INTRODUCING SUSTAINABLE DEVELOPMENT IN ENGINEERING EDUCATION: COMPETENCES, PEDAGOGY AND CURRICULUM

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Paraules clau: Education, Competences, Sustainability, Conceptual maps

ABSTRACT

Introducing sustainable development (SD) in engineering education has been a key topic in many technological universities [1], accreditation agencies and International and National networks of universities.
At the UNESCO chair of Sustainability of the Technical University of Catalonia (UPC) under their PhD program on Sustainability the authors have carried out a research on:

1. Which SD competences may engineers have when graduating?
2. How should SD competences be taught/learned at technological universities?
3. Which curriculum structure is more suitable to facilitate the acquisition of SD competences?

To evaluate the competences we compared three leading European universities in introduction of SD. The competences are classified in three categories: knowledge and understanding, skills and abilities and attitudes [2].
To evaluate the pedagogical approach that facilitates the SD learning we analysed 10 case studies of courses on Sustainability from 5 European technological universities. We used conceptual maps [3, 4] as assessment tool.
To analyse the curriculum design for SD 50 experts on curriculum design and teaching SD courses were interviewed.
The methodology and results of this work are presented and recommendations to introduce SD in technological universities in the three fields: competences, pedagogy and curriculum are suggested.

1. INTRODUCTION

Nowadays there are a considerable number of contrasting signs which highlight that our society is contributing to the planet's collapse: a growing environmental burden, tremendous wealth imbalances, an ecological footprint that is exceeding the earth's carrying capacity, people who can not cover their basic needs, etc. increase year after year. For the first time in history, humans are pervasive and dominant forces in the health and well-being of the earth and its inhabitants. We are the first generation capable of destroying the habitability of the planet for humans and other species. Engineers have played a key role in the unsustainabilities in our society.

This society needs scientists, engineers, and business people who design technological and economic activities that sustain rather than degrade the natural environment; activities that enhance human health and well-being. Therefore, "*a new kind of engineer is needed, an engineer who is fully aware of what is going on in society and who has the skills to deal with societal aspects of technologies*" [5]. In this context, higher education institutions have the responsibility to educate graduates who have achieved an ethical moral vision and the necessary technical knowledge to assure the quality of life for future generations. This implies [6] that sustainable development will be the framework in which higher education has to focus its mission.
In relation to SD, so far there is no direct relation between educated societies with the highest rate of "educated" citizens and the highest sustainability[i]. Sustainability demands a specific kind of learning; quoting E.F. Schumacher [7]: "*The volume of education… continues to increase, yet so do pollution, exhaustion of resources, and the dangers of ecological catastrophe. If still more education is to save us, it would have to be education of a different kind: an education that takes us into the depth of things*". Therefore a new kind of education is needed. Stephen Sterling [8] maintains that the nature of sustainability requires a fundamental change of epistemology, and therefore, of education.
Since Education for Sustainable Development has been on the agenda of many engineering faculties since the late nineties, many approaches have been developed to graduate well-trained engineers with the knowledge, abilities, values and attitudes needed to switch to SD. Related to these approaches to graduate sustainable engineers, three main questions arise:

1. Which SD competences must an engineer learn at university?
2. How can these competences be acquired efficiently? The role of pedagogy.
3. Which education structure is more effective for the required pedagogy and also to embed SD in the curriculum?

The first main question is a "*What*" question, which focuses on what competences: knowledge/understanding, skills/abilities and attitudes an engineer graduating in the 21st century should have in relation to SD. The second main question is a "*How*" question and focuses on how the education processes through the proper pedagogical strategies can make this learning achievable. The last main question is a "*Where*" question from the perspective of the curriculum and the organizational structure needed to apply the optimal didactics to achieve the goal of graduating sustainable engineers. A proposed answer to these questions is presented in the next sections.

2. EVALUATION OF SD COMPETENCES

The Organisation for Economic Co-operation and Development's (OECD) Education minister stated that "Sustainable Development and social cohesion depend critically on the competences of all of our population – with competences understood to cover knowledge, skills, attitudes and values" [9]. Therefore the definition of SD competences is a key subject in education in general and in engineering education in particular if the important role that engineers have as change agents to sustainability is considered.
Competences represent a dynamic combination of cognitive and meta-cognitive skills, knowledge and understanding, interpersonal, intellectual and practical skills, and ethical values. Fostering competences is the object of educational programmes. Competences will be formed in various course units and assessed at different stages.
In this work the description of competences embraces three strands:

- *Knowledge and understanding*: Theoretical knowledge of an academic field, the capacity to know and understand.
- *Skills and abilities*: practical and operational application of knowledge to certain situations.
- *Attitudes*: Values as an integral element of the way of perceiving and living with others and in a social context.

There have been many approaches to define the SD learning outcomes and/or competences that engineering students should have when graduating. An important milestone in the definition of learning outcomes and competences for engineering education is the Barcelona Declaration [10], which was the result of the work of the EESD 2004 conference scientific committee.

At a national level there have also been some approaches to defining SD competences and/or learning outcomes. For example in United Kingdom the Engineering Council defined the UK Standard for Professional Engineering Competence. Another example of competences for SD can be found in the Criteria for accrediting engineering programs from the Accreditation Board for Engineering and Technology. In the Netherlands the three technological universities (Delft University of Technology, Eindhoven University of Technology and the University of Twente) developed the Criteria for Academic Bachelor's and Master's Curricula [11]. At an international level an additional scheme is the CDIO™ INITIATIVE, an innovative educational framework of curricular planning and outcome–based assessment for engineering universities and schools.

The analysis of these examples of SD competences in engineering education shows that the communalities are very high and most competences are related:

- *Critical thinking* is regularly mentioned explicitly (…is able to critically reflect...; .. "why" and "what if" reasoning…) and implicitly (…understand how their work interacts with society and the environment…) in sets of competences. The idea of mental processes of discernment, analysis and evaluation in an open-minded point of view is often highlighted.
- *Systemic thinking* is expressed as the idea that everything interacts with the things around it and that the world therefore consists of complex relationships. The need for having the competence to move beyond the tradition of breaking reality down into disconnected parts.
- *Inter-trans-disciplinarity* is also stated as important for SD taking into account both, the participation of different professionals to solve problems and stakeholder participation in technological processes.
- *Values and ethics* are at the core of the meta-cognitive sets of competences, they are shown as the main force to change attitudes to act personally and professionally for SD.

In order to find out what the real situation at university level is, a comparison of the sustainability competences of bachelor engineering graduates from three European technological universities: Chalmers University of Technology (CUT) in Goteborg, Sweden, Delft University of Technology (DUT) in Delft, The Netherlands, and the Technical University of Catalonia (UPC) in Barcelona, Spain has been done.

Table 1 presents the commonalities between the three universities sorted by cognitive domain and clustered in keywords. The maximum level of achievement in the three universities according to Bloom's [12] and Krathwohl's [13] taxonomies is also introduced in the table.

From the comparison of SD competences between the three universities, the study shows that there is a strong convergence in the fundamental meaning of competences, although there is also a scarce matching among the descriptions formulated. The analysis of competences showed divergences in their descriptions, which makes it difficult to compare the programmes from different universities. Therefore progress needs to be achieved towards more similar descriptions in order to allow the EHEA system to make use of the transferability of European degrees, also in the domain of SD. The definition of competences is a learning process. This study shows that the definition of SD competences still has to be much improved in order to facilitate their integration into the engineering curricula.

It is important to see the matching between the SD generic competences proposed at supra-university level (accreditation agencies, professional bodies, etc.) and the competences stated at the three evaluated universities. For example, all require *Critical* *thinking*, *Systemic thinking*, *Inter-trans-disciplinarity* and *Values and ethics* to bachelor engineer graduates. However an important point for discussion is whether these SD competences are assessed in the programs and how they are evaluated.

Cognitive domain	Key word	Level of achievement
Knowledge and understanding	World current situation	Comprehension
	Causes of unsustainability	Comprehension
	Sustainability fundamentals	Comprehension
	Science, technology and society	Comprehension
	Instruments for sustainable technologies	Knowledge
Skills and abilities	Self-learning	Application
	Cooperation and transdisciplinarity	Evaluation
	SD Problem solving	Synthesis
	Systemic thinking	Evaluation
	Critical thinking	Evaluation
	Social participation	Evaluation
Attitudes	Responsibility Commitment SD challenge acknowledgement	Valuing
	Respect Ethical sense Peace culture	Organization
	Concern Risk awareness	Value complex

Table 1. SD key competence words for Bachelor degree at CUT, DUT and UPC

3. LEARNING IN SUSTAINABILITY ENGINEERING COURSES

A reorientation on pedagogy and learning processes is a must to achieve an effective education for sustainable development. Quoting the Barcelona declaration [10] "*teaching strategies in the classroom and teaching and learning techniques must be reviewed*". In that direction, recently, experts [14, 15, 16, 17, 18] are suggesting different schemes and actions to facilitate and promote this needed pedagogy transformation in higher education institutions and in engineering education specifically. Keeping in mind this new pedagogical approach needed for ESD, 10 case studies of specific Sustainability courses offered in 5 European technological universities have been examined, in which more than 500 students have participated. See Table 2. The methodology of analysis consists of, first, evaluating the SD learning achieved by students and, second, relating this learning to the pedagogy used in each case.

Conceptual maps (Cmaps) are used as an assessment tool to evaluate the SD learning achieved by students. The study is specifically based on Cmap assessment with the lowest degree of directness and no concept, linking line, linking phrase or Cmap structure was provided to students. The following assessment components have been considered in the analysis: the number of concepts, the relevance of concepts, the number of links and the complexity of the Cmap.

The research design used is the quasi-experimental pretest-posttest design. This design requires a Cmap (Cmap$_1$) to be recorded in a single group of individuals before the learning activity (L_A) and only one observation (Cmap$_2$) after the administration of the learning activity, since there is only one group of individuals. Therefore by comparing the results before and after the course, the learning achieved can be

evaluated. Nevertheless it should be borne in mind that conceptual maps are only evaluating the cognitive domain, which means how students understand Sustainability.
A 4-category taxonomy (taxonomy defined by the Sustainability Portal of the UNESCO Chair of Sustainability at UPC) have been applied in the analysis: Environmental, Social, Technological & Economic and Institutional.

Code	University	Learning activity	ECTS	Sample (Cmap1/Cmap2)
UPC-1	Technical University of Catalonia	Technology & Sustainability	5	201/226
UPC-2	Technical University of Catalonia	Technology & Sustainability	5	35/43
UPC-3	Technical University of Catalonia	Technology & Environment	5	30/31
UPC-4	Technical University of Catalonia	International Seminar on Sustainable Technology	5	19/19
DUT-1	Delft University of Technology	Energy III	8	32/26
DUT-2	Delft University of Technology	Societal aspects of information technology	4	68/45
CUT-1	Chalmers University of Technology	Global Chemical Sustainability	7	51/53
KPI-1	Kiev Polytechnic Institute	Sustainable Development	3	23/17
EUT-1	Eindhoven University of Technology	Technology & Sustainability	3	10/28
EUT-2	Eindhoven University of Technology	Technology & Sustainability	3	60/18
			Total	529/506

Table 2. Case studies data

In order to define what is expected to be learnt in these kinds of specific Sustainability courses, several EESD experts were also asked to draw an SD-related Cmap. The results of the Cmap analysis of this group of experts were taken as a reference and they were used to evaluate the results obtained by students.
In order to evaluate the Cmaps, two indexes were defined:

- A *category-relevance* index: it provides information about what students think sustainability is most related to.
- A *complexity* index: it evaluates how developed and inter-connected students see the concepts they have related to Sustainability, that is how complex do they see Sustainability.

The category-relevance index of the student case studies and the one of the experts' reference group are compared in order to evaluate the performance of students. The evaluation of the category-relevance indexes is known by measuring the difference between the distribution of the category-relevance of students and experts.
To be able to obtain the comparison of the distribution of the category-relevance indexes, the difference between the students' value and the experts' is measured for each category. These values are normalized according to the relative value of each category. Finally, all the category differences are added to obtain an absolute value, which is then divided by the number of categories. The result gives information about how far the category distribution of the students differs from the experts; therefore, the smaller the value the closer to the experts. Figure 1 shows the results of this comparison, both before and after taking the course, for the 10 case studies.
Before taking the course, the students in the UPC-4 case study were the ones whose category-relevance index was closest to the experts. Close to UPC-4 is the KPI-1 case study, whose sample included 2nd and 3rd cycle students. All the other case studies have similar results, which are far from the experts' values. After taking the course, again it is case study UPC-4 which is the one with the closest values to the experts' reference values. Case studies UPC-3, KPI-1 and CUT-1 follow with values ranging between 56% and 78%. The worst results are obtained in case studies EUT-1, EUT-2, and DUT-2. Except for the DUT-2 case study, in all the other case studies the results become closer to the experts' ones after taking the course. The results also show that

the worse the initial situation, the easier it is to improve; therefore the improvement ratio is generally higher in these case studies (UPC-3, DUT-1, UPC-1, UPC-2).

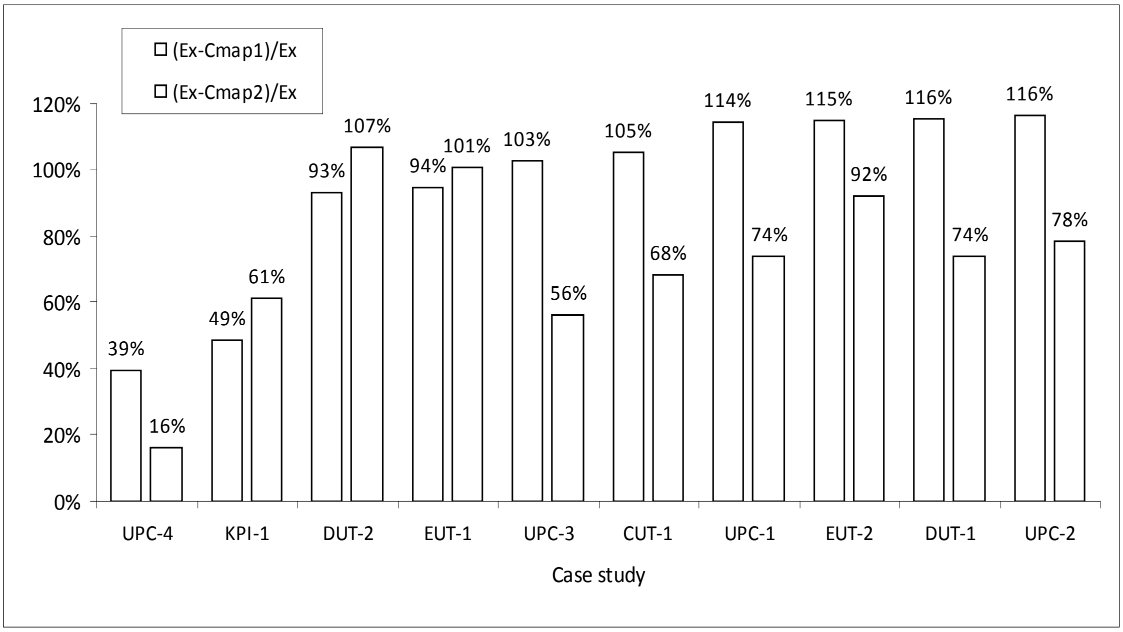

Figure 1. Category-relevance accumulative difference between case studies and experts

The *complexity-index* evaluates how developed and inter-connected students see the concepts they have related to Sustainability. In other words, it measures how complex students perceive sustainability to be. To analyse the complexity-index, the value of the index is obtained for each case study before and after taking the course. Then the values of the different case studies are compared and sorted from the higher to the lower values. The reference value for the analysis is the value obtained by the experts' group.

Before taking the SD course, the value of the complexity-index of most students was low. After taking the course, the value of the index increases for almost all students, but the increase is most significant in case study KPI-1. As already mentioned, the value of the index of KPI-1 is noteworthy, since it is even higher than the experts. After taking the course, the complexity-index value only decreases in two case studies, EUT-1 and UPC-4 (see figure 2).

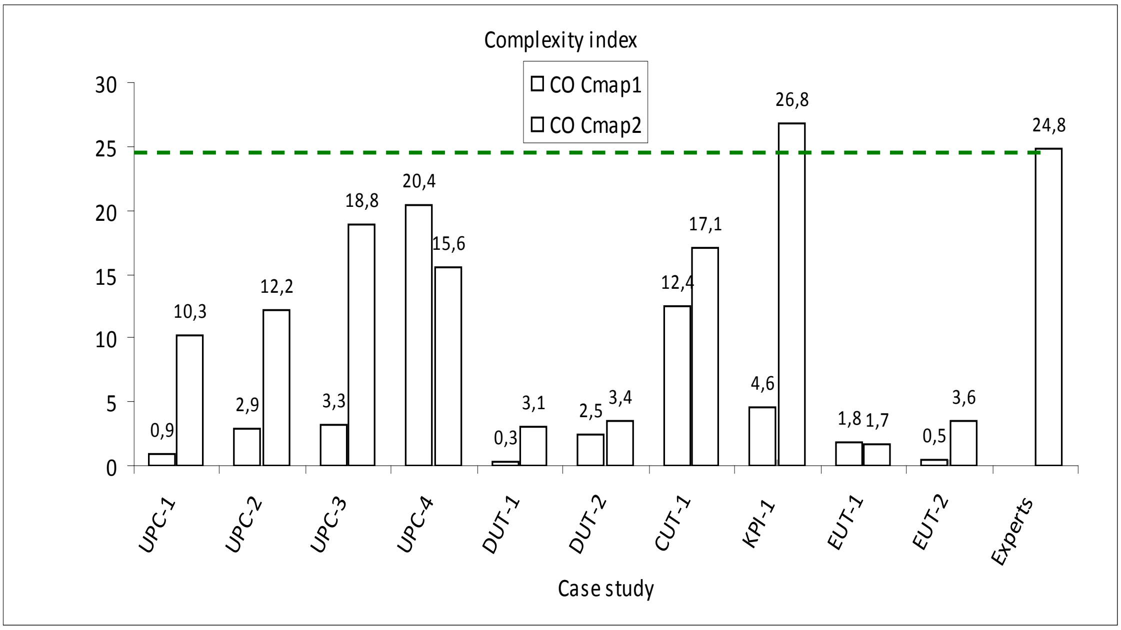

Figure 2. Evolution of the complexity-index in each case study

4. PEDAGOGY FOR SUSTAINABILITY LEARNING

In order to validate the pedagogy applied in the different case studies, two general levels were categorised:

- Passive learning: lecturing, writing exercises, problem demonstrations...
- Active learning: PBL, Problem base learning, case studies, etc.

In order to differentiate the different active learning methodologies the topography of approaches of active learning [19] is used. The topography is represented as two orthogonal axes (focus and nature), as can be seen in figure 3. Each one involves a particular set of educational methods that exploit a wide variety of facilitators such as a problem, project, context, task, equipment, tool, computer program, library study, discussion forum, workshop, research, experiment, artefact evaluation, and so forth.
The pedagogy used in each case study, has been classified according to Horvath's topography of approaches of active learning. Figure 3 shows the situation of each case study on Horvath's topography as determined by the pedagogy used. The colour of case studies shows the learning achieved in each case study. Three colours have been used:

- Red: limited learning (lower category-relevance and complexity indexes).
- Yellow: medium learning
- Green: higher learning (higher category-relevance and complexity indexes).

From the results shown in figure 3, it may be concluded that students achieve better cognitive learning as more community-oriented and constructive-learning pedagogies are applied.

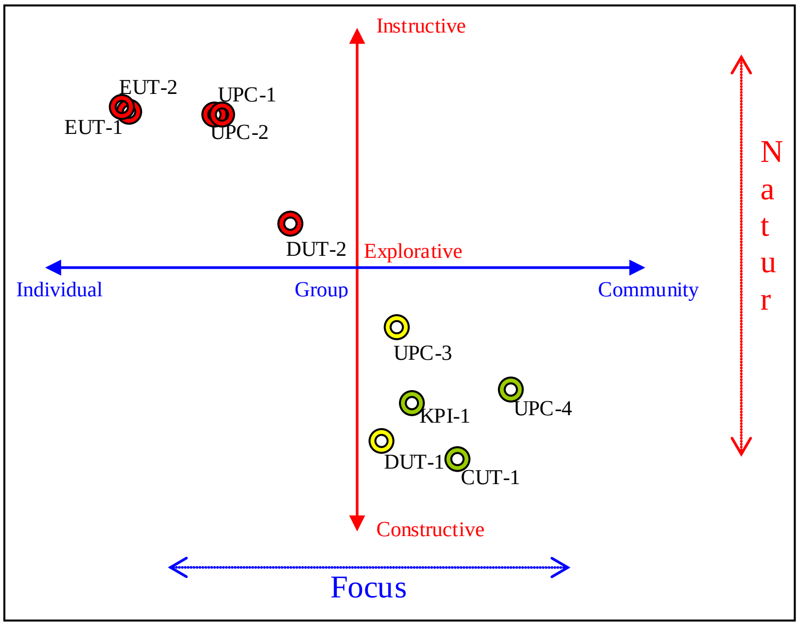

Figure 3 Topography of pedagogical approaches and learning of the analysed case studies

5. CURRICULA FOR SUSTAINABILITY

To analyse the curriculum design for SD experts on curriculum design and teaching SD courses were interviewed. The interview sample is formed by 45 experts from 19 European technological universities of Sweden (3 universities, 8 interviews), United Kingdom (4 universities, 6 interviews), The Netherlands and Belgium (8 universities, 28 interviews) and Spain (1 university, 3 interviews).
From the experts opinion and literature review, a SWOT scheme (see figure 4) is presented where the barriers and drivers to embed SD in the engineering curriculum are analysed.

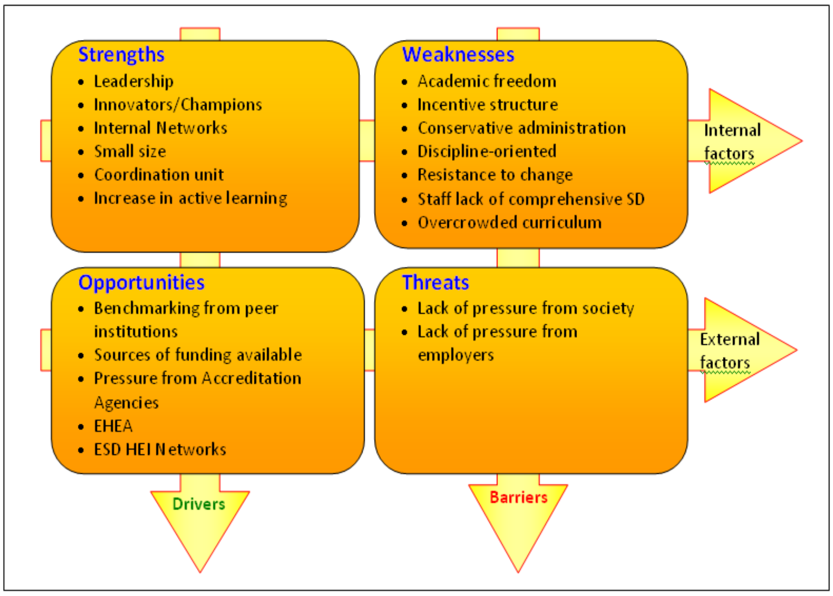

Figure 4. SWOT analysis of curriculum change for EESD

Despite the barriers to introducing ESD in HEI, there are some successful approaches in the literature. These approaches include different strategies.
In most cases Technological universities offer a *specific course on Sustainability* or Sustainable Technology in the 1st cycle (Bachelor's) and/or 2nd cycle (Masters)

students. Examples of these courses can be found at UPC, Chalmers University of Technology, Eindhoven University of Technology (EUT), University of Surrey, Delft University of Technology (DUT); Carnegie Mellon University, Ball State University, Monterrey Institute of Technology. These specific courses are offered as either compulsory or elective.
Some universities offer a *Minor/Track speciality*: To get the minor, students usually should take some elective courses which relate sustainability to their engineering speciality and focus their final thesis on a sustainability topic (these minors are offered both at 1st and 2nd cycle). Examples of this minor can be found at UPC, EUT, etc.
Masters degrees devoted to sustainability or Sustainable Technologies. At European level, a joint venture among the Royal Institute of Technology (KTH), Technical University of Catalonia and Delft University of Technology (DUT) under the Erasmus Mundus Action IV framework was created. In this SDPROMO project an online database is developed where all Sustainability and engineering related Masters programmes that are offered in Europe can be found.
Embedding of Sustainability contents in the entire curriculum. There have been many approaches in many universities. Some examples took place at DUT, Lund University, Chalmers University of Technology, UPC, Cambridge University, Rowan University, etc.
In order to achieve the embedding of SD many approaches have been carried out with more or less success:

- Training lecturers [20], although this approach has shown not to be very effective in some cases [21]. The main reason is the incentive structure in universities which prioritises research over education so lecturers have little time to be trained in SD. Moreover teachers usually do not like to be taught. Typically the lecturers who attend these training courses are the ones that are interested in SD. Therefore most of the faculty is not influenced by organising training courses for them.
- Design and implementation of Curriculum Greening plans for Schools and Departments at UPC [22].
- Facilitate learning tools and sources of information on ESD (Segalàs et al., 2002).
- The individual interaction method [21] builds on the idea that lecturers must be approached as sources of knowledge rather than as subjects of teaching efforts. This method has proven to be quite successful in finding links between a scientific discipline and SD and achieving integration of SD in the curriculum at CUT, DUT and UPC [23].

6. CONCLUSIONS

From the literature analysis and benchmarking of the three ESD active European technological institutions it is concluded that engineering students must have acquired the following SD competences when graduating: critical thinking, systemic thinking, to be able to work in transdisciplinary frameworks, and to have values consistent with the sustainability paradigm. These competences have been defined more explicitly under key words in table 1, where they have been sorted by the learning domains: knowledge & understanding, skills & abilities and attitudes.
In order to fulfil the requirements of the European Higher Education Area in terms of degree comparison and student mobility, while the definition of competences is broadly converging a common framework to define, describe and evaluate competences is needed.
Students achieve better cognitive learning as more community-oriented and constructive-learning pedagogies are applied. Multi-methodological experiential active learning education increases cognitive learning of sustainability.
Embedding sustainability within the curriculum does not only mean including new contents). If engineers are to contribute truly to SD, sustainability must become part of their paradigm and affect everyday thinking. This, on the other hand, can only be

achieved if SD becomes an integral part of engineering education programmes, not a mere 'add-on' to the 'core' parts of the curriculum.
There are many drivers and barriers identified (see figure 4) when trying to embed sustainability within the curriculum, and many attempts have been carried out at technological universities in order to achieve this goal. There are mainly four strategies applied: First a compulsory course for all graduates at 1st Cycle (Bachelor) level. Second, a minor or track on SD in both 1st Cycle and 2nd Cycle studies. Assuring the introduction of SD in the final thesis project of graduation and finally, and most challenging, intertwining sustainability in all the subjects/courses of the curriculum.
Up to the present embedding SD in the entire curriculum has shown to be the most difficult strategy to be achieved. The approaches applied so far (facilitate learning tools, develop learning materials, training lecturers, etc.) have shown to be necessary but not enough. Nevertheless, the individual interaction, a new avenue applied at DUT seems to open new horizons in order to increase the embedding of SD in the whole curriculum

References

1. Mulder, K.F., Segalas, J. & Cruz, Y. (2004). What professionals should know about sustainable development? Results of SD teaching experiences at engineering institutions as starting point for a course design. 1st European Networks Conference on Sustainability in Practice. Berlin. Germany. 1-4 April 2004.
2. Segalàs, J.; Ferrer-Balas, D.; Svanström, M.; Lundqvist, U. & Mulder K.F. (2009). What has to be learnt for sustainability? A comparison of bachelor engineering education competences at three European universities. Sustainability Science. 4 (1) pp. 17-27
3. Novak, J. D. (1998). Learning, creating and using knowledge, concept maps as facilitative tools in schools and corporations. Mahwah, NJ. Lawrence Erlbaum Associates.
4. Segalàs, J.; Ferrer-Balas, D. & Mulder, K. F. (2008). Conceptual maps: measuring learning processes of engineering students concerning sustainable development. Eur. Journal of Eng. Educ, 33(3), pp. 297-306.
5. De Graaff, E; Ravesteijn, W. (2001). Training complete engineers: global enterprise and engineering education. EJ. Eng. Educ. 26(4), pp. 419-427.
6. Corcoran P.B.; Calder W.; Clugston R.M. (2002). Introduction: higher education for sustainable development. Higher education Policy, 5(2), pp. 99-103.
7. Schumacher, E.F. (1973). Small is beautiful. Economics as if people mattered. Blond & Briggs Ltd., London.
8. Sterling, S. (2005). "Higher education, sustainability, and the role of systemic learning", in Corcoran, P.B., Wals, A.E.J. (Eds),Higher Education and the Challenge of Sustainability: Problematics, Promise and Practice, Kluwer, Boston, MA, pp.49-70.
9. Stevens C. (2008). Education for Sustainable Development. OECD workshop on education for sustainable development. Paris.
10. Barcelona Declaration. (2004). Engineering education in Sustainable Development Conference. Barcelona.
11. Meijers, A.W.M.; Overveld, C.W.A.M. & Perrenet, J.C. (2005). Criteria for Academic Bachelor's and Master's Curricula. Eindhoven University of Technology. Eindhoven.
12. Bloom B. S. (1956). Taxonomy of Educational Objectives, Handbook I: The Cognitive Domain. New York: David McKay Co Inc.
13. Krathwohl, D. R., Bloom, B. S., & Masia, B. B. (1973). Taxonomy of Educational Objectives, the Classification of Educational Goals. Handbook II: Affective Domain. New York: David McKay Co., Inc.
14. Fenner, R.A.; Ainger, C.M; Cruickshank, H.J. & Guthrie P.M. (2004). Embedding Sustainable Development at Cambridge University Engineering Department. International Conference on Engineering Education in Sustainable Development. EESD 2004. Barcelona.

15. Wals, A.E.J. & Corcoran, P.B. (2005). Sustainability as an outcome of transformative learning.Drivers and Barriers for Implementing Sustainable Development in Higher Education. Education for Sustainable Development in Action. Technical paper 3. UNESCO.
16. Lourdel, N. (2004). Méthodes pédagogiques et représentation de la compréhension du développement durable : Application à la formation des élèves ingénieurs. Projet de Thèse.
17. Sterling, S. (2004a). Sustainable Education. Re-visioning Learning and Change. Schumacher Briefings. Green Books. Bristol.
18. Canadell, A. (2006). Educació Sostenible. Criteris per a la introducció de la sostenibilitat en els processos educatius. Càtedra Unesco de Sostenibilitat. UPC. Terrassa.
19. Horvath, I. Wiersma, M., Duhovnik, J & Stroud, I. (2004). Navigated active learning in an international academic virtual enterprise. In: De Graaff, E. & HP Christensen (Eds.). Theme Issue Active Learning in Engineering Education. European Journal of Engineering Education. 29(4).
20. Bras-Klapwijk, R.M.; De Haan, A. & Mulder, K.F. (1999). Training of lecturers to integrate sustainability in engineering curricula.
21. Peet, D.J. & Mulder K.F. (2004). Integration of Sustainable Development in the curricula of Mathematics and Informatics. Engineering Education in Sustainable Development Conference. Barcelona.
22. Segalàs, J. (2004). Sustainability in engineering education. Thesis project. PhD on Sustainability, Technology and Humanism. UNESCO Chair of Sustainability. Technical University of Catalonia. Barcelona.
23. Holmberg, J; Svanström, M.; Peet, D.J.; Mulder, K.F.; Ferrer-Balas D. & Segalàs J. (2008). Embedding sustainability in higher education through interaction with lecturers: Case studies from three European technical universities, European Journal of Engineering Education, 33(3), pp. 271-282.