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Virtual and remote labs in education: A bibliometric analysis

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A B S T R A C T

Laboratory experimentation plays an essential role in engineering and scientific education. Virtual and remote labs reduce the costs associated with conventional hands-on labs due to their required equipment, space, and maintenance staff. Furthermore, they provide additional benefits such as supporting distance learning, improving lab accessibility to handicapped people, and increasing safety for dangerous experimentation. This paper analyzes the literature on virtual and remote labs from its beginnings to 2015, identifying the most influential publications, the most researched topics, and how the interest in those topics has evolved along the way. To do so, bibliographical data gathered from ISI Web of Science, Scopus and GRC2014 have been examined using two prominent bibliometric approaches: science mapping and performance analysis.

1. Introduction

Experimentation plays an essential role in engineering and scientific education. Whereas traditional hands-on labs offer students opportunities of experimentation with real systems (i.e., they provide “actual experience”), they involve high costs associated with equipment, space, and maintenance staff (Gomes & Bogosyan, 2009). Accordingly, new types of labs are being proposed. To characterize the different modalities of all available experimentation environments, two criteria were proposed in (Dormido, 2004):

1. According to the way resources are accessed for experimental purposes, environments can be *remote* or *local*.
2. According to the physical nature of the lab, environments can be *simulated* or *real plants*.

By combining those criteria, there can be four types of experimentation environments:

1. *Local access-real resource*. This combination represents traditional *hands-on labs*, where the student is in front of a computer connected to the real plant.

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2. *Local access-simulated resource.* The whole environment is software and the experimentation interface works on a simulated, virtual and physically non-existent resource, which together with the interface is part of the computer. This configuration could be defined as a *mono-user virtual lab.*
3. *Remote access-real resource.* Real plant equipment is accessed through the Internet. The user remotely operates and controls a real plant through an experimentation interface. This approach is named *remote lab.*
4. *Remote access-simulated resource.* This form of experimentation is similar to the one above, but replacing the physical system with a model. The student operates with the experimentation interface on a virtual system reached through the Internet. The basic difference is that several users can operate simultaneously with the same virtual system. As it is a simulated process, it can be instantiated to serve anyone who asks for it. Thus, we have a *multi-user virtual lab.*

Virtual and Remote Labs (VRLs) not only enable reducing costs, but they provide other important benefits (Gravier, Fayolle, Bayard, Ates, & Lardon, 2008):

1. *Availability*: VRLs can be used from anywhere at anytime, thus they support students geographically scattered, who besides are conditioned to different time zones.
2. *Accessibility* for handicapped people.
3. *Observability*: lab sessions can be watched by many people or even recorded.
4. *Safety*: VRLs can be a better alternative to hands-on labs for dangerous experimentation.

Nowadays, the use of VRLs is spreading across a variety of domains and educational degrees (Azad, Auer, & Harward, 2011; Dziabenko and García-Zubía, 2013; Fjeldly & Shur, 2003; García-Zubía and Alves, 2012; Gomes and García-Zubía, 2007). As a result, their research community and its scientific paper production has increased dramatically. This paper tries to provide a panoramic view on the research on VRLs by analyzing, through *bibliometric* techniques (Martin et al., 2011), the vast literature published on VRLs from its beginnings in 1993–2015. The outcomes of this analysis offer information regarding the following issues:

1. How numerous is the literature on VRLs? How has paper publication been distributed over the time?
2. Which are the most influential papers on VRLs?
3. Who are the most prolific authors? Who are the most relevant ones?
4. Which journals, conferences, etc. have published the majority of the papers? Which ones have received most citations?
5. Which are the main topics studied in the area? How has the interest in those topics evolved with time?
6. Which are the most impacting papers for a given topic along a certain period of time?

4422 records retrieved from GRC2014 (Zappatore, Longo, & Bochicchio, 2015), ISI Web of Science (ISIWoS) and Scopus have been processed using two approaches to examine bibliographical data: *performance analysis* (Garfield, 1977) and *science mapping* (Callon, Courtial, & Laville, 1991).

Performance analysis tries to quantify the impact of scientific actors (researchers, journals, etc.) on a research field by measuring how often a paper is cited. In particular, this paper uses *H-index* (Hirsch, 2005) to measure publication impact, which is one of the most popular indicators for citation analysis.

Science mapping attempts to display the structural and dynamic aspects of scientific research, delimiting a research field, and identifying, quantifying and visualizing its thematic subfields. To map the VRL research area, we have used a technique called *co-word analysis*, that measures the association strengths of publication keywords (Coulter, Monarch, & Konda, 1998).

Our work uses both performance analysis and science mapping in a complementary way. Science mapping supports visualizing the main topics in the literature, their evolutions and inter-relationships. Performance analysis helps to identify the most productive topics (in terms of number of published papers), and the most impacting ones (according to received citations).

The remainder of the paper is structured as follows: Section 2 summarizes the goals and educational context of this paper. Section 3 describes the methodology used to carry out our work. Section 4 reports the performance analysis of the whole VRL research area, identifying those papers that, due to their number of citations, should be considered as *classics*. Section 5 applies science mapping techniques to identify the cognitive structure and evolution of the literature on VRLs. Section 6 discusses the limitations inherent to the methodology we have applied, and it justifies the decisions taken to overcome such limitations. Finally, some concluding remarks are provided in Section 7.

2. Educational context and aim of our work

There is a general consensus on the benefits of hands-on labs to teach science and engineering (Chen, 2010; Corter, Nickerson, Esche, & Chassapis, 2004; Ma & Nickerson; Singer, Hilton, & Schweingruber, 2006). However, some works have raised questions on the educational value of VRLs. For example, hands-on labs are specially important to acquire haptic skills and instrumentation awareness, which are very difficult to obtain via VRLs (Abdulwahed & Nagy, 2011).

Nevertheless, different empirical studies have shown that VRLs enable learning results comparable to traditional hands-on labs (Gustavsson et al., 2009; Kostaras, Xenos, & Skodras, 2011; Lindsay & Good, 2005; Nedic, Machotka, & Nafalski, 2003; Nickerson, Corter, Esche, & Chassapis, 2007; Sicker, Lookabaugh, Santos, & Barnes, 2005; Tem Sun, Cheng Lin, & Jui Yu, 2008). Furthermore, many authors think that VRLs provide interesting advantages over hands-on labs. For example, VRLs are available 24 h a day, 7 days a week. In contrast, hands-on labs are often only available for short periods of time due to logistical and economical reasons. Forming and understanding scientific concepts is the result of an iterative learning process that requires experimenting repeatedly with the lab (Hmelo, Holton, & Kolodner, 2000; Kolb, 1983). For that reason, hand-on labs are sometimes insufficient to fulfill the desired impact on students' learning (Kirschner & Meester, 1988; Roth, 1994).

Regarding the particular advantages virtual labs have, they support experimentation about unobservable phenomena, such as thermodynamics, chemical reactions, or electricity (Chiu, DeJaegher, & Chao, 2015; Jaakkola, Nurmi, & Veermans, 2011; de Jong, Linn, & Zacharia, 2013; Levy, 2013; Liu, 2006; Zacharia & Constantinou, 2008; Zhang & Linn, 2011). In addition, they can adapt reality, i.e., properties of the underlying mathematical model of the virtual lab can be changed to make easier the interpretation of certain phenomena (Ford & McCormack, 2000). Moreover, experiments can emphasize prominent information or remove confusing details (Trundle & Bell, 2010). Virtual labs are also an ideal tool to enable pre-laboratory preparation (Abdulwahed & Nagy, 2011; Dalgarno, Bishop, Adlong, & Bedgood, 2009; Staden, Braun, & Tonder, 1987), which is essential to improve the lab learning experience of students (Pogacnik & Cigic, 2006; Rollnick, Zwane, Staskun, Lotz, & Green, 2001). Finally, virtual labs favor students' engagement into “what if” explorations where the outcomes of the virtual experiments can be immediately accessed (Hennessy et al., 2007).

In remote labs, students handle actual physical apparatus and get real data from physical experiments, i.e., from the same type of experiments that would be run in hands-on labs. Hence, students learn about the complexities of the real world, e.g., dealing with measurement errors whose simulation is far from trivial (Toth, Morrow, & Ludvico, 2009; de Jong et al., 2013).

Our belief is that virtual, remote and hands-on labs are not exclusive alternatives, but valuable educational resources that can be combined in one integral and complementary learning unit. Such belief is supported by experimental evidence, as the pre-post comparison study design performed by Zacharia (Zacharia, 2007), which showed that the combination of remote and virtual experimentation enhanced students' conceptual understanding more than the use of remote experimentation alone. In this line, Abdulwahed et al (Abdulwahed & Nagy, 2011) propose the blended usage of VRLs and hands-on labs to foster the Kolb's constructivist cycle (Kolb, 1983), and thus, enabling high order learning. In particular, Abdulwahed et al. advocate (i) using virtual labs in preparatory sessions, (ii) utilizing hands-on labs in interactive lectures that involve experimentation, and finally (iii) using remote labs to support students' repetitive experimentation.

Nowadays, the use of VRLs is spreading across all educational levels: from primary schools to higher education, from vocational learning to universities, and from self-education to technical colleges (Zappatore et al., 2015). Likewise, their application domain is widening: control engineering (Prada, Fuertes, Alonso, Garca, & Domnguez, 2015; Saenz, Chacon, De La Torre, Visioli, & Dormido, 2015; de la Torre, Guinaldo, Heradio, & Dormido, 2015), robotics (Jara, Candelas, Puente, & Torres, 2011), spectroscopy (Cartwright & Valentine, 2002; Scanlon, Colwell, Cooper, & Paolo, 2004), thermodynamics (Chiu et al., 2015), etc. As a result, their research community and its scientific paper production is rapidly increasing.

The goal of this paper is guiding the stakeholders involved in the research, design, implementation and usage of VRLs (i.e., researchers, developers, lecturers, and faculty/university administration (Stefanovic, 2013)) through the vast literature available at the moment to identify the most researched topics, how the interest on that topics has evolved, the most relevant papers (in general and for each of the identified topics along a given period of time), the main sources of publication, and the most prolific/relevant authors.

Somehow related to our work, several literature reviews have been published on VRLs. Those reviews are mostly focused on particular aspects. To the extent of our knowledge, the only attempt to offer a panoramic view of the whole literature on VRLs is (Zappatore et al., 2015), where Zappatore et al. analyze 2389 bibliographical records.

To characterize the VRL literature, Zappatore et al. follow a quantitative approach, i.e., their analysis is limited “to count papers” to find the most prolific authors and sources of publication. Our work enriches that analysis by providing a qualitative dimension, e.g., identifying not only who/which authors/sources have written/published most papers, but who/which of them are the most relevant for the VRL community.

3. Materials and methods

To undertake the bibliometric analysis described in this paper, the workflow proposed in (Börner, Chen, & Boyack, 2003; Cobo, López-Herrera, Herrera-Viedma, & Herrera, 2011) has been used, which is composed of the following steps:

1. *Data retrieval.* The starting point of our analysis was GRC2014, a bibliographical database specifically dedicated to VRLs, which was created by Zappatore et al. (2015). Unfortunately, GRC2014 has the following drawbacks:
   - *It covers a short time span.* It just includes records on papers for the time span 2008–2013.
   - *It does not provide information regarding paper citation.* From the 2389 records it stores, just 611 of them include how many times the corresponding papers have been cited (i.e., only 25.58% of all the records).

To overcome the aforementioned limitations, we complemented GRC2014 with data gathered from Scopus and ISIWoS, which are the most reliable bibliographical databases at the moment (Gomez-Jauregui, Gomez-Jauregui, Manchado, & Otero, 2014; Vieira & Gomes, 2009). To do so, we performed the query in Fig. 1 for the time span 1993–2015 on those databases. The asterisk pattern character means zero to many characters and it is used in our query to catch the noun plurals. Line 2 in the query constraints results to the educational context. Lines 3–4 refer to virtual labs, while lines 5–6 correspond to remote labs. Lines 7–8 are about online experimentation in general. Finally, Lines 9–10 collects names of significant research projects in the VRL area. Some project names have been discarded because they generate more false positives than correct results: "Sahara" (homonymy with the corresponding geographical region), "VISIR" (whose acronym also stands for the very large telescope spectrometer), and "LiLa" (that usually indicates Lithium–Lanthanum compounds in chemistry) (Zappatore et al., 2015).

2. *Data aggregation.* The scatter plot in Fig. 2 shows the number of citations of the records common to ISIWoS and Scopus, including the corresponding regression line as well. ISIWoS has a more selective procedure to include bibliographical references than Scopus. As a result, Scopus provides more records than ISIWoS, and the citations tend to be higher as well. For the query we performed, the Pearson's correlation coefficient of the citation counts is 0.94. Therefore, the information provided by both databases is rather consistent.

As most records on GRC2014 do not include citation information, and the citation data of Scopus and ISIWoS is coherent, we decided to compute the citation count for the common records as the maximum of the citations given by ISIWoS and Scopus.

As a result of aggregating the data from GRC2014, ISIWoS and Scopus, we ended up with a set of 4422 bibliographical records.

3. *Preprocessing.* The data retrieved from bibliographical databases usually have errors. For instance, references may be duplicated, authors' names may appear in different ways, etc. So, it is necessary to preprocess the data before carrying out any analysis.

To track the evolution of the VRL research area and measure its performance, we have used two approaches that require analyzing publication keywords and citations: Co-Word Analysis and H-index. Hence, we have performed a laborious pre-processing procedure to:

(a) Standardize keywords; e.g., the following keywords included in the data were considered synonyms: "Virtual lab", "Virtual laboratory", "Virtual laboratory system", "Virtual computer lab", "Virtual and distance laboratory", "Virtual web laboratory", and "Web-based virtual laboratory".

(b) Correct invalid citations; e.g., reference (Gravier et al., 2008) appears cited in the raw data gathered from ISIWoS as "Gravier C., 2008, INT J ONLINE ENG, V4" and "Gravier J., 2008, INT J ONLINE ENG, V4".

4. *Analysis.* There are two main approaches to examine bibliographical data (Noyons, Moed, & Van Raan, 1999), which have been used jointly in this paper:
   (a) *Performance analysis* tries to quantify the impact of scientific actors (researchers, journals, etc.). In particular, the performance analysis we have carried out is based on H-index.

```
1  TOPIC =
2  ("education" OR "learning" OR "teaching") AND
3  ("virtual lab*" OR "virtual experiment*" OR "virtual instrumentation" OR
4     "virtual engineering environment" OR
5   "remote lab*" OR "remote experiment*" OR "remote process visualization" OR
6     "remote engineering" OR
7   "web*lab*" OR "online lab*" OR "web experiment*" OR "online experiment*" OR
8     "online engineering" OR
9   "iLab" OR "NetLab" OR "Labshare" OR "SmartLabs" OR "Lab2Go" OR "Go-Lab" OR
10    "WebLab-DEUSTO" OR "eMERSION" OR "Lab@Future")
```

Fig. 1. Query to gather data from ISIWoS and Scopus.

(b) *Science Mapping* looks for identifying the cognitive structure and evolution of a research field.

To preprocess and analyze the bibliographical data, the open source software tool SciMAT (Cobo, Lopez-Herrera, Herrera-Viedma, & Herrera, 2012) has been used, which is freely available at:
http://sci2s.ugr.es/scimat/.

4. Performance analysis

The main approach to evaluate research performance is *paper citation analysis* (Moed, 2009), whose main tenet is "the more often a paper becomes cited, the greater its influence on the field" (Garfield, 1979). One of the most popular indicators for citation analysis is *H-index*, which was introduced by Hirsch (2005) to measure the scientific performance of a researcher through her publications. Its original definition is:

"a scientist has index h if h of her n papers have at least h citations each, and the other $(n-h)$ papers have $\leq h$ citations each".

Compared to alternative approaches, H-index has the following advantages:

- It comprises in a single indicator two aspects that traditionally have been measured separately using different indicators: the quantity and the impact of the scientific output of a researcher.
- It has been proven to be robust in the sense that it is insensitive to: (i) a few outstandingly highly cited papers (increasing the H-index requires receiving citations in a large number of papers) (Vanclay, 2007), and (ii) a set of lowly cited papers.

In the following subsections, H-index is used to identify the main papers, authors and sources of publication of research on VRLs.

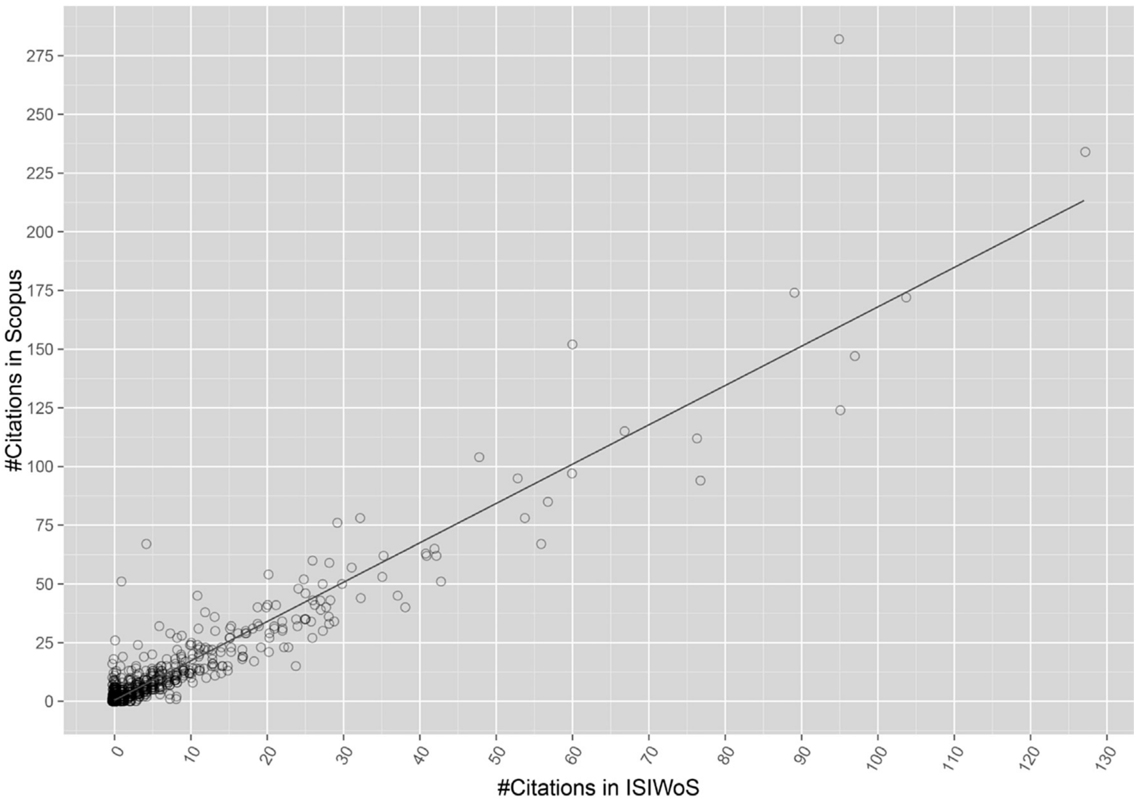


Fig. 2. Number of citations in Scopus vs number of citations in ISIWoS for publications common to both systems.

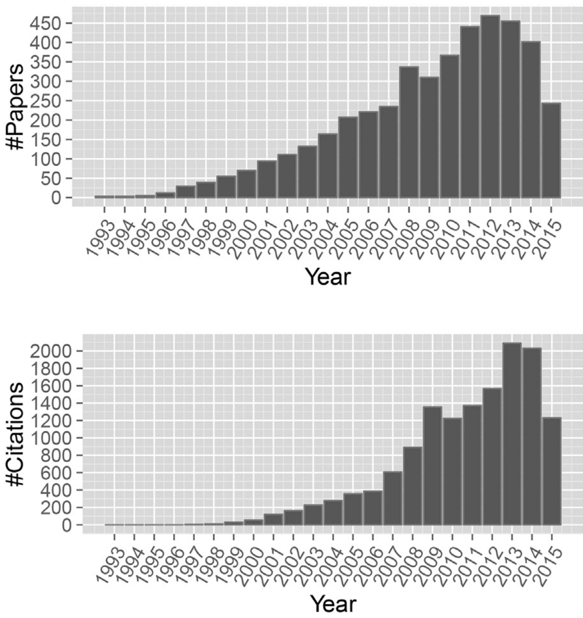


Fig. 3. Number of published papers and citations per year.

4.1. *Identifying the main papers*

Fig. 3 depicts the evolution of paper performance along the years. It shows: (i) how many papers on VRLs have been published per year, and (ii) the number of citations those papers have received. As Fig. 3 shows, the interest on VRLs has increased over the time since there is a growing trend of the number of published papers and citations.

Garfield (1977) defined the concept of *citation classics* to identify the papers most frequently cited in a research field. Analyzing the citation classics of an area (i) helps recognizing the major advances in the discipline, (ii) provides historical perspective of its scientific progress, and (iii) identifies the main intellectual actors of the research field.

Martinez, Herrera, Lopez-Gijon, & Herrera-Viedma (2014) proposed adapting the H-index definition as follows to support the analysis of citation classics:

> "a research area has index h, if h of the n papers published in the area have at least h citations each, and the other $(n-h)$ papers have $\leq h$ citations each".

The top h papers of a research area constitute its *H-core*, which identifies the highest-performance publications of the area. In particular, Table 1 summarizes the H-core of the VRL field, whose H-index is 50. The last column describes the thematic network for each classic according to the science mapping results reported in Section 5 (the notation THEMATIC NETWORK$^{\text{period}}$ has been used).

The following subsections briefly summarize each of the classics listed in Table 1, by grouping them into five categories: (i) general papers that introduce the concept of VRLs and predict their pedagogical impact in the future, (ii) articles presenting approaches to build, manage, and deploy VRLs, (iii) papers describing particular VRLs, (iv) articles on VRL support for collaborative learning, and (v) papers about the experimental assessment of the VRL educational effectiveness.

4.1.1. *General papers on VRLs*

Dormido (2004) provides a precise definition of VRLs, discussing their particular advantages and disadvantages. The author also predicts their pedagogical impact in the near future in the education of control-engineering.

Gustavsson et al. (2009) illustrate the importance of remote experimentation by presenting several labs, in special, the VISIR platform for electrical experiments. The paper also justifies that remote labs are indispensable and cannot be substituted by virtual labs because they offer the possibility of seeing the differences between the results of calculations based on models and the actual behavior of the physical world.

Bourne et al. (2005) predict the impact that online methods are going to have in engineering education in the short-term future, concluding that online methods in general, and VRLs in particular, will support delivering education to broader audiences.

Balamuralithara and Woods (2009) discuss the current trends in VRLs. Moreover, it summarizes some key points (cost, accessibility, safety, maintenance, equipment/facilities needed, reality and actual control, etc.) that institutions should take into account to select what lab modality (hands-on, virtual or remote) is more suitable to their interests.

Table 1
Citation classics.

	Type of source	Year of publication	#Citations	Thematic network
Ma et al.: Hands-On, Simulated, and Remote Laboratories: A Comparative Literature Review (Ma & Nickerson,)	Journal	2006	287	R-LAB[2]
Aktan et al.: Distance learning applied to control engineering laboratories (Aktan, Bohus, Crowl, & Shor, 1996)	Journal	1996	234	V-LAB[1]
Harward et al.: The iLab shared architecture a web services infrastructure to build communities of Internet accessible laboratories (Harward et al., 2008)	Journal	2008	208	R-LAB[2]
Gomes et al.: Current Trends in Remote Laboratories (Gomes & Bogosyan, 2009)	Journal	2009	177	R-LAB[2]
Dormido: Control learning: present and future (Dormido, 2004)	Journal	2004	173	V-LAB[1]
Bourne et al.: Online Engineering Education: Learning Anywhere, Anytime (Bourne, Harris, & Mayadas, 2005)	Journal	2005	155	R-LAB[2]
Ko et al.: Development of a web-based laboratory for control experiments on a coupled tank apparatus (Ko, Chen, Chen, Zhuang, Chen Tan, 2001)	Journal	2001	148	V-LAB[1]
Joolingen et al.: Co-Lab: research and development of an online learning environment for collaborative scientific discovery learning (van Joolingen, de Jong, Lazonder, Savelsbergh, & Manlove, 2005)	Journal	2005	124	COLLAB-LEARN[2]
Gillet et al.: Collaborative web-based experimentation in flexible engineering education (Gillet, Ngoc, & Rekik, 2005)	Journal	2005	122	COLLAB-LEARN[2]
Casini et al.: The automatic control telelab: A user-friendly interface for distance learning (Casini & Prattichizzo, 2003)	Journal	2003	115	V-LAB[1]
Shen et al.: Conducting laboratory experiments over the Internet (Shen et al., 1999)	Journal	1999	115	V-LAB[1]
Hercog et al.: A DSP-based remote control laboratory (Hercog, Gergic, Uran, & Jezernik, 2007)	Journal	2007	112	R-LAB[2]
Sanchez et al.: A Java/Matlab-based environment for remote control system laboratories: illustrated with an inverted pendulum (Sanchez, Dormido, Pastor, & Morilla, 2004)	Journal	2004	111	R-LAB[2]
Nickerson et al.: A model for evaluating the effectiveness of remote engineering laboratories and simulations in education (Nickerson et al., 2007)	Journal	2007	105	R-LAB[2]
Tzafestas et al.: Virtual and remote robotic laboratory: comparative experimental evaluation (Tzafestas, Palaiologou, & Alifragis, 2006)	Journal	2006	97	R-LAB[2]
Lindsay et al.: Effects of laboratory access modes upon learning outcomes (Lindsay & Good, 2005)	Journal	2005	96	R-LAB[2]
Ko et al.: A Web-based virtual laboratory on a frequency modulation experiment (Ko et al., 2001)	Journal	2001	85	V-LAB[1]
Zacharia: Comparing and combining real and virtual experimentation: An effort to enhance students' conceptual understanding of electric circuits (Zacharia, 2007)	Journal	2007	83	R-LAB[2]
Balamuralithara et al.: Virtual laboratories in engineering education: The simulation lab and remote lab (Balamuralithara & Woods, 2009)	Journal	2009	80	R-LAB[2]
Gustavsson et al.: On Objectives of Instructional Laboratories, Individual Assessment, and Use of Collaborative Remote Laboratories (Gustavsson et al., 2009)	Journal	2009	79	R-LAB[2]
Koretsky et al.: Enhancement of student learning in experimental design using a virtual laboratory (Koretsky, Amatore, Barnes, & Kimura, 2008)	Journal	2008	76	R-LAB[2]
Corter et al.: Constructing Reality: A Study of Remote, Hands-on, and Simulated Laboratories (Corter et al.,)	Journal	2007	75	R-LAB[2]
Ertugrul et al.: Towards Virtual Laboratories: a Survey of LabVIEW-based Teaching/Learning Tools and Future Trends (Ertugrul, 2000)	Journal	2000	75	V-LAB[1]
García-Zubía et al.: Addressing software impact in the design of remote laboratories (García-Zubía, Orduña, Lopez-de Ipina, & Alves, 2009)	Journal	2009	74	R-LAB[2]
Gillet et al.: Hands-On Laboratory Experiments in Flexible and Distance Learning (Gillet, Latchman, Salzmann, & Crisalle, 2001)	Journal	2001	74	V-LAB[1]
Valera et al.: Virtual and remote control laboratory development (Valera, Diez, Valles, & Albertos, 2005)	Journal	2005	69	V-LAB[1]
Arpaia et al.: A measurement laboratory on geographic network for remote test experiments (Arpaia, Baccigalupi, Cennamo, & Daponte, 1998)	Conf.	1998	69	V-LAB[1]
Bertocco et al.: A client-server architecture for distributed measurement systems (Bertocco, Ferraris, Offelli, & Parvis, 1998)	Conf.	1998	67	V-LAB[1]
Ogot et al.: An Assessment of In-Person and Remotely Operated Laboratories (Ogot, Elliott, & Glumac, 2003)	Journal	2003	66	V-LAB[1]
Huba et al.: Modular approach to teaching PID control (Huba & Simunek, 2007)	Journal	2007	65	R-LAB[2]
Lowe et al.: Evolving Remote Laboratory Architectures to Leverage Emerging Internet Technologies (Lowe, Murray, Lindsay, & Liu, 2009)	Journal	2009	64	R-LAB[2]
Ferrero et al.: ReMLab: a Java-based remote, didactic measurement laboratory (Ferrero, Salicone, Bonora, & Parmigiani, 2003)	Journal	2003	64	V-LAB[1]
Ko et al.: A large-scale Web-based virtual oscilloscope laboratory experiment (Ko et al., 2000)	Journal	2000	63	V-LAB[1]
Dalgarno et al.: Effectiveness of a Virtual Laboratory as a preparatory resource for Distance Education chemistry students (Dalgarno et al., 2009)	Journal	2009	62	R-LAB[2]
Dormido et al.: Development of a web-based control laboratory for automation technicians: The three-tank system (Dormido et al., 2008)	Journal	2008	62	R-LAB[2]
Canfora et al.: Remotely accessible laboratory for electronic measurement teaching (Canfora, Daponte, & Rapuano, 2004)	Journal	2004	62	V-LAB[1]
Abdulwahed et al.: Applying Kolb's Experiential Learning Cycle for Laboratory Education (Abdulwahed & Nagy, 2009)	Journal	2009	59	R-LAB[2]
Jara et al.: Real-time collaboration of virtual laboratories through the Internet (Jara et al., 2009)	Journal	2009	58	COLLAB-LEARN[2]
Sanchez et al.: Virtual and remote control labs using Java: a qualitative approach (Sanchez, Morilla, Dormido, Aranda, & Ruiperez, 2002)	Journal	2002	56	V-LAB[1]

Table 1 (*continued*)

	Type of source	Year of publication	#Citations	Thematic network
Bellmunt et al.: A distance PLC programming course employing a remote laboratory based on a flexible manufacturing cell (Bellmunt, Miracle, Arellano, Sumper, & Andreu, 2006)	Journal	2006	54	R-LAB[2]
Colwell et al.: Using remote laboratories to extend access to science and engineering (Colwell, Scanlon, & Cooper, 2002)	Journal	2002	53	V-LAB[1]
Wiesner et al.: Comparison of student learning in physical and simulated unit operations experiments (Wiesner & Lan, 2004)	Journal	2004	52	V-LAB[1]
Hennessy et al.: Pedagogical approaches for technology-integrated science teaching (Hennessy et al., 2007)	Journal	2007	52	R-LAB[2]
Scanlon et al.: Remote experiments, re-versioning and re-thinking science learning (Scanlon et al., 2004)	Journal	2004	52	V-LAB[1]
Forbus et al.: CyclePad: An articulate virtual laboratory for engineering thermodynamics (Forbus et al., 1999)	Journal	1999	52	V-LAB[1]
Guimaraes et al.: REAL: a virtual laboratory for mobile robot experiments (Guimaraes et al., 2003)	Journal	2003	51	V-LAB[1]
Ferrero et al.: A simulation tool for virtual laboratory experiments in a WWW environment (Ferrero & Piuri, 1999)	Journal	1999	51	V-LAB[1]
Albu et al.: Embedding Remote Experimentation in Power Engineering Education (Albu, Holbert, Heydt, Grigorescu, & Trusca, 2004)	Journal	2004	50	V-LAB[1]
Shin et al.: A web-based, interactive virtual laboratory system for unit operations and process systems engineering education: Issues, design and implementation (Shin, Yoon, Lee, & Lee, 2002)	Journal	2002	50	V-LAB[1]
Restivo et al.: A remote laboratory in engineering measurement (Restivo, Mendes, Lopes, Silva, & Chouzal, 2009)	Journal	2009	50	R-LAB[2]

4.1.2. Approaches to build, manage, and share VRLs

García-Zubía et al. (2009) present an exhaustive analysis of software technologies to implement both the client and server sides of remote labs. For the client side, security, intrusivity (e.g., does the lab need permissions to access the hard disk?), bandwidth requirements, web-browsers, installation, etc. are analyzed. For the server side, three technologies (Java, .NET, and Python) are compared in terms of robustness, web services libraries, development tools, price, etc.

Hercog et al. (2007) present a framework for rapid remote lab implementation in the field of automatic control. The proposed solution is based on in-house developed embedded control hardware and two commercial software packages: MATLAB/Simulink and LabVIEW. As application example, a digital-signal-processor-based remote control lab is described.

Gomes and Bogosyan (2009) overview available technologies for the development of remote labs, describing several examples of remote labs in industrial electronics education.

Shen et al. (1999) discuss what approaches and technologies should be used to implement remote labs (e.g., the client-server architecture, the Java language, etc.). As an application example, a lab on semiconductor device characterization is built.

Ertugrul (2000) give reasons in favor of using LabVIEW to develop VRLs. In particular they summarize a number of LabVIEW-based virtual instrumentation applications in several domains: electrical and electronics engineering, mechanical engineering, biomedical engineering, control, instrumentations and computer-assisted general purpose labs, etc.

Valera et al. (2005) advocate developing VRLs by using two integrated MATLAB-based software packages, namely, MATLAB Web Server (by Mathworks) and WinCon (by Quanser Consulting).

Ferrero and Piuri (1999) propose a technological framework to develop remote labs. On the server side, the actual setup is controlled with LabVIEW virtual instruments. The client side is implemented in Java. The client-server connection use three standard protocols: HTTP, FTP, and TCP/IP.

Bertocco et al. (1998) describe a client-server architecture for the remote control of distant instrumentation in a multiple-user, multiple-laboratory environment. The approach includes a queue mechanism, which provides information about the actual server load. The communication between the server and the clients is performed at instrument level or by means of encoded requests that minimize the network-imposed overhead.

Sanchez et al. (2002) argue that virtual labs should be interactive and dynamic, supporting that users visualize on the fly how the model behavior evolves according to the values of the interactive variables. This way, the qualitative aspects are immediately highlighted graphically and numerically as a response to the users actions. To enable such kind of lab, the authors propose a solution based on Java.

Colwell et al. (2002) introduce the design and description of a prototype system to support remote experimentation on science and engineering. This system was the main goal of the European Union funded project PEARL. In addition, the authors summarize several labs created with the system: a remote electron microscope, a spectrometer, visual inspection of printed circuit boards, and a digital electronic bench.

Harward et al. (2008) describe the iLab architecture, which supports delivering VRLs for a potentially unlimited number of users. Thus, by supporting the cross-institutional sharing of VRLs, iLab contributes to improve lab utilization levels, share costs, and increase the lab audience.

Lowe et al. (2009) argue that the successful use of remote labs requires taking into account the desired educational outcomes, the pedagogical design, and the technology supporting the lab. The paper analyzes two architectures to deploy and manage remote labs, iLab and UTS, identifying their strengths and shortcomings.

4.1.3. Description of particular VRLs

According to their field of application, classics describing particular labs can be organized in the following areas:

1 .*Control engineering*. In their seminal paper, Aktan et al. (1996) describe a control engineering remote lab as a proof of concept of the idea of remote lab.

Ko et al., (2001) describe a remote lab for teaching control education using a coupled tank apparatus. The lab has the capability to implement strategies for manual, proportional integral derivative, general state-space, and fuzzy logic control.

Sanchez et al. (2004) describe a lab for controlling an inverted pendulum, which is implemented using a novel Java-based approach.

Dormido et al. (2008) describe a VRL for experimentation on a nonlinear multiple-input-multiple-output system: the three-tank plant. The lab not only supports the virtual and remote modes, but also their superimposition to compare the theoretical results of the mathematical model that underlies the virtual lab with the actual behavior of the remote lab.

Casini and Prattichizzo (2003) present a remote lab, which supports students to choose a control law, change the control parameters on-line, and design their own controller through the MATLAB/Simulink environment.

Huba and Simunek (2007) present a VRL to teach Constrained Time-Delayed Proportional-Integral-Derivative Control. The lab is mainly created with Easy Java Simulations, which is an authoring tool that speeds up the creation of VRLs.

Gillet et al. (2001) present a remote lab for control-engineering education. The lab includes virtual reality representations to reinforce the pedagogical effectiveness of the experience and to facilitate the interactivity of the students with the system.

2. *Chemistry*. Forbus et al. (1999) describe a virtual lab to analyze and design thermodynamic cycles. The lab uses artificial intelligence techniques to understand students' design and thus help them to analyze and improve their design.

Koretsky et al. (2008) describe a virtual lab for chemical vapor deposition processes. The goal of the lab is engaging students in certain aspects of the experimental design, specifically, the experimental strategy, the analysis and interpretation of data, and the iterative process of redesign.

Shin et al. (2002) describe a virtual lab for unit operations and control experiment of separation processes, including distillation and drying. The lab is implemented with several programming languages: Java, C++ and Visual Basic. The paper includes a positive empirical assessment on the pedagogical effectiveness of the lab.

3. *Electrical and electronic measurement*. Arpaia et al. (1998) describe RemLab, a distributed architecture for remote experiments in the field of electrical and electronic measurements. RemLab is hierarchically organized with a general server and several measurement laboratories geographically distributed.

Ko et al. (2000) present an oscilloscope remote lab. It uses real-time video to capture the display of the actual oscilloscope, and LabVIEW for local instrument control.

Ferrero et al. (2003) describe a remote lab for electrical measurement, which is completely implemented in Java and takes advantage of the Java Native Interface (JNI) to interact with the low-level drivers of the instruments and boards.

Canfora et al. (2004) describe a remote lab for electronic measurement, which is implemented in Java and supports that multiple students perform measurement experiments accessing multiple instruments through a common server.

4. *Others*. Albu et al. (2004) describe a remote lab for power engineering education. The lab is implemented with LabVIEW and is able to protect the equipment from accidental misuse than produce voltages or currents outside a established range.

Bellmunt et al. (2006) describe a remote lab for electrical engineering based on a flexible manufacturing cell, which is a small-scale industrial system where students can learn and become familiar with real industrial components, such as position sensors, pneumatic and electrical actuators, drives, programmable logic controllers, and industrial communication networks.

Ko et al. (2001) present a remote lab for frequency modulation in telecommunications. The system uses a double client-server structure where access to the experiment is via two rounds of client-server processing.

Guimaraes et al. (2003) present a remote lab for mobile robot experiments. The lab is implemented in Java, uses the Common Object Request Broker Architecture (CORBA), and supports teleoperating a XR4000 mobile robot.

Restivo et al. (2009) describe a remote lab for measuring and determining mechanical material characteristics. The software is programmed with LabVIEW and deployed into the learning management system Moodle. The paper reports the successful validation of the lab with the students, and it also summarizes other remote labs developed with the same approach.

4.1.4. Collaborative learning and VRLs

van Joolingen et al. (2005) justify the importance of organizing science education around collaborative inquiry. Moreover, it presents the learning environment Co-Lab in which groups of learners can experiment through VRLs, and express acquired understanding in a runnable computer model.

Gillet et al. (2005) describe a web service that enables collecting and sharing preparatory notes and experimental results with both peers and teaching assistants.

Jara et al. (2009) extend the EJS authoring tool to provide synchronous interaction of multiple participants with a given VRL. This way, any VRL created with EJS gets automatically support for collaborative work, transforming the lab itself into a communication medium among learners.

4.1.5. Assessing the educational effectiveness of VRLs

Ma and Nickerson perform a literature review on VRLs. As a result of analyzing 60 papers, the authors find that (i) the area has a wide disciplinary spectrum (although most of the articles are focused on engineering education), and (ii) there is not enough empirical evidence to support advocates nor detractors for each different type of lab, thus more experimental studies are needed to assess the learning effectiveness of VRLs.

Nickerson et al. (2007) propose a model for systematically testing the educational effectiveness of a given remote lab in terms of students' cognition and motivation.

Tzafestas et al. (2006) describe a VRL in the field of robotics, which is used to compare the pedagogical effectiveness of hands-on, remote, and virtual labs. According to the experimental results, it seems that virtual labs can be as effective as remote and hands-on labs.

Lindsay and Good (2005) use the calibration of a piezoelectric accelerometer to empirically compare the educational effectiveness of hands-on, remote, and virtual labs. The study concludes that, in terms of learning outcomes, those different types of labs are not equivalent as each modality has its own strengths and weaknesses.

Zacharia (2007) test the value of combining hands-on and virtual labs with respect to changes in students conceptual understanding of electric circuits. The empirical study concludes that students who used both the virtual and hand-on labs achieved a better understanding than those that just used the hands-on lab.

Corter et al. describe the results of a large-scale study comparing learning outcomes and student preferences for hands-on, remote, and virtual labs. According to the study, although students expressed preference for traditional hands-on labs, VRLs were equally effective to learn the relevant concepts.

Ogot et al. (2003) use an experiment on fluid mechanics, which is part of an undergraduate mechanical engineering curriculum, to experimentally evaluate the educational effectiveness of remote labs compared to hands-on labs. The results show no significant difference in the educational outcomes.

Dalgarno et al. (2009) use a 3D virtual lab on Chemistry to assess the pedagogical value of virtual labs. The empirical results show that virtual labs are helpful to familiarize students with the real lab environment prior to their lab sessions.

Scanlon et al. (2004) report an empirical assessment on the effectiveness of remote labs in the context of the European Union funded project PEARL. The findings suggest a real potential and opportunity for remote experimentation to provide an alternative to practical work in the traditional lab setting.

Wiesner and Lan (2004) report empirical evidence on the usefulness of virtual labs in chemical engineering education. In particular, the authors conclude that virtual and hands-on labs complement each other and thus should be used together to enhance student learning.

Hennessy et al. (2007) describe a qualitative study on the educational effectiveness of virtual labs. According to the results, virtual labs showed to be a valuable pedagogical resource. In addition, the authors summarize lessons learned on how to use virtual labs to empower learning in science lessons.

Abdulwahed and Nagy (2009) describe an empirical study to measure the pedagogical effectiveness of hands-on and VRLs to support the Kolb's learning cycle, i.e., to foster a balanced acquisition of concrete experience ability, reflective observation ability abstract conceptualization ability, and active experimentation ability. According to the study, VRLs are effective to activate the prehension dimension of Kolb's cycle and thus, they complement hands-on labs.

4.2. Identifying the main authors

Fig. 4 represents the distribution of papers per author along the years. This figure helps to get an idea about how many researchers have been involved in the field along the time, how many of them have been occasional authors, and how many have focused their research mostly on VRLs.

Figs. 5 and 6 show the most prominent authors on VRLs. Fig. 5 summarizes the authors who have written a major number of papers. Fig. 6 shows the authors whose papers have received the biggest number of citations. It should be noted that both figures only take into account the papers gathered from GRC2014, ISIWoS and Scopus. For instance, according to Scopus, S. Dormido has written 251 papers not only on VRLs, but also on Control Engineering, Robotics, etc. Hence, Fig. 5 just represents the 60 of those that are about VRLs.

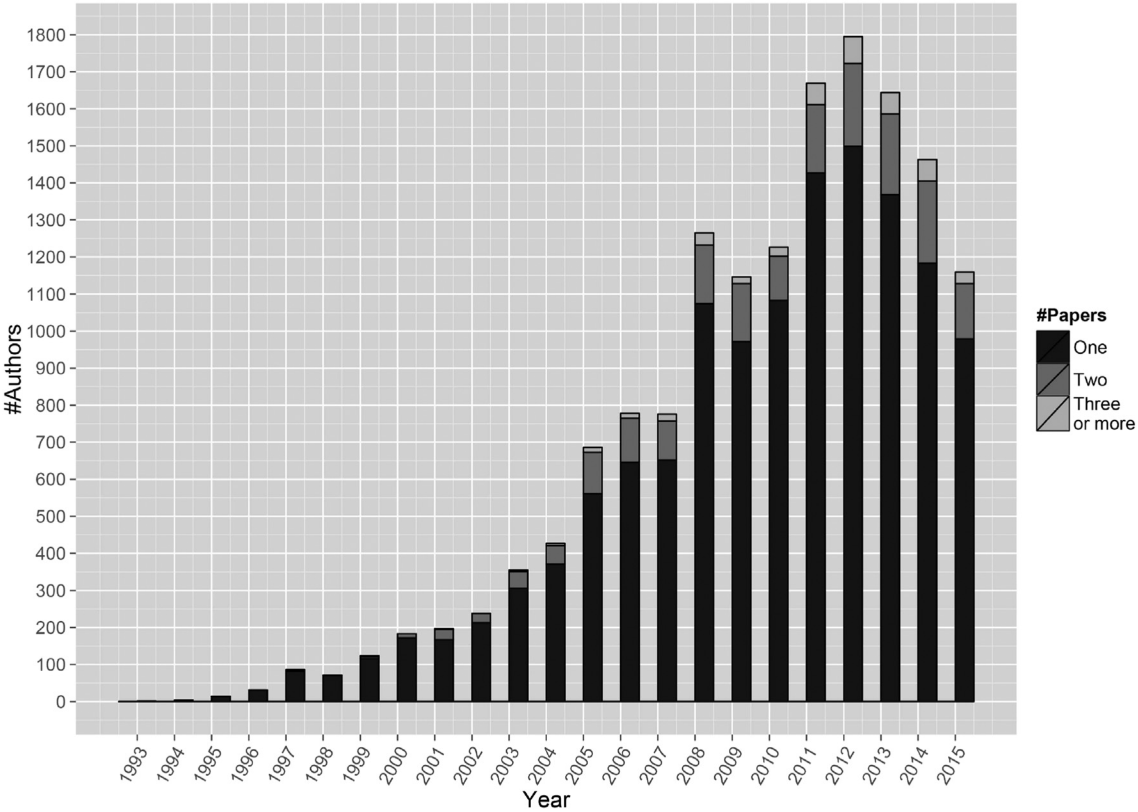


Fig. 4. Number of papers per author.

4.3. Identifying the main sources of publication

Figs. 7 and 8 show the most prominent journals and conferences on VRLs. Fig. 7 summarizes the sources which have published the largest number of papers on VRLs. Fig. 8 shows the sources whose papers have received the biggest number of citations.

5. Science mapping

In this paper, a particular science mapping approach known as co-word analysis has been used to identify the main topics of a scientific field and their inter-relationship. It measures the association strengths of terms representative of the publications in the field by analyzing the co-occurrence frequency of pairs of keywords. Several measures have been proposed to estimate the association strength between publication keywords. van Eck and Waltman (2009) performed an analysis of many of those measures, concluding that *equivalence index* (Callon et al., 1991) is the most appropriate one for normalizing co-occurrence frequencies. In bibliometrics, equivalence index is also known as *proximity index* (Rip & Courtial, 1984), *probabilistic affinity index* (Zitt, Bassecoulard, & Okubo, 2000), and *association strength* (Coulter et al., 1998; van Eck & Waltman, 2007).

The equivalence index $e_{A \leftrightarrows B}$ of two keywords A and B is defined by Equation (1), where $c_{A \leftrightarrows B}$ is the number of publications where A and B appear together, and c_A and c_B are the total number of documents that include A and B, respectively.

$$e_{A \leftrightarrows B} = \frac{c^2_{A \leftrightarrows B}}{c_A \cdot c_B} \quad (1)$$

The value of $e_{A \leftrightarrows B}$ falls into the interval [0,1]:

- When there is no publication where A and B appear together as keywords, $c_{A \leftrightarrows B} = 0$, and thus $e_{A \leftrightarrows B} = 0$
- If A and B are keywords that always appear together, $c_A = c_B = c_{A \leftrightarrows B}$, and thus $e_{A \leftrightarrows B} = 1$

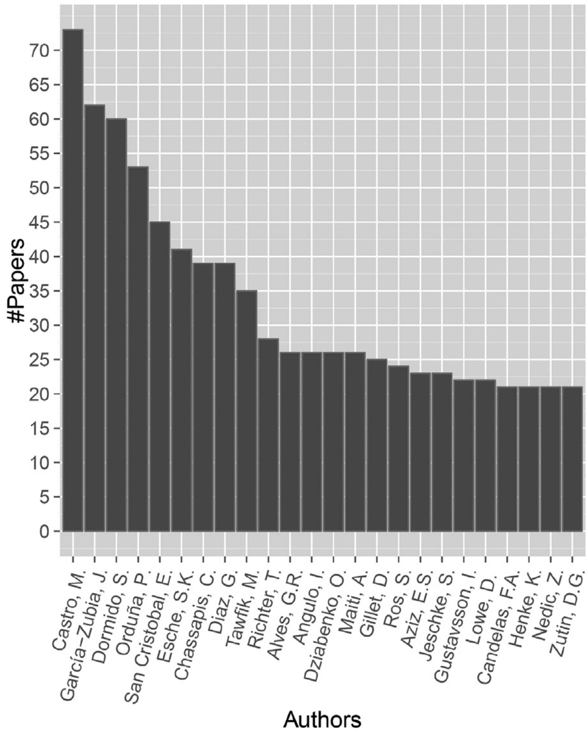


Fig. 5. Most prolific authors.

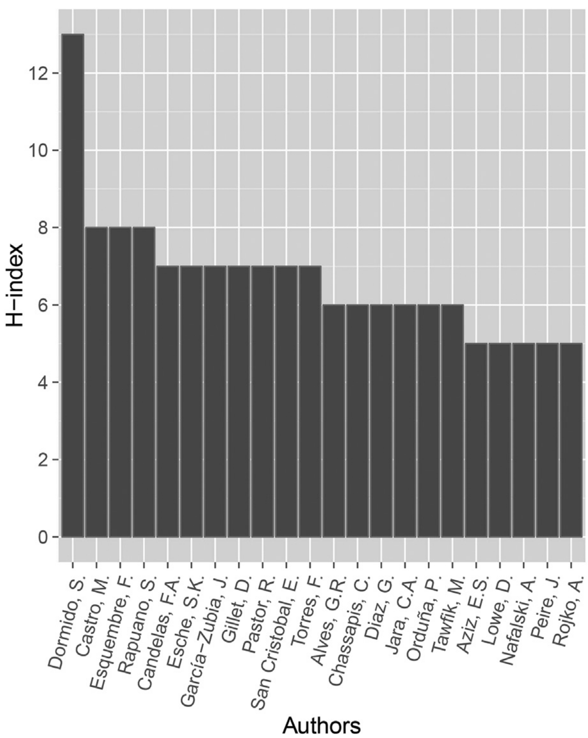


Fig. 6. Most cited authors.

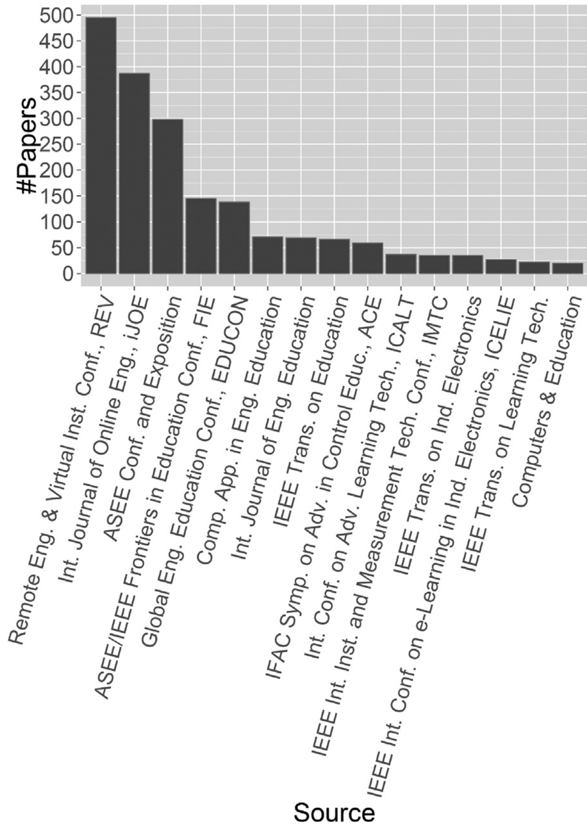


Fig. 7. Sources with most papers.

A clustering algorithm can use the equivalence index to identify research topics by looking for groups of strongly linked keywords (Callon, Law, & Rip, 1986, 1991; Kandylas, Upham, & Ungar, 2010). In such a way, each detected topic is modeled by a cluster of interrelated keywords known as a *thematic network*. In this paper, the algorithm of *simple centers* (Callon et al., 1991) has been used to get the clusters, each one representing a topic. This algorithm has been successfully used in a number of co-word studies (Bailon-Moreno, Jurado-Alameda, & Ruiz-Baños, 2006; Cobo et al., 2011; Coulter et al., 1998; Lopez-Herrera et al., 2009) and has the advantage of producing labeled clusters (in contrast to other alternative approaches that generate unlabeled clusters, which need to be revised by an expert to identify the topics they represent). Algorithm 1 summarizes in pseudocode how the approach works.

Algorithm 1: simple_centers

Input $\min_{\text{occurrences}}$; $\min_{\text{co}\cdot\text{occurrences}}$; $\min_{\text{keywords}}$; $\max_{\text{keywords}}$;
Output *set of clusters;*
begin
  Remove all keywords included in less than $\min_{\text{occurrences}}$ publications;
  repeat
    Get the link with highest $e_{A\leftrightarrows B}$ from all possible keywords to begin a cluster;
    From that link, form other links in a breadth-first manner, until no more links are possible due to $\min_{\text{co}\cdot\text{occurrences}}$ or $\min_{\text{keywords}}$ or $\max_{\text{keywords}}$;
    The keyword which participates in more links is considered the cluster center and so it provides the cluster name;
    Remove all incorporated keywords from the list of subsequent available keywords;
  until *No two remaining keywords co-occur frequently enough to begin a cluster*;

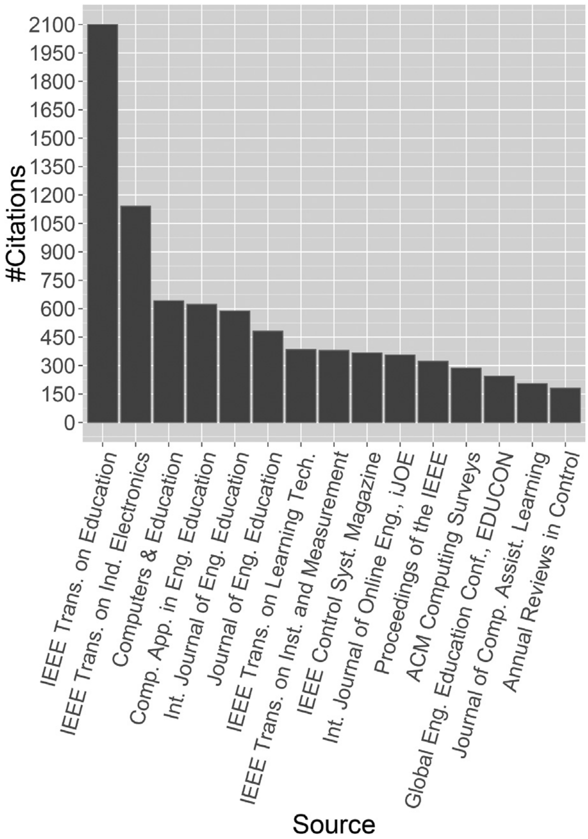


Fig. 8. Most cited sources.

Since the equivalence index has the drawback of being high when keywords appear infrequently but almost always together, a clustering algorithm guided by that index might overestimate the importance of those keywords and create irrelevant clusters (Coulter et al., 1998). To overcome that problem, the simple center algorithm needs to be adjusted through the following parameters:

- The minimum number of publications where keywords are required to appear ($min_{occurrences}$).
- The minimum number of publications where a pair of keywords need to appear together to be taken into account ($min_{co\cdot occurrences}$). If this parameter is too high, few links may be formed; if it is too low, an excessive number of links may result. In the former case, subspecialities in a field may not emerge; in the latter case, more representative and well-connected topics will be harder to detect due to the noise of less representative and less well-connected ones (Coulter et al., 1998).
- The minimum and maximum number of keywords a cluster can group ($min_{keywords}$ and $max_{keywords}$). These parameters set the size of the clusters.

In the analysis described in this paper, the parameters of Algorithm 1 were set to $min_{occurrences} = 3$, $min_{co\cdot occurrences} = 2$, $min_{keywords} = 2$, and $max_{keywords} = 7$.

To characterize the evolution of research on VRLs along the time, the procedure proposed by (Cobo et al., 2011; Coulter et al., 1998) was followed. Thus, the bibliographical data were divided into three consecutive periods of time: 1993–2004, 2005–2009, and 2010–2015. As discussed by Cobo et al. (2011), to achieve good results in the analysis of co-citation clusters over consecutive periods of years, it is needed a balanced period length: short enough to prevent smoothing excessively the data and long enough to include sufficient publications for the analysis. As most papers were published from 2005 ahead on, Period 1 lasts 12 years to include enough publications for the analysis. Hence, out of a total of 4422 documents, 723 were published in Period 1, 1316 in Period 2, and 2383 in Period 3.

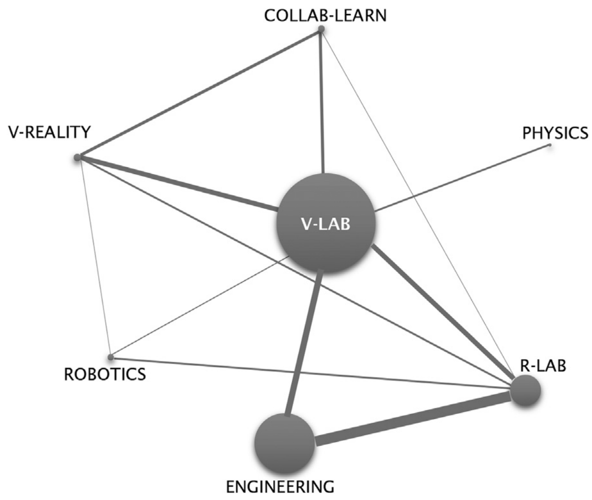


Fig. 9. V-LAB: the only thematic network for Period 1.

5.1. Period 1: 1993–2004

As a result of applying the simple centers algorithm on all records of Period 1, just one thematic network emerges. Fig. 9 shows the structure of that network. Keywords are represented as nodes whose volume is proportional to their associated number of publications. The equivalence index of two keywords *A* and *B* is depicted by the thickness of the edge that links *A* to *B*.

The following conclusions are drawn from Fig. 9:

- Virtual Lab (V-LAB) is not only the keyword most frequently included in VRL papers from 1993 to 2004 (i.e., the biggest node in Fig. 9), but also the keyword which co-occurs with a major number of network keywords (that is why it is placed in the center of Fig. 9). In other words, virtual labs were the research motor for the first period.
- Whereas virtual labs were applied to teaching engineering, robotics and physics, the application domain of Remote Labs (R-LABs) was more reduced (just engineering and robotics).
- The use of Virtual Reality (V-REALITY) to enhance the experience of lab users has been explored from the first VRLs (according to our bibliographical data, the first reference on VRLs and virtual reality dates from 1998 (Firmeza & Ramos, 1998)).
- Preventing students' social isolation by supporting collaborative learning (COLLAB-LEARN) has been taken into account from the beginning of research on virtual labs (according to our bibliographical data, the first reference on VRLs and collaborative learning dates from 1999 (Vouk, Bitzer, & Klevans, 1999)).

Table 2 reports the performance of the period summarizing the number of publications on the network V-LAB, the total number of citations they received, the H-index for V-LAB, and those publications that should be considered as classics for V-LAB. In Tables 2–4, the H-core of a thematic network *T* is computed taking into account those papers that include at least one keyword of *T*. Core papers are listed in descending order according to their number of received citations using the notation $[\text{reference}]_{\text{times cited}}$.

5.2. Period 2: 2005–2009

Period 2 includes two thematic networks: R-LAB and COLLAB-LEARN. Fig. 10 shows both networks. Table 3 summarizes the performance of the period.

According to Table 3, R-LAB is the most important network for Period 2 in terms of quantity (being the network about which more papers were published), but also in terms of impact (being the network with the most citations). From Fig. 10a, the following conclusions are drawn:

- Though V-LAB remains being the keyword most frequently included in VRL papers, R-LAB becomes the central keyword of the network.
- Engineering and robotics continue being the main application fields of remote labs in education.
- The need for assessing the effectiveness of VRLs in education emerges as an essential issue for online experimentation.

Table 2
Thematic network performance for Period 1.

Thematic network	#Papers	#Citations	H-index	H-core
V-LAB	723	5101	32	(Aktan et al., 1996)$_{234}$, (Dormido, 2004)$_{173}$, (Ko et al., 2001)$_{148}$, (Shen et al., 1999)$_{115}$, (Casini & Prattichizzo, 2003)$_{115}$, (Sanchez et al., 2004)$_{111}$, (Ko et al., 2001)$_{85}$, (Ertugrul, 2000)$_{75}$, (Gillet et al., 2001)$_{74}$, (Arpaia et al., 1998)$_{69}$, (Bertocco et al., 1998)$_{67}$, (Ogot et al., 2003)$_{66}$, (Ferrero et al., 2003)$_{64}$, (Ko et al., 2000)$_{63}$, (Canfora et al., 2004)$_{62}$, (Sanchez et al., 2002)$_{56}$, (Colwell et al., 2002)$_{53}$, (Wiesner & Lan, 2004)$_{52}$, (Scanlon et al., 2004)$_{52}$, (Forbus et al., 1999)$_{52}$, (Guimaraes et al., 2003)$_{51}$, (Ferrero & Piuri, 1999)$_{51}$, (Albu et al., 2004)$_{50}$, (Shin et al., 2002)$_{50}$, (Iskander, 2002)$_{45}$, (Schmid, 1999)$_{44}$, (Ertugrul, 2000)$_{41}$, (Climent-Bellido, Martinez-Jimenez, Pontes-Pedrajas, & Polo, 2003)$_{40}$, (Candelas et al., 2003)$_{39}$, (Nedic et al., 2003)$_{37}$, (Röhrig & Jochheim, 1999)$_{36}$, (Müller & Wiesner, 2002)$_{33}$

Table 3
Thematic network performance for Period 2.

Thematic network	#Papers	#Citations	H-index	H-core
R-LAB	1101	6444	34	(Ma & Nickerson,)$_{287}$,, (Harward et al., 2008)$_{208}$, (Gomes & Bogosyan, 2009)$_{177}$, (Bourne et al., 2005)$_{155}$, (Hercog et al., 2007)$_{112}$, (Nickerson et al., 2007)$_{105}$, (Tzafestas et al., 2006)$_{97}$, (Lindsay & Good, 2005)$_{96}$, (Zacharia, 2007)$_{83}$, (Balamuralithara & Woods, 2009)$_{80}$, (Gustavsson et al., 2009)$_{79}$, (Koretsky et al., 2008)$_{76}$, (Huba & Simunek, 2007)$_{65}$, (Corter et al., Ma)$_{75}$, (García-Zubía et al., 2009)$_{74}$, (Valera et al., 2005)$_{69}$, (Lowe et al., 2009)$_{64}$, (Dalgarno et al., 2009)$_{62}$, (Dormido et al., 2008)$_{62}$, (Abdulwahed & Nagy, 2009)$_{59}$, (Bellmunt et al., 2006)$_{54}$, (Hennessy et al., 2007)$_{52}$, (Restivo et al., 2009)$_{50}$, (Rapuano & Zoino, 2006)$_{46}$, (Leva & Donida, 2008)$_{43}$, (Wu, hua She, Zeng, & Ohyama, 2008)$_{42}$, (Aydogmus & Aydogmus, 2009)$_{41}$, (Tem Sun et al., 2008)$_{41}$, (Selmer, Kraft, Moros, & Colton, 2007)$_{38}$, (Jaakkola & Nurmi, 2008)$_{38}$, (Gröber, Vetter, Eckert, & Jodl, 2007)$_{37}$, (Hassan, Dominguez, Martinez, Perles, & Albaladejo, 2007)$_{35}$, (Marques, Rocha, Rafael, & Martins, 2008)$_{34}$, (Anisetti et al., 2007)$_{34}$
COLLAB-LEARN	166	1069	11	(van Joolingen et al., 2005)$_{124}$, (Gillet et al., 2005)$_{122}$, (Jara et al., 2009)$_{58}$, (Bochicchio & Longo, 2009)$_{24}$, (Callaghan, Harkin, McGinnity, & Maguire, 2006)$_{20}$, (Hanson et al., 2009)$_{15}$, (Vargas et al., 2008)$_{15}$, (Granado, Colmenares, Strefezza, & Alonso, 2007)$_{15}$, (Barros, Read, & Verdejo, 2008)$_{14}$, (Noguez & Sucar, 2006)$_{14}$, (Schaf & Pereira, 2009)$_{12}$

Table 4
Thematic network performance for Period 3.

Thematic network	#Papers	#Citations	H-index	H-core
R-LAB	1953	2834	16	(de Jong et al., 2013)$_{46}$, (Jara et al., 2011)$_{42}$, (Zacharia & Olympiou, 2011)$_{41}$, (Jaakkola et al., 2011)$_{35}$, (Fabregas, Farias, Dormido-Canto, Dormido, & Esquembre, 2011)$_{33}$, (Koretsky, Kelly, & Gummer, 2011)$_{29}$, (Scalise et al., 2011)$_{27}$, (Goodwin, Medioli, Sher, Vlacic, & Welsh, 2011)$_{24}$, (Stefanovic, Cvijetkovic, Matijevic, & Simic, 2011)$_{23}$, (Abdulwahed & Nagy, 2011)$_{23}$, (Pyatt & Sims, 2012)$_{21}$, (Colak, Demirbas, Sagiroglu, & Irmak, 2011)$_{18}$, (Tawfik, Sancristobal, Martin, Diaz, & Castro, 2012)$_{17}$, (Santana, Ferre, Izaguirre, Aracil, & Hernández, 2013)$_{16}$, (Zhang, nez de Pablos, & Zhang, 2012)$_{16}$, (Tawfik et al., 2012)$_{16}$
V-REALITY	112	123	6	(Andujar, Mejias, & Marquez, 2011)$_{29}$, (Callaghan, McCusker, Losada, Harkin, & Wilson, 2013)$_{9}$, (Jara, Candelas, Torres, Dormido, & Esquembre, 2012)$_{9}$, (Mejías Borrero & Andújar Márquez, 2012)$_{7}$, (Salzmann & Gillet, 2011)$_{7}$, (Ocaya, 2011)$_{6}$
LMS	167	178	9	(Vargas et al., 2011)$_{28}$, (Tawfik et al., 2013)$_{22}$, (Sancristobal et al., 2011)$_{14}$, (Tawfik et al., 2013)$_{12}$, (Terkowsky, Pleul, Jahnke, & Tekkaya, 2011)$_{12}$, (Rojko, Jezernik, & Pester, 2011)$_{11}$, (Barrios et al., 2013)$_{10}$, (Terkowsky et al., 2011)$_{10}$, (Tawfik et al., 2012c)$_{9}$
WEB-SERVICES	81	96	5	(Peredo, Canales, Menchaca, & Peredo, 2011)$_{13}$, (Dutta, Prakash, Estrada, & Pop, 2011)$_{9}$, (Orduña, Bailey, DeLong, de Ipiña, & García-Zubía, 2014)$_{8}$, (Osten, Wilke, & Pedrini, 2013)$_{6}$, (Xu, Huang, & Tsai, 2012)$_{5}$

- Sharing VRLs among organizations by providing lab inter-operability is recognized as an important feature to reduce the costs associated to VRLs. Most approaches to support such inter-operability are based on web services.
- The convergence between VRLs and LMSs starts taking place (according to our bibliographical data, the first reference on VRLs and LMSs dates from 2005 (Garcia-Famoso & Moya, 2005)). Many authors agree on the interesting features that can be achieved by deploying VRLs into LMSs, e.g., user administration, rich inter-user communication (forums, messages, etc.), student assignments delivering, grade management, etc.

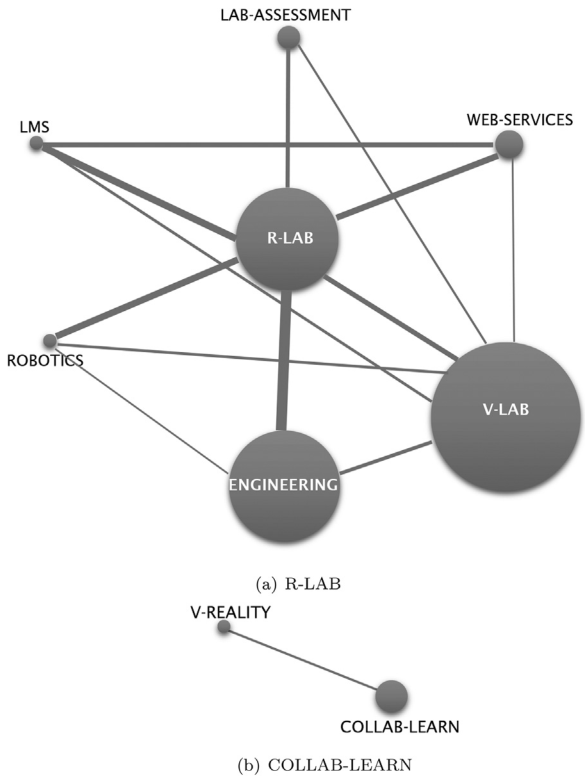


Fig. 10. Thematic networks for Period 2.

Finally, in order to provide VRLs with a social dimension, the role that collaborative learning and virtual reality play in Period 2 becomes more important. Both keywords co-occur in 166 papers and form the separated thematic network depicted by Fig. 10b.

5.3. *Period 3: 2010–2015*

Period 3 is composed of four thematic networks: R-LAB, V-REALITY, WEB-SERVICES and LMS. Fig. 11 shows those networks and Table 4 summarizes the performance of the period.

The R-LAB network behaves similarly to the previous period: (i) it is the most important network in terms of quantity and impact, (ii) the central keyword of the network is R-LAB and the keyword about which more papers were published is V-LAB, and (iii) the need for assessing the effectiveness of VRLs remains being an important issue. According to the equivalence indices, depicted by the thickness of the edges in Fig. 11, whereas (i) remote labs are more used for teaching engineering, robotics and electronics, (ii) virtual labs seem more suitable for natural sciences (physics in particular).

Besides V-REALITY and COLLAB-LEARN, new keywords are added to the V-REALITY network (3D-MODELING and SERIOUS GAMES). This highlights the effort being carried out to improve the learning process effectiveness by providing VRLs with entertainment and social 3D-based immersive environments.

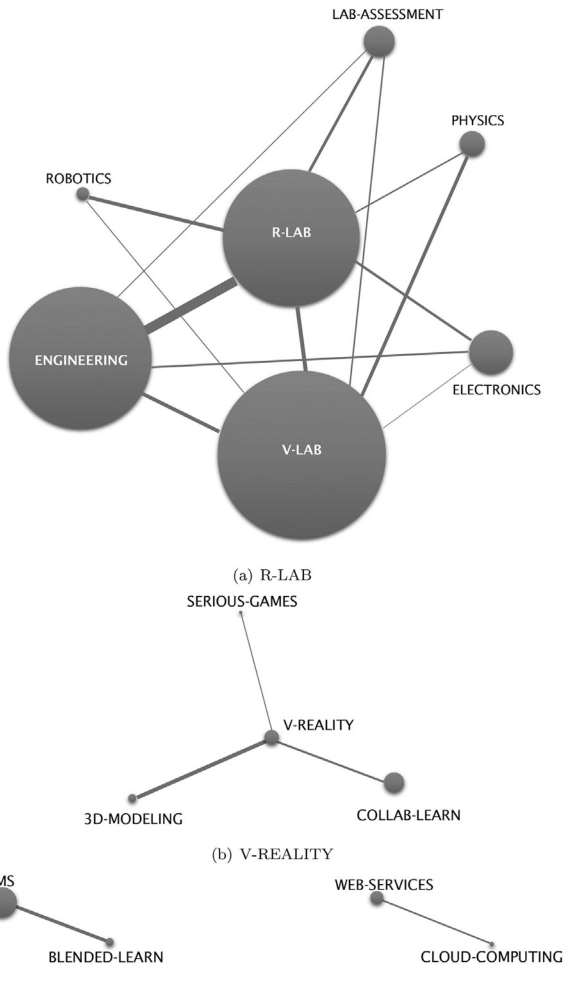
WEB-SERVICES becomes a separated network. In order to reduce expenses and energy consumption, new approaches look for using web services and cloud computing technologies.

LMS also emerges as an independent network. The widespread use of VRLs and LMSs goes beyond pure distant learning, being applied to blended learning programs.

6. Discussion on the applied methodology

The following points discuss the limitations inherent to the methodology used in this paper, and they also justify the decisions taken to overcome such limitations:

1. *Query to gather the bibliographical data.* As mentioned in Section 3, the database GRC2014, provided by Zappatore et al. (2015), has been used as the initial bibliographical collection for our work. To enrich that database with citation



(a) R-LAB

(b) V-REALITY

(c) LMS

(d) WEB-SERVICES

Fig. 11. Thematic networks for Period 3.

information, and to widen that collection with new papers, we performed the query in Fig. 1 on Scopus and ISIWoS. Obviously, different queries would produce distinct results.

Our query was designed and iteratively polished by three of the authors of this work who are experts on VRLs and regularly publish research on this area (*anonymized for review*).

The query includes terms usually shown as *topics of interest* in conferences and journals specialized in VRLs, such as the International Conference on Remote Engineering & Virtual Instrumentation (REV), the Experiment@International Conference, and the International Journal of Online Engineering (iJOE). Moreover, it extends Zappatore et al.'s query, by adding the following terms: virtual experiment*, web experiment*, online engineering, remote engineering, remote process visualization, remote engineering, virtual instrumentation, and virtual engineering environment (all of them limited to education, learning, or teaching).

2. *Bibliographical databases.* Although there are several freely available databases, such as Google Scholar (GS), CiteSeerX, Microsoft Academic Search, getCITED, etc., the paid subscription databases ISIWoS and Scopus are currently the most reliable (Gomez-Jauregui et al., 2014; Vieira & Gomes, 2009).

If the query in Section 3 had been performed against databases different to ISIWoS and Scopus, the gathered information would have not been the same as the one analyzed in this paper. For instance, as Franceschet (2010) notes, ISIWoS and GS have distinct philosophies. To provide a safeguard against low-quality or low-impact material being indexed, ISIWoS uses a selective inclusion procedure where in-house editors assess candidate publication outlets using criteria such as timeliness, peer-review process, international diversity of editors and authors, citation impact, and self-citation rate. In contrast, GS includes everything that resembles scholarly work, based on automatic format inspection rather than content inspection, thereby risking inflation of its record (de Winter, Zadpoor, & Dodou, 2014). It has been argued that, because of its automatic inclusion process, GS is susceptible to errors in metadata (Jacso, 2008) and to indexing of non-scientific works (Cathcart & Roberts, 2005; Franceschet, 2010; Jacso, 2005; Vine, 2006).

3. *Period setting and parametrization of the simple centers algorithm.* To get good performance in the analysis of co-citation clusters over consecutive periods of years, it is needed a balanced period length: short enough to prevent smoothing excessively the data and long enough to include sufficient publications for the analysis (Cobo et al., 2011). In addition, equivalence index has the drawback of being high when keywords appear infrequently but almost always together. As a result, the simple centers algorithm may overestimate the importance of those keywords and create irrelevant clusters. To avoid the aforementioned problems, two of the authors of this paper (*anonymized for review*), who are experts on bibliometrics, set the length of the time periods and experimentally adjusted the simple centers algorithm parameters.
4. *Keyword standardization.* If the input to the simple centers algorithm included too many keywords, the output might be hard to interpret: there would be a high number of clusters, composed of many keywords interrelated with low equivalence indices. To overcome this problem, the standardization presented in Section 3 was performed.

To properly undertake such standardization, it is needed a deep knowledge of the VRL research area, specially to discard and group the keywords. In our case, this task was carried out by three of the authors of this work who are experts on VRLs (*anonymized for review*). Whenever they had doubts regarding the meaning of particular keywords, they carefully read the corresponding papers to put the words into context.

7. Concluding remarks

As a result of more than twenty years of research, VRLs have reached such a maturity degree that makes possible their current application to a variety of educational scenarios (primary schools, higher education, universities, distance learning, etc.) for learning a diversity of subjects (engineering, physics, chemistry, etc.).

Since 2005, the production of scientific papers on VRLs has grown dramatically. At the moment, more than four thousand articles on VRLs have been published. In this paper, two well-known bibliometric techniques have been used to analyze such immense literature. Thanks to science mapping, the main researched topics, the evolution of the interest in those topics and the relationships among topics have been identified. Thanks to performance analysis, the most influential papers, the most impacting authors, and the journals and conferences that have published most papers have been identified. We hope our analysis helps anybody interested in VRLs to browse the available literature on such valuable educational resource.

In particular, the undertaken analysis reveals the following areas of active research which we think will be developed in the short-term future:

1. *Efficient combination of virtual and remote labs.* There is a significative equivalence index between V-LAB and R-LAB, which reflects that a number of papers deal with both types of labs. As each kind of laboratory has its own strengths, the challenge is finding how to combine both labs in a complementary way to achieve specific learning outcomes.

That is, virtual labs have some unique affordances: (a) modifying or simplifying real-world models to make phenomena more visible to learners and adaptable to multiple cognitive levels, (b) performing a wide range of experiments faster and more easily, providing immediate feedback about errors to the students and thus the opportunity to repeat the same experiment immediately, (c) helping students to visualize objects and processes that are normally beyond perception, (d) undertaking experiments too expensive or difficult to carry out with real plants, etc.

Likewise, remote labs provide other affordances which are not supported by virtual labs: (a) handling actual physical apparatus and getting real data, (b) learning about the existence of different types of measurement errors and how to deal with them, etc.

Moreover, depending on the given learning objectives, the same features may be considered advantages or drawbacks. For instance, the existence of true measurement errors is needed to train students on the identification and management of such errors in the real world. Nevertheless, measurement errors can be distractive when students are introduced to complex new phenomena.

Therefore, the use of each type of lab should be subordinated to the learning objectives under consideration, and thus the combined application of both virtual and remote labs will be frequently needed. In this sense, it is worth noting the framework proposed by Olympiou and Zacharia (2012), which looks for the systematic blending of virtual and remote labs to suit specific learning objectives. Such framework is composed of the following steps:

(a) Identifying the learning objectives (cognitive, affective, and psychomotor related objectives) and the target group characteristics (e.g., prior knowledge and skills).
(b)Identifying what affordances of virtual and remote labs are required to achieve the learning objectives distinguished in the first step.

(c) Creating the corresponding labs, or even better, locating existing labs and reusing them whenever it is possible.
(d)Supporting the effective blending of both types of labs, e.g., informing students which mode (virtual or remote) should be used along the experiment session, training them to switch between the virtual and remote modes, etc.

Successfully fulfilling those steps is far from trivial and needs for automated support. For instance, think about searching for existing labs that match the learning objectives, or that, at least, maximize their number, or cover the most essential objectives. Furthermore, the automated search should ensure that the labs satisfy the quality levels established by the user, and it should also estimate the cost of adapting a lab when none of the available labs cover the complete set of required learning objectives. Hence, it is our opinion that the activities involved in Olympiou et al.'s framework will be object of further research in the close future.

2. *Collaborative learning.* Socio-constructivist theories argue that learning is a constructive and collaborative process. As the classic paper by van Joolingen et al. (2005) states, VRLs support effective constructivist learning because enable learners acting like scientists. That is, learners undertake experiments to discover relationships between phenomena, and construct models to express their understanding. Thus, learning activities are more constructive by nature than, for instance, listening to lectures or solving paper-and-pencil physics problems. According to socio-constructivism, task performance should preferably occur in collaboration with peers, and it should be regulated by the learners (instead of the teacher or the learning material).

Although there is empirical evidence of the positive effects that collaborative features have on VRLs (van Joolingen et al., 2005; Shyr, 2012), most of the online labs developed to date lack of support for collaborative work. To overcome such limitation, the following complementary approaches have been proposed:

(a) Deploying VRLs into LMSs. Learning Management Systems support the administration, documentation, tracking, and reporting of training programs, classroom and online events. In addition, LMSs enable rich contexts for students' social interaction. Therefore, by integrating VRLs into LMSs, VRLs take advantage of the LMSs capacity to support the virtual interaction among participants (students and teachers) by means of both synchronous (e.g., chat, videoconference …) and asynchronous (e.g., whiteboards, forums, mailing list …) collaboration tools. As a matter of example, (Bochicchio & Longo, 2010; de la Torre et al., 2015) integrates VRLs into Moodle.
(b) Embedding VRLS into virtual worlds. Some researchers suggest that both entertainment and highly immersive environments promote effective learning. To do so, VRLs are embedded into virtual worlds that provide multiple communication channels between users and improve presence and awareness in the learning process. For instance, (Garcia-Zubia et al., 2010) integrates VRLs into Second Life, (Fayolle, Gravier, & Jailly, 2010) into the Sun Project Wonderland, and (Arango, Chang, Esche, & Chassapis, 2007) into the game Half-Life 2.
(c) Supporting VRLs to be handled by multiple participants at the same time. Under a simplistic approach, collaboration is limited to the use of communication tools such as chat or video-conference applications. Other approaches go beyond by supporting the simultaneous interaction of several participants with the same lab (Jara et al., 2012; de la Torre et al., 2013). This way, the VRL itself acts as the main communication medium among participants.

Thematic networks V-REALITY and LMS in Period 3 shows that collaborative support for VRLs has been object of research for the last years. We think this trend will keep on going in the future.

3. *VRL assessment.* Testing the pedagogical effectiveness of the VRL concept has been a major concern for a long time. Nowadays, as a number of empirical studies have shown that VRLs provide similar learning outcomes than traditional hand-on labs (Brinson, 2015), the research focus is being sifted towards models that enable evaluating the efficacy of specific VRLs to meet particular educational objectives.

In this line, the classic paper by Nickerson et al. (2007) proposes a model for the systematic testing of the educational effectiveness of a given remote lab. Such model measures the impact of the lab in terms of student's cognition and motivation. In particular, the following factors are evaluated:

(a) Lab suitability to accomplish the learning objectives.
(b) Lab support for social coordination.
(c) Lab capability to accommodate student's individual differences, e.g., to take into account the student' grade level, cognitive style, psychological development etc.

In addition and more recently, *learning analytics* have started to be applied to collect and analyze extensive information about the student's interaction with the VRL (a) to assess the lab effectiveness (Wuttke, Hamann, & Henke, 2015), (b) to characterize how a given lab is used in different contexts (e.g., distinct institutions or types of institutions) (Orduña et al., 2014), (c) to support students' continuous evaluation (Romero, Guenaga, Garcia-Zubia, & Orduña, 2014), etc. From our point of view, the usage of learning analytics in the VRL context enables deeper levels of assessment unseen to date. Therefore, we believe this new type of assessment will be object of intensive research in the following years.

4. *VRL sharing.* To reduce the development and maintenance costs of VRLs, important efforts are being made to improve software reuse. Moreover, research on architecture and software design is enabling inter-operable bridges via web services to share remote labs among different institutions.

In this direction, it is particularly remarkable the iLab[1] shared architecture, which was described in the classic paper by Harward et al. (2008). The iLab project started at the Massachusetts Institute of Technology in 1998 and it still remains in use and development (Colbran & Schulz, 2015). iLab pursues the following aims:

(a) Being a highly scalable environment federated in such a way that it can serve a potentially unlimited number of users and VRLs.
(b) Separating the responsibility for sharing VRLs and managing their users. To do so, iLab provides a middleware to enable students scheduling lab sessions.
(c) Fostering easy use and administration for lab providers, system administrators, instructors, and students.
(d) Supporting lab equipment to be accessed through multiple interfaces adapted to different pedagogical levels and computing environments for users.

Besides iLab, there are other prominent management systems and repositories for VRLs, such as WebLab Deusto,[2] Labshare Sahara,[3] and UNILabs[4]. As those systems share the same rationale and are mostly equivalent, it seems logical to go a step beyond by creating a *network of networks of labs* that support students accessing a much bigger amount of VRLs. This VRL sharing is challenging because, despite their similarities, those systems have their own particularities that difficult their interconnection. As a matter of example, to operate VRLs in an interactive way, (a) users of iLab and UNILabs need to schedule labs in advance using a booking system, (b) the WebLab-Deusto scheduling system is mainly based on queuing, and (c) the Labshare Sahara scheduling system integrates both schemes: queuing and booking. So, interconnecting those systems imply dealing with different scheduling schemes.

To overcome this kind of problems, current research is being made on the creation of bridges between systems. In this line, Lowe et al. (2016) and Orduña et al. (2014) propose a bridge between iLab and Labshare Sahara, and a bridge between iLab and WebLab Deusto, respectively.

Since the cross-institutional sharing of VRLs is essential to improve utilization levels, shared costs, and access to a broader range of lab apparatus, we strongly believe that this line of research is going to be essential in the short-term future.

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