Patterns and trends in Engineering Education in Sustainability: a vision from relevant journals in the field

Abstract

Purpose

To identify patterns and trends taking place in engineering education in sustainability, through analyzing the evolution of research conducted in relevant publications in the field of engineering education for sustainability in the last decades.

Design / methodology / approach

Firstly, a bibliometric approach has been applied, adopting a co-word analysis based on co-occurrence of the keywords (300 items) in articles from three indexed journals related to engineering, education or sustainability. The selection of the articles has been based on the appearance of the previous three *terms* in the topic and title fields of the journal, where journal scope (based in the categories of the InCites Journal Citation Reports) covered at least two topics and the third topic was applied in the search, as follows:

- International Journal of Sustainability in Higher Education. Scope of the journal: sustainability and education. Keyword search: *engineering* (20 papers)
- Journal of Cleaner Production. Scope of the journal: sustainability and engineering. Keyword search: *education* (122 papers)
- International Journal of Engineering Education. Scope of the journal: engineering and education. Keyword search: s*ustainability* (29 papers)

Secondly, to identify topological patterns and their evolution a structural and temporal analysis of the network of keywords and a categorization of the keywords in thematic clusters (named categories) have been performed.

Results

The most relevant categories in terms of corresponding number of keywords, even though these have decreased in recent years, are those related with institutional and policy aspects to embedding or applying sustainability in higher education. At the same time, categories related to the professional development of faculty members, implementation and use of learning strategies (i.e., real-world learning experiences, educational innovative initiatives/tools/techniques) and cross-boundary schemes (i.e., transdisciplinarity, ethics, networking, etc.) increase their relevance in the last five years, signaling some of the challenging fields of interest in Engineering Higher Education in Sustainability in the near future.

Practical implications

Knowledge of the trends in devising sustainability education in engineering allows for designing curricular schemes and learning strategies to achieve competences, which are key factors for the change towards sustainability.

Originality / value

This research has a strong strategic value since it indicates the focus of future research efforts and networking on some of the topics of greatest concern in engineering higher education for sustainability.

1 Introduction

Actions for sustainability have been promoted from the different areas of environment, society and economy, with the longed for common aspiration to face multiple interconnected sustainability crises in a world that can no longer be conceived as “society without nature and nature without society” (Beck, 1992; Latour, 1993; van Breda *et al.,* 2016).

In September 2015 countries adopted the sustainable development goals to end poverty**,** protect the planet and ensure prosperity for all as part of the *2030 Agenda for Sustainable*

Development: Transforming our world, with specific targets to be reached. In this context appropriate technologies are just another instrument to achieve sustainability as a “holistic concept that requires the strengthening of interdisciplinary linkages in the different branches of knowledge” (A/RES/72/223).

When dealing with interconnected problems, finding integrated solutions is a complex undertaking, reaffirming the need to tackle them with a transdisciplinary approach (van Breda *et al*., 2016) aimed at integrating expert or academic knowledge with the practical or traditional knowledge from actors outside of academia (Scholz *et al.*, 2006; Brundiers *et al.*, 2010; Brown, 2014) to co-produce outcomes that could be both socially useful for transitioning and scientifically innovative to formulate new guiding principles (Jahn *et al*., 2012; Lang *et al.*, 2012).

From the academic side, scientific journals and conferences continue to be important forums for exchanging scientific information on research findings, concepts, policies and innovative procedures or technologies. In reference to the former consideration of journals as exchanging forums,, 2017, Zhou et al. characterized the *Journal of Cleaner Production* (JCLP) publications, identifying “low/no-fossil-carbon transformations” as the main related issue in three of the four areas, in which the JCLP historical of publications focused, namely: a) industrial applications; b) environmental management initiatives; c) governmental environmental policies and regulations; d) education, training and facilitation of changes toward SD.

In the present article, authors focus on the fourth identified area, while extending the array to two more indexed journals (introduced afterwards), related to engineering, education or sustainability. *The International Journal of Sustainability in Higher Education* (IJSHE) is a fully-refereed academic journal aiming since 2000, to document and disseminate what universities and colleges are doing to pursue the path of sustainable development. The JCLP is a transdisciplinary journal founded in 1993, focusing on cleaner production, environmental, and sustainability research and practice. The *International Journal of Engineering Education*

(IJEE) is an independent journal, serving as an archival forum of scholarly research related to engineering education since 1994.

On the other hand, referring to conferences as exchanging forums, Segalàs and colleagues (Segalàs *et al*., 2018) analyzed the evolution since 2002 and future challenges of the Engineering Education in Sustainable Development Conference, as an exchanging platform of concepts, policies and strategies to enhance a sustainable education, through the characterization of the published papers, the identification of topic categories and interviews to experts. Relevance declining categories were related with environmental topics and management and policies. On the contrary transdisciplinarity, topics from humanities and circular economy increased their relevance. Additionally transdisciplinarity was considered crucial to improve engineering education in sustainability, in parallel to real implementation at universities and networking.

In the literature review priority similar considerations can be distilled towards the academic need to transition from a focus on technical issues to more ‘messy’ problems that require an integrative, adaptive, collaborative, ultimately transdisciplinar approaches in the interface science-society (Clark and Button, 2011; Balsiger, 2014; Vilsmaier and Lang, 2015; Tejedor and Segalas, 2018), which necessitate new methods and tools, but also the development and teaching of new engineering paradigmatic schemes (Byrne *et al.*, 2013; Halbe *et al.*, 2015; Remington-Doucette *et al.*, 2013).

This paper aims at go deeper into these last considerations with the use of complex networks science based on paper keywords co-occurrence analysis (Newman, 2010). We additionally examine the temporal evolution and penetration process of the fields of Inter- and Transdisciplinarity into dynamic networks with the goal to identify how these fields are affecting Engineering Education in Sustainability.

The paper is organised as follows. In the Materials and Methods section, we present our database, the creation process of our network, following a co-word analysis of the keywords of papers related to Engineering Higher Education in Sustainability (EESD). We explain the centrality measures used to characterize the topology of the network and to assess the evolution of its structural features. We also present and identify the thematic categories. In the Results section, we detect structural patterns and particularly central keywords, and relate them to our EESD categories, with the objective of explaining and detecting differences between transdisciplinar collaborative frameworks towards sustainability. We finish with the Discussion section, where we recap and identify some key trends for future work.

2 Materials and methods

With the advent of the indexing and availability of scholarly documents and literature, we have begun to quantitatively understand the process by which scientific fields emerge (Börner, 2010, 2015; Bettencourt and Kaiser, 2015). These quantitative methods commonly include one or a mixture of population contagion dynamical models for the spread of ideas and the emergence and development of scientific fields (Bettencourt *et al.*, 2006, 2008; Bettencourt and Kaur, 2011) and the structural analysis of networks.

This can be about collaboration between scientists (Newman, 2001; Barabási *et al.*, 2002; Liu *et al.*, 2005; Bettencourt *et al.,* 2009; Bettencourt and Kaiser, 2015). Here, two scientists are considered connected if they have co-authored one or more papers together, or connectivity between articles, in order to detect communities, fields or disciplines. Articles can be connected by means of the paper's references list (i.e., if they are cited in the same bibliographic list; a methodology known as co-citation analysis (Small, 1973); if they share common references; a methodology known as bibliographic coupling analysis (Kessler, 1963).

Finally it can be done by means of words (from the paper itself or its keywords); a methodology known as co-word analysis (Callon *et al.*, 1983; Callon *et al.,* 1991). This methodology assumes that a paper's keywords constitute an adequate description of its content or, the links the paper established between problems (Ding *et al.*, 2001). In the structural analysis of these networks, communities are detected by modularity measures

(Newman, 2002) and information about these communities is retrieved by means of qualifiers on the nodes.

For this paper, we adopted co-word analysis. The co-word analysis is an important bibliometric approach based on co-occurrence analysis and has been widely applied to illustrate how concepts, ideas, and problems within a given scientific field interact and to explore the concept network within the relevant field (see Liu *et al.*, 2016 and references therein). Here we consider a network formed by keywords as nodes. Two keywords are connected if they appear in the same paper, and the weight of the link between them depends on their probability of co-occurrence across the various papers. Thus constructed, the structural analysis of this network serves as a proxy for the conceptual structure of a specific discipline. It allows a time-series record of the changes that occurred in the conceptual space and it can reveal patterns and trends in a specific discipline by measuring the association weight of representative terms in relevant publications (Ding *et al*., 2001).

2.1 Identification of journals

In order to define the scope of our investigation, a general search was made in WOS for *TI=(engineering AND education AND sustainability) OR TS=(engineering AND education AND sustainability)*; refined by *years 2001 to 2017* and *Type of document: Articles*, bringing 448 articles. The more contributing indexed journals were identified (Journal of Cleaner Production – JCLP; Sustainability – SUSTDE; International Journal of Sustainability in Higher Education – IJSHE; Journal of Professional Issues in Engineering Education and Practice – JPIEEP; International Journal of Engineering Education – IJEE) and further selected in terms of bringing together the research topics in pairs, as follows (selected journal in bold in Table 1).

Research topics (in pairs)	Sustainability and engineering		Sustainability and education	Engineering and education	
Identified journals	*JCLP*	SUSTDE	*IJSHE*	JPIEEP	*IJEE*
Journal Impact Factor	5.6	2.1	1.9	1.3	0.6

Table 1. Compilation of data for the selection of the journals identified in the Web of Science database based on the joint appearance in pairs, of the research topics in the Journal Citation Reports categories. Selected journals are shown in bold.

Regarding the choice between IJEE and JPIEEP, we realized that the first records contributor to our search was IJEE, what makes us likely to deepen in the journal metrics. When looking at the count as a percentage of the first ten countries contributions to each journal, JPIEEP is the only journal where more than 50% of the contributions come from USA (53%), being 44% for IJEE, 37% for IJSHE and 32% for JCLP. Since perceiving it slightly biased, we considered IJEE to be a more related journal to our area of expertise and influence that could better fit the scope of our research.

2.2 Network dataset

To create the keywords network, a search has been conducted of the keywords in articles (171 items) from three indexed journals related to Sustainable Engineering (JCLP), Sustainability in Higher Education (IJSHE) and Engineering Education (IJEE). The selection of the articles has been based on the appearance of the terms engineering, education and sustainability in the *topic* and *title* fields of the articles in the journals IJSHE, JCLP and IJEE respectively, assuring that Engineering Education in Sustainability is all covered in the papers (see Table 2).

Journal/terms	Engineering	Education	Sustainability
International Journal of Sustainability in Higher Education – IJSHE	20 papers		
Journal of Cleaner Production – JCLP		122 papers	
International Journal of Engineering Education – IJEE			29 papers

Table 2. Scheme for the search of articles in the Web of Science database and number of papers identified in each journal, based on the appearance of the terms in the topic and title fields of the articles.

Redundant, capital or lowercase letter, and similar keywords have been filtered and reorganized into a coherent and unique list where those related to the same concept have been grouped in a unique *chosen keyword*, which maintains in the network the weight of the number of keywords that is assigned to it. For example, *Higher education for sustainability* includes *Higher Education*, *Higher Education for Sustainability,* and *Higher Education for Sustainable Development*. Our final set includes 300 keywords out of a total amount of 871 initially identified keywords

2.3 Network Metrics

We quantified the structural features of the networks using the following network metrics (see Newman, 2010, and references therein):

- **Average degree and degree distribution.** A key centrality measure of a node is its *degree*, k_i, representing the number of links node i has to other nodes. In an undirected[1] network with N nodes (i.e., size of a network), the *average degree* is defined as:

$$\langle \boldsymbol{k} \rangle = \frac{\mathbf{1}}{\boldsymbol{N}} \sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{N}} \boldsymbol{k}_{\boldsymbol{i}} = \frac{\mathbf{2}\boldsymbol{L}}{\boldsymbol{N}} \quad (1)$$

where L is the total number of links. The degree distribution p_k is giving the probability that a randomly selected node in the network has k links. Since p_k is a probability, it

[1] Network connections can be *undirected* or *directed.* Undirected ones simply exist between two people or things, being mutual relationships. They cannot exist unless they are reciprocated. Directed ones have a clear origin and destination and may be reciprocated or not.

must be normalised, i.e. $\sum_{k=1}^{\infty} p_k = 1$. For a fixed network of size N, the degree distribution is the normalised histogram $p_k = \frac{N_k}{N}$, where N_k is the number of degree k nodes, and its cumulative degree distribution P_k is giving the probability that a randomly selected node in the network has k or more links.

- **Clustering coefficient.** The local clustering coefficient captures the degree to which the neighbours of a given node link to each other (Watts and Strogatz, 1998). For a node i with degree k_i the local clustering coefficient is defined as:

$$\boldsymbol{C_i = \frac{2L_i}{k_i(k_i - 1)}} \tag{2}$$

where L_i represents the number of links between the k_i neighbours of node i. Here we use the average clustering coefficient of a network $\langle C \rangle$ as:

$$\boldsymbol{\langle C \rangle = \frac{1}{N}\sum_{i=1}^{N} C_i} \tag{3}$$

- **Average path length and diameter**. Most networks are built to ensure connectedness. In an undirected network two nodes i and j are connected if there is a path between them on the graph. A path is a route that runs along the links of the network, its length representing the number of links the path contains. The shortest path d_{ij} between nodes i and j has the fewest number of links. The average path length, denoted $\langle d \rangle$, is the average shortest path between all pairs of nodes in the network. The network diameter, denoted D, is the maximal shortest path in the network.
- **Betweenness centrality.** For every pair of vertices in a connected graph, there exists at least one shortest path between the vertices such that either the number of edges that the path passes through (for unweighted graphs) or the sum of the weights of the edges (for weighted graphs) is minimised. The betweenness centrality for each vertex is the number of these shortest paths that pass through the vertex (Barrat *et al.*, 2004). This measure is formalized as follows:

$$b_i = \sum_{s \neq i \neq t} \frac{d_{st(i)}}{d_{st}} \quad (4)$$

where d_{st} is the total number of shortest paths from node s to node t, and $d_{st(i)}$ is the number of those paths that pass through vertex i.

2.4 Content analysis in Categories

In order to facilitate the descriptive analysis and categorization of our set of network keywords, they were classified under nine thematic categories, grouped in turn according to three relevant levels (or points of view) in the field of EESD (Table 3).

The first level refers to *educational systems* that any keyword is related to, including the following categories (identified with its code in parenthesis): Institutional and policies (1), Curricular structure (2), Educational strategy (3), Competences / behavioural aspects (7) and Academic/professional development (8). The second level is related to the topics that the paper is about, in alignment to the *three pillars of sustainability* (environmental, economic and social) and it includes the "Topics" following categories: techno-environmental (4), techno-economics (5) and socio-cultural (6). Finally, a third level contains "Td and collaborative networking (9)" category, as a transversal category, that takes into consideration those papers that deal with *transdisciplinary and collaborative approaches*.

Level	Name of the category	Code	Description	No. of keywords
Educational systems	Institutional and policies	1	Strategies and measures for embedding sustainability at the institutional or policies level	45
	Curricular structure	2	Planning and development of curricular adjustments for switching to sustainability	25
	Educational strategy	3	Didactic strategies and models for teaching and learning sustainability	65
	Competences/ behavioral aspects	7	Research for and development of competences, skills and behavioral change based learning for SD	42
	Academic/professional development	8	Training and development of professional and academic skills toward sustainability	13
Sustainability Pillars	Topics: techno-environmental	4	Contents referring to environmental and technological issues	47
	Topics: techno-economics	5	Contents referring to environmental and technological issues	8
	Topics: socio-cultural	6	Contents referring to social and cultural issues	19
	Td and collaborative networking	9	Cooperation, collaborative networks and learning frameworks co-creation toward sustainability	36
			Total	300

Table 3. Name, code, description and number of keywords of the nine identified thematic categories of keywords. Additionally, the level in which categories are grouped is indicated.

3 Results

3.1 Descriptive of the number of publications evolution and the keywords distribution (2001-2018)

Being 300 the number of keywords that the network contains, the 78% of them appear in the JCLP, which indicates a cross-sectional feature of the journal. In the IJSHE and IJEE are appearing the 22% and 25% respectively of the keywords in the network (see Table 4). On the other hand, the IJSHE is the journal with the highest number of keywords per article, with 3,3 keywords/article, while JCLP is the one with the lowest ratio at 1,7 keywords/article.

	IJSHE	JCLP	IJEE	Total
Num. of keywords	66	233	75	300
% of appearance	22	78	25	100
Papers	20	122	29	171
Keyword/papers	3,3	1,9	2,6	1,7

Table 4. Distribution of keywords in the JCLP, IJSHE and IJEE

Throughout the period considered, from 2001 to 2018, the evolution of the number of analysed papers tend to follow different patterns in each journal, but a common growing trend (see Figure 1). First publications in the area of research, appeared in 2007 for IJEE and in 2010 for IJSHE, while JCLP was published from 2003 onwards. In this growing trend there is differently, a temporal interval with a very low ratio of publications, being zero for IJSHE (in years 2008, 2009, 2011) and IJEE (in years 2009, 2010, 2012), while just one article in the area, was published for IJEE (in 2008) and JCLP (2008, 2009, 2011).

The evolution of publications is shown in Figure 1.a, with JCLP having a continuous growth and the higher publication ratio since 2011. The other two journals seem to show an opposite evolution. On the one hand, IJSHE shows a more regular growth, starting exactly from 2011, although its number of publications is in general, the lowest. On the other hand IJEE shows a very irregular publication ratio, being higher until 2011. Finally, 2018 starts with abundant number of publications, considering that only the first semester is analysed.

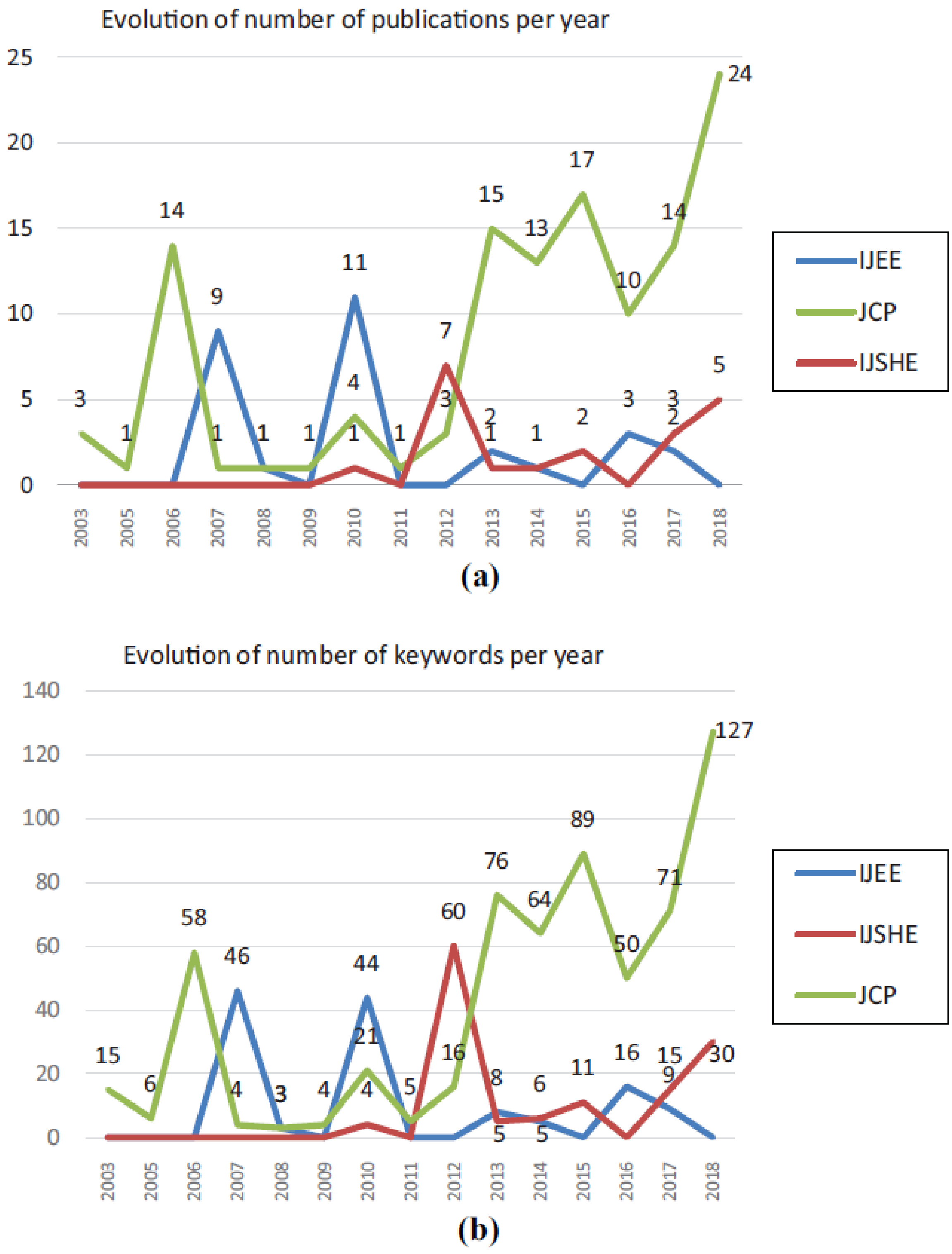

Figure 1. Number of publications per year (Figure 1.a) and number of author's keywords per year (Figure 1.b) in the research period (2003-2018) for the journals IJSHE, JCLP and IJEE.

The total number of keywords is 871, where 609 correspond to JCLP, and 131 equally to each journal IJSHE and IJEE. The evolution of the number of keywords in the analyzed period

(Figure 1.b) goes in parallel to the published articles per year, being higher when the publication ratio increases. IJSHE contributed in 2012 with the high level of 60 keywords, with the double of published articles than JCLP, while since then increases for the last journal.

3.2 Network metrics

Figure 2 presents some characteristic snapshots of the temporal evolution of the keywords' networks for journals IJSHE, JCLP and IJEE, including the global network, where all three individual networks are included as one unique network[2]. All graphs are undirected, without self-loops and they present a unique component with all vertices connected to, at least, one other vertex. In terms of clustering coefficient, and since keywords appear connected if they are in the same paper, differences are not significant between networks. Graph densities (i.e., the ratio between the actual number of edges over the maximum number of edges if each node were connected to each other) are also very low.

In this figure, the colour of the edges maps to publication year, helping to visualize their evolution. The global network nodes have been featured with shapes and colours corresponding to the different categories (1- triangle maroon; 2- square orange; 3- diamond fuchsia; 4- circle lime; 5- circle green, 6- circle olive; 7- disk black; 8- square red; 9- sphere blue). What is shown is that keywords in Categories 1 and 2 have the highest degrees, followed by those in Categories 7 and 9. On the other hand, *Interdisciplinarity* ends up with a degree of 28 (position 10 of 300, 3,3 above 100) and *Transdisciplinarity* end up with a degree of 26 (position 15 of 300, 5 above 100), meaning that their importance places them very high in terms of degree, what indicates that they quickly connect with other topics.

[2] Graph figures created with NodeXL package software (https://www.smrfoundation.org/nodexl/).

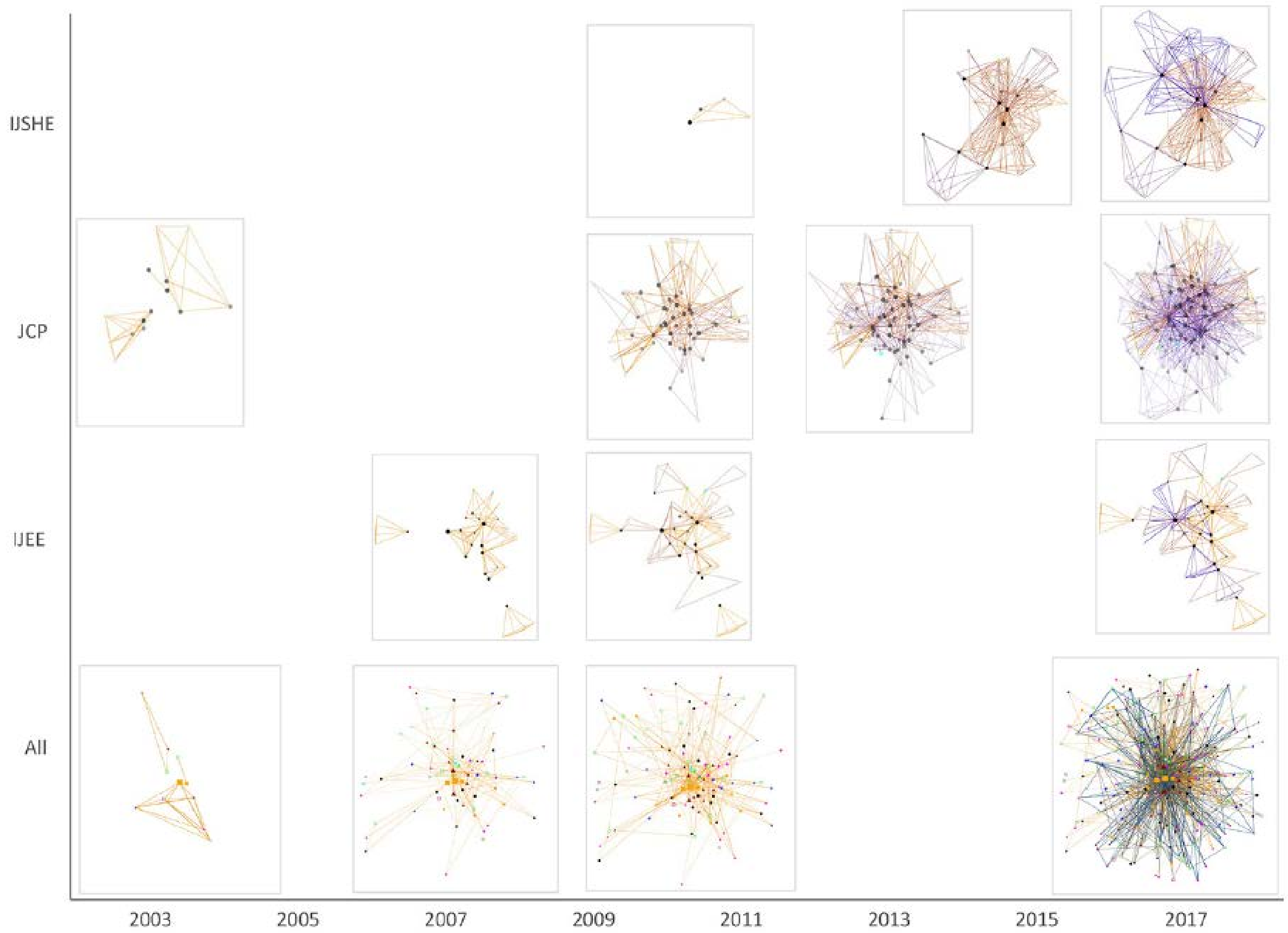

Figure 2. Snapshots for the temporal evolution of the keywords' networks for journals IJSHE, JCLP, IJEE and the global one for all journals. Edge colour represents the field publication year, with a colour palette from the orange (first year) to blue (last year)

Table 5 shows the current (i.e., year 2017) network metrics for journals IJSHE, JCLP, IJEE and the total network. From a global point of view, all networks show similar topological patterns, albeit some noticeable differences arise.

Network	*IJSHE*	*JCLP*	*IJEE*	Global
Graph metrics				
Vertices	66	233	75	300
Unique edges	266	859	199	1233
Edges with duplicates	133	420	45	689
Duplicate edges ratio	0.50	0.48	0.22	0.56
Total edges	399	1,279	244	1,922
Diameter	3	4	6	4
Average path length	1.96	2.36	2.75	2.36
Graph density	0.14	0.03	0.07	0.03
Degree				
Minimum	3	1	1	1
Maximum	55	131	32	181
Average	9.5	8.4	6.0	9.9
Betweenness centrality				
Minimum	0	0	0	0
Maximum	889	10,628	1,084	18,794
Average	32	159	69	220

Table 5. Current (i.e., year 2017) network metrics for the individual networks of the journals IJSHE, JCLP, IJEE and for the global network resulting of aggregating the three journals.

3.2.1 IJSHE

In the most recent years of the publication period (2010 to 2018), the institutional implementation of sustainability is discussed (edges in blue), differently than in previous years, when were explored mainly topics related to the environment, the environmental adequacy of educational centers and their relation to sustainability (edges in orange). Concern for a more sustainable society and the methods/ tools/ frameworks for the transition occur in intermediate years (in purple). *Interdisciplinarity* appears in 2012 and ends with a degree of 17 (position 5 of 66, 7.5 above 100), while *Transdisciplinarity* appears in 2014 and ends with a degree of 10 (position 17 of 66, 25.7 above 100).

In terms of vertex-specific metrics we find the following results for the network' keywords:

a) **Average degree and degree distribution**. The higher degrees correspond to *Sustainability in Higher Education* (55), *Engineering and architectural education for sustainability* (41), *University* (34) and *Education for Sustainability* (29). The next is *Interdisciplinarity* and *Education with community*, both with a degree of 17, while *Transdisciplinarity* ends up with 10. Although *Interdisciplinarity* and *Transdisciplinarity* appear respectively in 2012 and 2014, their importance places them very high in terms of degree, indicating that they quickly connect with all the topics. The IJSHE higher connectivity is shown in terms of the graph density (i.e., 0.14), one order of magnitude over the other graphs' densities.

b) **Average path length and diameter**. This network has the lowest average path length (1.96) and diameter (3), a fact that characterizes its high connectivity. In this network, it is easier to move from one keyword to another following a shortest path, compared to the other networks.

c) **Betweenness centrality**. The search process of the papers used in the Web of Science database makes some particular important keywords to be present at each stage of our search, a fact that generates a high degree for these particularly relevant keywords. For these keywords, the highest degree implies, at the same time, the highest Betweenness centrality (i.e., *Sustainability in Higher Education*, 889). For this centrality measure, *Interdisciplinarity* has 20 (11^{th} position) and *Transdisciplinarity* 6,5 (i.e., 18^{th} position)

3.2.2 JCLP

The amount of publications in JCLP has increased from 2013 (orange edges), in the most recent years of the publication period (2003 to 2018) (purple edges). *Transdisciplinarity* appears in 2013 and ends with a degree of 14 (position 29 out of 233, 12 above 100), while *Interdisciplinarity* appears in 2014 and ends with a degree of 13 (position 32 out of 233, 13 above 100).

In terms of vertex-specific metrics we find the following results:

a) **Average degree and degree distribution**. The higher degrees correspond to *Sustainability in Higher Education* (131), *Higher Education for Sustainability* (105), and *Education for sustainability* (82) and *Reform of curriculum for sustainability* at universities with a degree of 76. The following keywords in terms of degree are related to topics of different Categories as Institutional and policies, Curricular structure, Educational strategy and Competences/ behavioural aspects (few). *Transdisciplinarity* ends with a degree of 14, surrounded by *Systems thinking* and *Higher Education Institutions*, both ending with a degree of 14. *Interdisciplinarity* ends with a degree of 13, surrounded by *Circular Economy systems*, *Future studies/visions* and *Quality assurance*, all ending with the same degree. The degree distribution follows a power law (Barabási, *et al.*, 2000), indicating that the connectivity is dominated by some few but very much connected keywords which act as hubs in the system (i.e., *Sustainability in Higher Education* and *Higher Education for Sustainability*).

b) **Average path length and diameter**. This network has intermediate values of average path length (2.36) and diameter (4). The fact that it comprises most of the nodes of the global network implies a topology similar to this last one.

c) **Betweenness centrality**. Due to the search process of the papers used in the Web of Science database, the star effect causes the keyword with the highest degree to be the one with the most Betweenness Centrality, being the keyword *Sustainability in Higher Education* with a degree of 10627,5, while the Average Degree is 159,1. *Transdisciplinarity* has 169,4 (27th position) and *Interdisciplinarity* 32,3 (59th position).

3.2.3 IJEE

In this journal, the amount of publications seems to maintain or indeed decrease a bit in recent years. Apart from sustainability aspects in HEIs, aspects appear the most recent years related to students, their representativeness and learning strategies and techniques. Just before, fields of research revolve around educational frameworks relating different learning environments, included disciplines and cultures (*Inter*- and *Transdisciplinarity*, *Systems thinking*, *Active learning*, *Real-world learning experiences*, etc.). In addition unlike the other journals, typical engineering topics (i.e., Mining, Petroleum, Water) often appear, even sometimes in relation to social learning (i.e., *Cross-cultural education*, *Social Sustainability*, *Service Learning*, etc.).

a) **Average degree and degree distribution.** The higher degrees correspond to *Sustainability in Higher Education* (32) and *Sustainability of campus* (28), followed by a group of four keywords namely, *Underrepresented students groups* (15), *Education for Sustainability* (14), *Real-world learning experiences* (14), *Reform of curriculum for sustainability at universities* (14). *Interdisciplinarity* and *Transdisciplinarity* end up respectively with a degree of 8 (position 14 of 75, 20 above 100), and a degree of 5 (position 31 of 75, 41 above 100), showing a low connectivity level, which is related to the network's disconnected topology. It should be noted that both appear in 2003, at the beginning of the publication period (2003-2017).
b) **Average path length and diameter**. This network has the highest values of average path length (2.75) and diameter (6), indicating a much more disconnected topology, where it is more difficult to move from one keyword to another following the shortest path.
c) **Betweenness centrality**. Due to the search process of the papers used in the Web of Science database, the star effect causes the keyword with the highest degree to be the one with the most Betweenness Centrality, being the keyword *Sustainability in Higher Education* with a degree of 1084.

4 Discussion

Results shown in the previous section offer new strategies to assess and analyze the evolution of the research in this three journals, highly devoted to Engineering Education in Sustainability in the last two decades, both from an individual (i.e., journal) point of view, and a global one. The next sections explain in terms of the structural analysis of the networks, the evolution of each of the three individual journals networks (4.1) and the global one (4.2). Finally, section 4.3 features the main trends of the identified Categories of keywords, by means of clustering them from the three relevant points of view of EESD (see Section 2.3).

4.1 Journal networks evolution analysis

4.1.1 IJSHE

This journal presents from de beginning (2010) concern on institutional strategies for sustainability learning and the relation with society. In 2012 there is a peak of publications mostly in the institutional and curricular area, bringing the keywords *Complexity* and *Interdisciplinarity* to the arena. Later on (2014) seems to appear a curricular transition towards society, when *Transdisciplinarity* keyword appears. In further years (2015 to 2017), the concern is growing to move to society (*Social responsibility*, *Sustainable societies*, *Regional cooperation for sustainability…)* by means of, both institutional strategies (*Commitment and implementation of sustainability in HEI*, *Global partnership*) and learning strategies (*Service learning*, *Active learning*, *Volunteering*…). Finally, case studies and industrial aspects (*Industry competency model*, *Cleaner production*, *Energy engineering education for sustainability*) seem to have the will of reinforcing relationships beyond the university.

In terms of network shape, IJSHE presents an intermediate topology between JCLP and IJEE, with some keywords used in particular articles and others with greater connectivity in the network.

4.1.2 JCLP

The JCLP presents a more connected topology, with a higher number of long distance connections between nodes which indicates a more global behavior in the sense that all keywords are much more mutually connected, with the same keywords being used in different articles. As a particular case and in order to ease the analysis of this populated web, we have clustered the big amount of keywords into the thematic Categories explained in section 2.3 (see Figure 3). In the first period predominate the institutional topics and those referring to the adequacy of the curricular structure for sustainability, although three areas appear that will be dripping constantly in the complete analyzed period, corresponding to the Categories: Td and collaborative networking (9), Topics: techno-environmental (4) and Academic/professional development (8). Keywords related to the Td and collaborative networking category (*Inter-* and

Transdisciplinarity, *Networking*, *Social Impact*, *Sustainable societies*, *Holistic approach*, *Social responsibility*, *Public debate, Cross-cultural education,* etc.), have been appearing with considerable betweeness centralities, showing a kind of “bridge” score, where a gap exists.

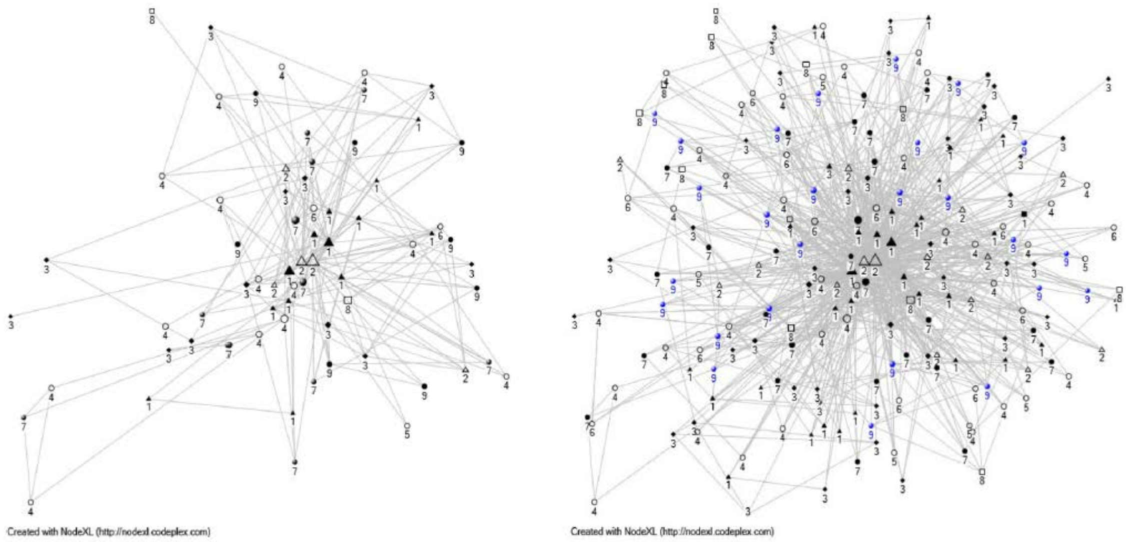

Fig 3. Snapshots for the temporal evolution of the JCLP keywords’ networks in 2010 and 2017. Dark colours of nodes indicate high Betweeness centrality. The different numbers and shapes indicate the classification in Categories, namely: 1- Institutional and policies, 2- Curricular structure, 3- Educational strategy, 4- Topics: techno-environmental, 5- Topics: techno-economics and 6- Topics: socio-cultural, 7- Competences/ behavioural aspects, 8- Academic/professional development, 9- Td and collaborative networking

In the second period, after 2013, the number of publications increases. Although all the Categories are represented, keywords related to Educational strategy (3) and Competences/ behavioral aspects (7) increase their number. Keywords related to Td and collaborative networking (9) continues to preponderate.

4.1.3 IJEE

The different areas to which the keywords refer are uniform throughout the period of publication of this journal, from 2007 to 2017. The most of the keywords point to topics referring to institutional and curricular aspects of the introduction of sustainability in the engineering higher education. From the very beginning the keywords *Interdisciplinarity* and *Transdisciplinarity* appear but they are not very significant, although both and other keywords related to new cross-disciplinary frameworks and collaborative paradigms appear later, On the other hand, relevance is given to real case studies of education for sustainability in engineering in different countries, with a North-South component. Another IJEE peculiarity is that presents the highest proportion of articles with keywords related to students representativeness, additionally with high relevance (for example the keyword *Underrepresented students groups*, with a Degree of 365, position 3 of 75). On the other hand, do not appear keywords referring to the training of academics (included in Category 8). Finally, many keywords refer to educational strategies (included in Category 3) have appeared in the last period of years.

The linear network shape of IJEE point to a low connectivity, i.e. the necessity to travel longer topological distances to find a path between the different nodes (article keywords), thus suggesting that research is made in different areas separately, where articles use different keywords from one another.

4.2 Global network modularity analysis

Modularity analysis provides information on the relationship between connections in a network. Networks with high modularity have dense connections between the nodes within modules but sparse connections between nodes in different modules (also called clusters, groups, or communities).To measure the strength of division of our network into modules, we make use of a modularity algorithm (Newman, 2002). In our case study, the network keywords are divided into nine different modules. The algorithm gathers certain keywords in a proximity grouping, so that the network is distributed in these nine automatically separated kind-of knowledge domains (i.e., modules characterized by connections between keywords that tend to appear more often than in a pure random case). By crossing this atomization in modules (one to nine), with the distribution of keywords in the thematic Categories, it is shown that some keywords are not clearly classified within a domain of knowledge. On the contrary they are used in a generalized way throughout the network. Specifically, only the keywords belonging to two of the nine Categories are present in all modules (shown in Figure 5, with different shades of grey). Keywords belonging to these two thematic Categories, namely Institutional and policies and Transdisciplinary and collaborative networking, permeate the entire network, indicating that these topics have spread throughout all the areas of knowledge addressed by all journals.

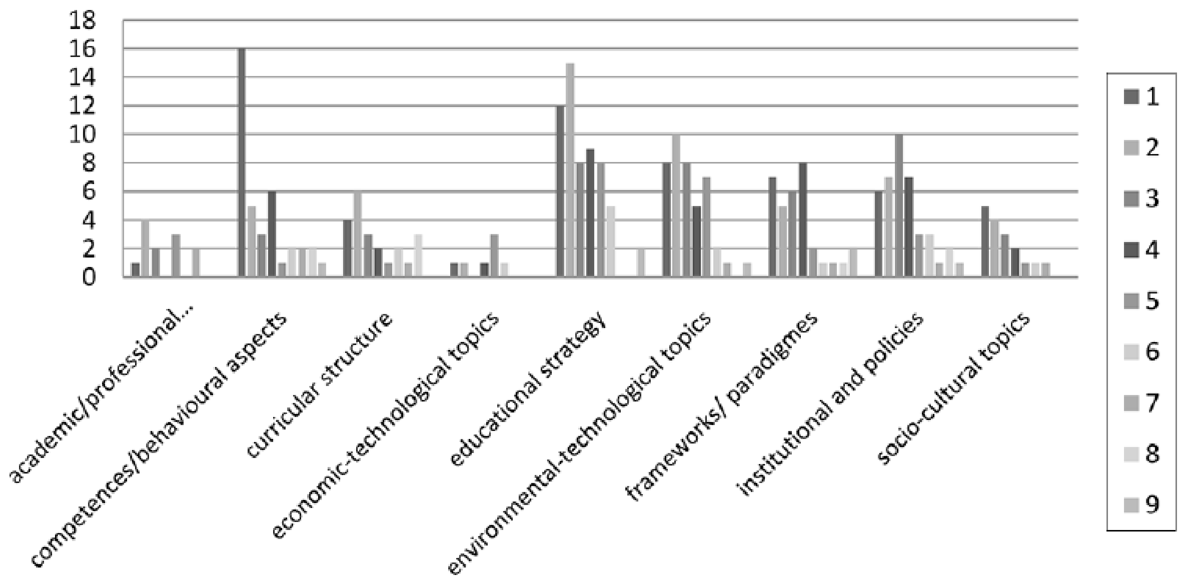

Fig 4- Number of keywords by module (1 to 9, in grey scale) and category (x axis). Categories Institutional and policies and Transdisciplinary and collaborative approaches appear in all modularity clusters, indicating that they have spread throughout all the areas of knowledge of the network.

4.3 Research trends

The evolving research trends have been explored along three periods of five years each: 2003-2007, 2008-2012 and 2013-2017, discarding 2018 to avoid bias. As explained in section 2.3, the nine thematic Categories has been analysed from three points of view present for years in the engineering higher education for sustainability, namely: categories related to different aspects of the *educational system* (1- Institutional and policies, 2- Curricular structure, 3- Educational strategy, 7- Competences/ behavioural aspects and 8- Academic/professional development); categories that are considering the *three pillars of sustainability* (4- Topics: techno-environmental, 5- Topics: techno-economics and 6- Topics: socio-cultural); and Category 9 referring to aspects related to *transdisciplinar and collaborative approaches* to bring together academia and society for co-creative learning schemes towards sustainability. This last category has been analysed independently due to its cross-cutting effect and the relevance shown in previous studies (see Segalas, *et al*., 2018 and references therein; Balsiger, 2014; Muhar, *et al*., 2013; Rieckmann, 2012).

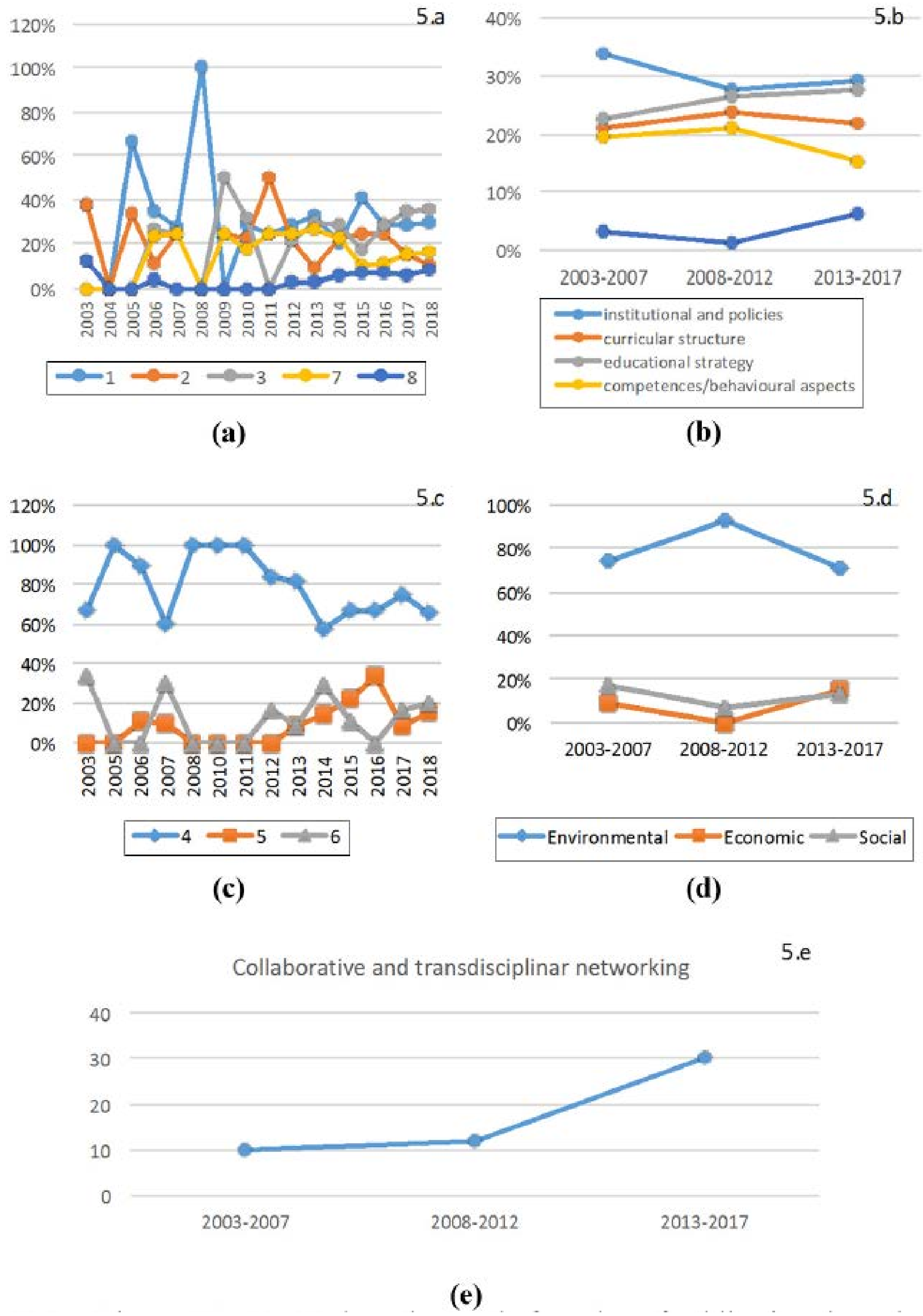

Figure 5. Results of evolution in percentage of papers published per Category in the three relevant points of view in the field of higher engineering education for sustainability: Educational system (5a, 5b); Three pillars of Sustainability (5c, 5d); Transdisciplinary and collaborative approaches (5e), during the analysed years. Figures 5a, 5c, 5e show the trend of number of publications in each period (2003-2008; 2008-2012; 2013-2017), while figures 5b and 5c show a comparative of annual publications.

Regarding the *three pillars of Sustainability* (Figure 5c, 5d), we can see that the Techno-environmental pillar keeps being the most relevant (keywords in around 80% of papers). Both the Socio-cultural and Economic have increased during the last 5 years, even though there's still some way to go to achieve a balanced relevance of the three pillars. Being highlighted this lack of social training in engineering education in preliminary studies (Segalàs *et al*., 2009; Cech, 2014) we can assume that the trend is not changing at the pace it should.

At the *educational system* level (Figure 5a, 5b), Institutional and policies, is the category gathering the most of the network keywords used, indicating a maintained interest over time, although it has decreased in recent years. Also keywords have remained at a similar level or slightly decreased, related to competencies and behavior-based learning (campus related learning activities, service learning), as well as those related to curricular adjustments to incorporate sustainability.

Keywords of the category Educational strategies are increasing relevance over time, related to the use of strategies to learn (real-world learning experiences, educational innovative initiatives/tools/techniques). Likewise, although with a smaller amount of keywords involved, the category Academic and professional development of faculty has risen sharply in recent years. The former suggests that an ongoing interest in didactic and innovative educational approaches, indeed regarding to faculty training, is appearing.

Finally, the considerable increase of keywords related to the category Transdisciplinary and collaborative networking (from 10 in 2003-2007 to 30 in 2013-2017; see Figure 5.e) consistently with its permeation through the network, indicates a widening interest in applying crossing boundaries schemes (transdisciplinarity, ethics, networking, etc.) into Engineering Higher Education in Sustainability.

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