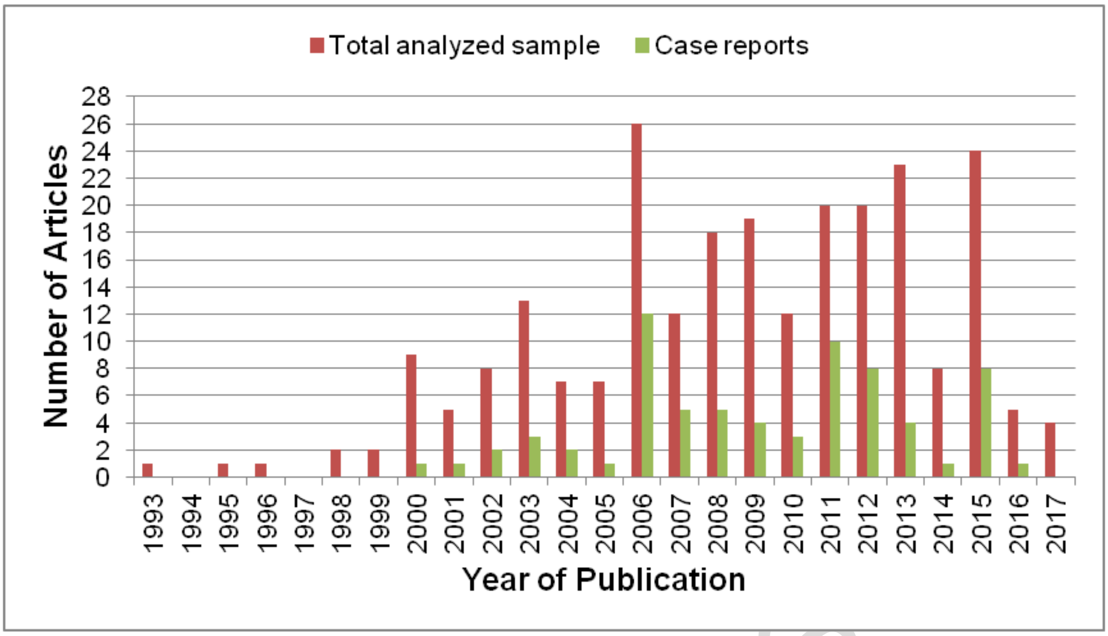

Figure 1: Summary of Basic Sample Characteristics – Distribution of Articles per Year (Total and Case Reports)

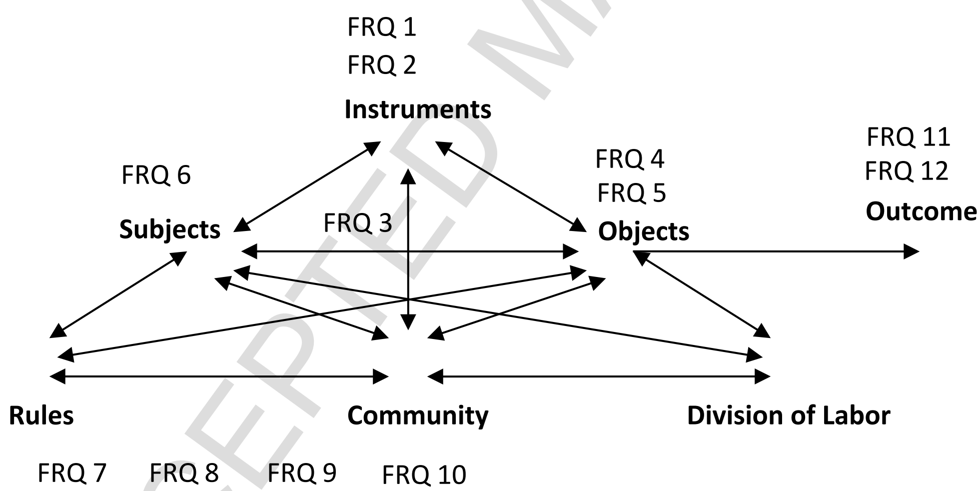

Figure 2: The Positioning of Our Research Questions in Engeström's General Model of an Activity System

Table 1: Summary of Screening Procedure

Screening Step	Number of Articles in Sample
Original sample	1622
Duplicates removed	1230
Apparently unrelated articles removed	408
After cut-off point	299
Articles that could be retrieved	232
Additional articles from the references added	247
Final Sample	247

Table 2: Case Reports (Europe) – Universities Where Implementations Have Occurred and Corresponding Article(s)

University of Implementation	Reference	Level[1]	Discipline
Technical University Berlin, Germany	Othman et al., 2012	u, p	chemical process engineering
Aalborg University, Denamrk	Lehmann et al., 2008	u, p	environmental engineering
Technical University of Denmark, Denmark	McAloone, 2007	u, p	general engineering
University of Thessaly, Greece	Manoliadis, 2009	u	civil & environmental engineering
Limerick University, Ireland	Quinn et al., 2009	u	general engineering
Kaunas University of Technology, Lithuania	Staniskis & Stasiskiene, 2007	p	environmental engineering
Technical University of Lodz, Poland	Doniec, 2006	u, p	production engineering
Politechnical University Valencia, Spain	Pellicer et al., 2016	p	civil engineering
Technical University of Catalonia, Spain	Segalàs et al., 2010	u	general engineering
Technical University of Catalonia, Spain	Mulder, 2004	u, p	general engineering
Technical University of Catalonia, Spain	Capdevila et al., 2002	u, p	general engineering
Technical University of Catalonia, Spain	Mulder et al., 2010	u	general engineering
Chalmers University, Sweden	Svanström, 2012	u, p	civil & environmental engineering
Royal Institute of Technology, Sweden	Bergeå et al., 2006	p	environmental engineering
Malardalen University, Sweden	Bergeå et al., 2006	p	environmental engineering
University of Kalmar, Sweden	Bergeå et al., 2006	p	environmental engineering
Chalmers University, Sweden	Lundqvist & Svanström, 2008	u	general engineering
Blekinge Institute of Technology, Sweden	Missimer & Connell, 2012	u, p	general engineering
Ersamus University, The Netherlands	Baas et al., 2000	p	environmental engineering
Delft University of Technology, The Netherlands	Segalàs et al., 2010	u	general engineering
Delft University of Technology, The Netherlands	Kamp, 2006	u	general engineering
Delft University of Technology, The Netherlands	Quist et al., 2006	u	general engineering
Delft University of Technology, The Netherlands	Mulder, 2004	u, p	general engineering
Delft University of Technology, The Netherlands	Mulder et al., 2010	u	general engineering
Delft University of Technology, The Netherlands	Peet et al., 2004	u	general engineering
Delft University of Technology, The Netherlands	Boks & Diehl, 2006	n	industrial design engineering
Newcastle University, UK	Glassey & Haile, 2012	u	chemical engineering
Imperial College London, UK	Fisk & Ahearn, 2006	p	environmental engineering
University of Leeds, UK	Lozano et al., 2015	u, p	environment and business
University of Manchester, UK	Tomkinson et al., 2008	u	general engineering
Cambridge University, UK	Fenner et al., 2005	u, p	general engineering
University of Plymouth, UK	Kagawa, 2007	u	general engineering
State University of Chemical Engineering, Ukraine	Zadorsky, 2006	u, p	chemical engineering
Kiev Polytechnic Institute, Ukraine	Segalàs et al., 2010	u	general engineering

[1)] u – undergraduate; p – postgraduate; n – not clear

Table 3: Case Reports (North America) – Universities Where Implementations Have Occurred and Corresponding Article(s)

University of Implementation	Reference	Level[1]	Discipline
University of British Columbia, Canada	Costa & Scoble, 2006	u, p	mining
University of Calgary, Canada	Johnston et al., 2007	u	general engineering
Universidad Autonoma Metropolitana, Mexico	Juárez-Nájera et al., 2006	u	general engineering
Pennsylvania State University, USA	Riley et al., 2006	u, p	architectural engineering
Michigan Technological University, USA	Michelic et al., 2006	p	civil & environmental engineering
Georgia Tech, USA	Watson et al., 2013	u	civil & environmental engineering
Colorado State University, USA	Siller, 2001	u	civil engineering
Catholic University of America, USA	Kelly, 2008	u	civil engineering
University of Missouri, USA	Kevern, 2011	u	civil engineering
University of Nebraska, USA	Alahmad et al., 2011	u, p	civil engineering
Florida A&M University (FAMU), USA	Clark & Gragg III, 2011	u	civil engineering
University of Toledo, USA	Apul & Philpott, 2011	u	civil engineering
University of Colorado, USA	Bielefeldt, 2011	u, p	civil engineering
University of Texas at Arlington, USA	Weatherton et al., 2015	u	civil engineering
Rose-Hulman Institute of Technology, USA	Price & Robinson, 2015	u	civil engineering
California Polytechnic State University, USA	Braun, 2010	u	electrical engineering
Washington University, USA	Wolcott et al., 2011	u, p	engineering design
University of Nebraska, USA	Dvorak et al., 2011	u	environmental engineering
University of Colorado, USA	Amadei et al., 2009	u	general engineering
University of California, USA	Bacon et al., 2011	u	general engineering
Kettering University, USA	Aurandt & Butler, 2011	u	general engineering
University of Oklahoma, USA	Aurandt & Butler, 2011	u	general engineering
Iowa State University, USA	Bhandari et al., 2011	u	general engineering
The James Madison University, USA	Nagel et al., 2012	u	general engineering
University of New Haven, USA	Aktas, 2015	u	general engineering
United States Air Force Academy, USA	Christ et al., 2015	u	general engineering
Worcester Polytechnic Institute, USA	Lesar et al., 2012	u	material science and engineering
Iowa State University, USA	Lesar et al., 2012	u	material science and engineering
California Polytechnic State University, USA	Lesar et al., 2012	u	material science and engineering
Clemson, USA	Barnes & Jerman, 2002	n	not clear
Medical University of South Carolina, USA	Barnes & Jerman, 2002	n	not clear
University of South Carolina, USA	Barnes & Jerman, 2002	n	not clear
University of New Haven, USA	Aktas et al., 2015	u, p	not clear

[1)] u – undergraduate; p – postgraduate; n – not clear

Table 4: Case Reports (Africa, Asia, Australia and Other) – Universities Where Implementations Have Occurred and Corresponding Article(s)

University of Implementation	Reference	Level[1]	Discipline
University of Cape Town, South Africa	von Blottnitz, 2006	u	chemical engineering
National Pingtung University of Science and Technology, Taiwan	Tsai, 2012	u	general engineering
Tajen University of Technology, Taiwan	Tsai, 2012	u	general engineering
Sultan Qaboos University, Oman	Abdul-Wahab et al., 2003	u	civil engineering
RMIT University, Australia	Sharma, 2009	u, p	architecture and design
RMIT University, Australia	Jollands & Parthasarathy, 2013	u	chemical engineering
University of Sydney, Australia	El-Zein et al., 2008	u	civil engineering
Curtin University, Australia	Rosano & Biswas, 2015	u, p	civil and mechanical engineering
Curtin University, Australia	Biswas, 2012	u, p	general engineering
Swinburne University, Australia	Lockrey & Bissett Johnson, 2013	u	product development engineering
Not clear	Chau, 2007	u	civil engineering
Not clear	Steinemann, 2003	u	civil engineering
Not clear	Gutierrez-Martin & Hüttenhain, 2003	n	general engineering
Not clear	Lu & Zhang, 2013	u	general engineering
Not clear	O'Rafferty et al., 2014	u	product development engineering

[1)] u – undergraduate; p – postgraduate; n – not clear

Table 5: Summary of Future Research Questions (FRQs) Emerging from Our Review

Future Research Question (FRQ)		
Implemented practice	FRQ1:	Which approach to integrating sustainability into the engineering curricula is best suited to expose students to sustainability issues?
	FRQ2:	What tools should (and could) be developed and used to support active learning on sustainability and sustainable development in engineering curricula?
Subjects and Objects of the Practices	FRQ3:	How does the interaction between a teacher's and student's knowledge and value frameworks influence the integration of sustainability into the curricula?
	FRQ4:	How does the knowledge framework and value framework differ between undergraduate and postgraduate students?
	FRQ5:	What is the relationship between students' knowledge framework and value framework in the context of sustainability and sustainable development?
	FRQ6:	How can faculty be motivated to integrate sustainability into the curricula?
(Other) Stakeholders	FRQ7:	How are accreditation requirements related to sustainability realized in practice?
	FRQ8:	What sustainability related hard and professional (soft) skills does industry require from engineering students?
	FRQ9:	How do parents (and their view of their child's future) impact the integration of sustainability and sustainable development into engineering curricula?
	FRQ10:	How does society (e.g. in the form of social media) impact the integration of sustainability and sustainable development into engineering curricula?
Outcome or Results	FRQ11:	What are appropriate measures to capture the competencies and learning outcomes associated with integrating sustainability into engineering curricula?
	FRQ12:	How does student acquisition of competencies and learning outcomes evolve over time?