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Cloud computing and education: A state-of-the-art survey

José A. González-Martínez*, Miguel L. Bote-Lorenzo, Eduardo Gómez-Sánchez, Rafael Cano-Parra

Escuela Técnica Superior de Ingenieros de Telecomunicación, Universidad de Valladolid, Paseo de Belén 15, 47011 Valladolid, Spain

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A B S T R A C T

This paper surveys the state of the art on the use and research of cloud computing in education following a systematic methodology. After a comprehensive search of the scientific literature, 112 works were selected for the review. The survey identifies and analyzes the advantages and risks that the use of cloud computing may have for the main stakeholders in education, which can be useful to identify the scenarios in which the use of cloud computing in an educational context may have significant advantages. Furthermore, the survey categorizes and discusses the main technical and domain-specific research challenges, thus facilitating researchers the task of finding relevant issues, in which they can focus their efforts.

1. Introduction

Cloud computing is a distributed computing paradigm that enables access to virtualized resources including computers, networks, storage, development platforms or applications (Mell & Grance, 2009). These resources can be unilaterally requested, provisioned and configured by the user with a minimal interaction with the cloud provider. Furthermore, resources can be rapidly scaled up and down to meet the user's needs, thus creating the illusion of infinite resources available at any time. Resource utilization can be measured in the cloud to be controlled and, sometimes, to charge customers in a pay-per-use basis.

With the support of important industry stakeholders like Google, Amazon or Microsoft, cloud computing is being widely adopted in different domains. Cloud services such as Google Mail[1] or Dropbox[2] have become everyday tools for millions of people. Many companies currently use cloud-based applications such as Salesforce[3] and small and big businesses are embracing virtual infrastructures offered, for instance, by Amazon Web Services (AWS)[4] or Microsoft Azure[5] (Marston, Li, Bandyopadhyay, Zhang, & Ghalsasi, 2011). Among governments, initiatives such as the Federal Cloud Computing Initiative,[6] promote the use of cloud computing, and other organizations, like NASA,[7] are using cloud infrastructures for research, as well.

In the Technology-Enhanced Learning (TEL) domain, the use of cloud-based technologies has also been identified as a key trend (Johnson, Adams, & Cummins, 2012) that enables access to online services anywhere and promises scalability, enhanced availability and cost savings (McDonald, Breslin, & MacDonald, 2010). These affordances are brought about by using cloud computing in contrast to conventional

* Corresponding author. Tel.: +34 983 42 3698.
E-mail addresses: gonmarjn@jcyl.es, jgonmar@gsic.uva.es (J.A. González-Martínez).

1 http://www.gmail.com.
2 http://www.dropbox.com.
3 http://www.salesforce.com.
4 http://aws.amazon.com.
5 http://www.windowsazure.com.
6 http://info.apps.gov/node/2.
7 http://nebula.nasa.gov.

http://dx.doi.org/10.1016/j.compedu.2014.08.017
0360-1315/

computational infrastructure, where both hardware and software are owned and kept by organizations at their premises, maintained, and often developed by their own technical staff.

In education, cloud computing caters for desirable properties to provide e-learning services, especially in scenarios where these services are computer-intensive (virtual worlds, simulations, video streaming, etc.), or are offered in a high-scale way, as in Massive Open Online Courses (MOOCs). The cloud can provide students and teachers with tools to deploy computing resources on-demand for lectures and labs according to their learning needs. For instance, teachers can create virtual computers (commonly named Virtual Machines or VMs) on demand with pre-installed software to deploy computing laboratories rapidly (Chine, 2010). Some educational institutions are already using cloud computing to outsource email services, to offer collaboration tools and data storage for students and to host institutional Virtual Learning Environments (VLEs) (Sclater, 2010a). Other affordances of cloud computing may yield new learning scenarios where ubiquity, advanced online tools and collaboration come together to create innovative opportunities for education. On the other hand, cloud computing brings new risks when compared to the conventional IT model such as security, performance, or interoperability that now have to be considered.

The adoption of cloud computing in education has come hand in hand with an important research effort. There are a great number of scientific contributions that address the topic from different perspectives trying to harness cloud computing services for education. A systematic review of these heterogeneous contributions that assesses the advantages and limitations of the use of cloud computing in education and that provides a coherent picture of the current research challenges in this domain can be of great interest for educational practitioners and institutions in order to identify opportunities to use the cloud in their own context. In addition, such a review can also be very useful for researchers to identify relevant issues and challenges in which they can focus their efforts. These challenges can be either technical issues (i.e., how to improve the cloud technology itself to meet domain-specific needs) or domain-specific opportunities (i.e., how to leverage cloud computing services for pedagogical uses).

A first attempt to carry out such a review was made by Fasihuddin, Skinner, and Athauda (2012). However, it did not follow a systematic methodology to try to ensure the comprehesiveness of the review. Furthermore, it analyzes the advantages and research challenges of the use of cloud computing in education at a shallow level. In addition, the risks of the adoption of cloud computing in education are not identified. It is noteworthy that other studies have been published reviewing the usage of cloud computing in relevant application areas, such as health care (AbuKhousa, Mohamed, & Al-Jaroodi, 2012), governance (Smitha, Thomas, & Chitharanjan, 2012), or commerce (Motahari-Nezhad, Stephenson, & Singhal, 2009).

This paper presents a review of the existing literature on the use of cloud in education following the methodology proposed by Kitchenham and Charters (2007), which has already been used in similar works in other research fields. The review identifies and analyzes the main advantages and limitations of the use of cloud computing in education as well as the current research challenges in this field. Furthermore, it illustrates these issues with relevant learning scenarios found across the literature.

This paper is thus structured as follows. Section 2 provides some background information on cloud computing, characteristics, services and deployment models. Section 3 explains the methodology followed to carry out this review. The main benefits and affordances of cloud computing for education are detailed in Section 4, as well as its risks in Section 5. The main research challenges are identified in Section 6. Finally, discussion and the main conclusions are laid out in Section 7.

2. Background on cloud computing

The cloud computing paradigm offers a pool of virtual resources (hardware, development platforms or services) available over the network. These computing capabilities can be provisioned and released to scale rapidly according to demand (Vaquero, Rodero-Merino, Cáceres, & Lindner, 2008).

Cloud computing services are typically categorized into three main types (Mell & Grance, 2009; Zhang, Cheng, & Boutaba, 2010): *Infrastructure as a Service* (IaaS), *Platform as a Service* (PaaS), and *Software as a Service* (SaaS). At the lowest level of abstraction, IaaS is found which provides the consumer with processing, storage, networking, and other computing resources on-demand, for instance, under the abstraction of a Virtual Machine. Examples of IaaS are Amazon EC2[8] and Google Compute Engine,[9] which provide VMs on demand. Eucalyptus[10] and OpenStack[11] are both examples of open source middleware that organizations can use to build their own IaaS. The base software that enables the creation of VMs (i.e., virtualization) is called hypervisor, of which some of the most widely used are Xen,[12] VMWare,[13] and Hyper-V.[14] Hypervisors create different instances of VMs in the native computer which share the actual resources of the host machine and can be dynamically scaled and terminated when they are no longer needed (Buyya, Yeo, Venugopal, Broberg, & Brandic, 2009). Virtualization affords better resource utilization (important for the provider), but also implies computational overheads that decrease performance (important for the service consumer), as reported for example by Wang and Ng (2010). Nevertheless, improvements in software and hardware are bringing performance of virtualized servers closer to native computation (McDougall & Anderson, 2010).

The following level, PaaS, is usually built upon IaaS and allows the user to deploy onto the cloud infrastructure applications created using programming and runtime environments supported by the provider. Software developers and IT staff, but also non-technical users, employ resources at this level. At this layer, Google App Engine (GAE)[15] and Microsoft Windows Azure provide programming and deployment frameworks.

[8] http://aws.amazon.com/ec2/.
[9] https://cloud.google.com/products/compute-engine/.
[10] http://www.eucalyptus.com.
[11] http://www.openstack.org.
[12] http://www.xenproject.org.
[13] http://www.vmware.com.
[14] http://www.microsoft.com/OEM/en/products/servers/Pages/hyper_v_server.aspx.
[15] https://appengine.google.com.

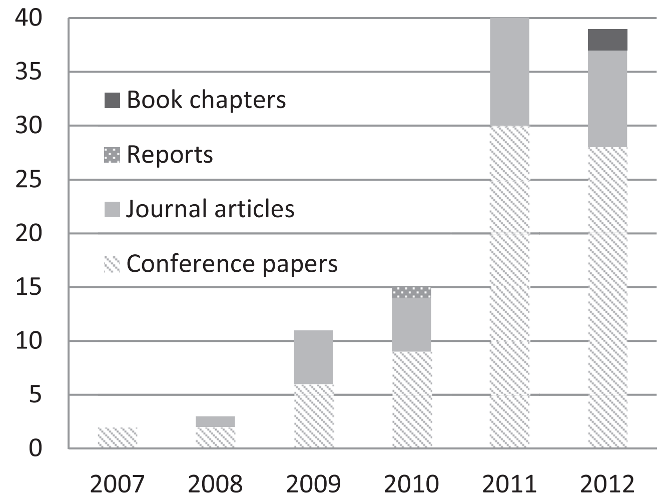

Fig. 1. Distribution of relevant studies (112) by year, number and type of publication.

Finally, SaaS is nowadays the best-known model, consisting of applications offered by the provider over the network, instead of being run on the user's computer. Resources found at this level range from actual applications to multimedia or web services, and are usually accessed via a web client (Zhang et al., 2010). Examples of SaaS software are Google Docs,[16] Salesforce, or Dropbox.

All these services can be offered by a cloud provider according to different deployment models (Mell & Grance, 2009). *Public clouds* are found if the cloud infrastructure is provisioned for the use by the general public. Alternatively, when the cloud infrastructure is provisioned for the exclusive use of a single organization, it is called a *private cloud*. If the cloud infrastructure is used by a specific community of consumers from organizations that have shared concerns, the deployed platform is a *community cloud*. A mix of these types of clouds is a *hybrid cloud*, where the infrastructure is a combination of two or more different cloud infrastructures (public, private, or community).

All in all, service and deployment models of cloud computing disrupt the traditional provision of computing capabilities, because in the former case, virtualized hardware and software are provided on-demand and managed by third parties, achieving the required scalability and availability, and reducing upfront costs. Cloud computing also extends the previous Application Service Provider (ASP) model in that cloud providers own and manage their own hardware and software, and clients share the computational infrastructure in a multi-tenant architecture (Chong & Carraro, 2006). Besides, the cloud computing paradigm differs from other computing paradigms such as grid computing, but share similar visions. Unlike grid computing, in cloud computing, virtualization is essential, the resource sharing is centralized, and the business model is often based on pay-per-use (see Vaquero et al., 2008). The cases analyzed in the literature use a mix of the aforementioned cloud services and deployments, showing diverse proposals where cloud computing can benefit education, which will be the subject of this study.

3. Review methodology

The methodological guidelines suggested by Kitchenham and Charters (2007) for literature reviews in software engineering were followed to conduct this state-of-the-art survey. This methodology has already been used in other systematic reviews for similar fields (see Carvalho, Neto, Garcia, Assad, & Durao, 2013; Hashizume, Rosado, Fernández-Medina, & Fernandez, 2013; Magnisalis, Demetriadis, & Karakostas, 2011). The literature search covered contributions until and including December 2012, and was performed using the databases considered most relevant to find the targeted studies: IEEE Xplore Digital Library, ACM Digital Library, ScienceDirect, Scopus and Springer. The search string used was: ("cloud" OR "virtualization") AND ("education" OR "learning" OR "teaching"). This search string was conceived with the aim of retrieving a high number of the studies available in the databases that were relevant for the review even if the results of the query returned many other works not relevant for the survey (i.e. the query pursued having a high recall in spite of a low precision, in terms of information retrieval). Relevant studies not found after this search were expected to appear among the referenced bibliography of these results, as it was the case, and they were also included in a second analysis iteration. Only primary studies published in English and contained in journals (both printed and in press), conference proceedings, books and white papers were considered. Additional studies from specific conferences on cloud computing and education (WCLOUD[17] and LTEC[18]) were also included. A total of 351 candidate articles resulted from the initial search.

Each candidate study went through a series of stages until its eventual selection: 1) assess the title, and discard if not related to cloud computing in education; 2) read the abstract, exclude if unrelated to cloud computing in education; 3) retrieve the study and read the introduction and conclusions, discard if the contribution is similar to other more relevant study by the authors; and 4) critically assess the quality of the contribution, discard in case of low quality. The quality parameters taken into account were the degree of relation of the study with the use of cloud computing in the educational domain, the relevance of the contribution for the educational domain, as well as the credibility, soundness, clarity, research methodology, and writing quality of the contributions. After this phase, 87 studies passed the quality assessment.

A data extraction process was then conducted to collect the following information from each contribution: summary and main results, research questions posed, applicable educational areas and contexts, benefited educational roles, learning scenarios envisioned, maturity of

[16] http://docs.google.com.
[17] http://ceur-ws.org/Vol-945/.
[18] http://ltec.usal.es.

the research, reported affordances and benefits of cloud computing, cloud deployment models used, cloud platforms and applications described, and related bibliography. From this data extraction process, a new set of candidate studies for the review emerged from the analyzed bibliography. This set of 75 new studies followed a new iteration of quality assessment. There were 25 additional studies that passed the second quality assessment and went through another data extraction process.

In summary, 426 studies were considered for this review, of which 112 passed the selection process. Fig. 1 summarizes some bibliometric data of the 112 studies of the selected literature. As it is depicted, the number of studies grows over the years, which shows the novelty and the increasing interest of the scientific community on cloud computing in education. Besides, most of the contributions are conference papers, which hints at a certain lack of maturity of the work in this field.

Finally, a qualitative analysis of the 112 results was performed to synthesize the main findings. Since the objective of this study is to identify benefits, risks, and research challenges, the categorization performed in the qualitative synthesis follows this same structure as it is shown in the next sections, accompanied by illustrative scenarios. The approach followed was bottom-up, considering the salient characteristics and scenarios of these studies and defining and categorizing them into areas.

4. Benefits and affordances of cloud computing for education

The main stakeholders in education (i.e., learners, educational practitioners, educational institutions, and the IT personnel) can benefit from using cloud computing, but not all of them profit equally from all its advantages. Some of these affordances refer to the learning and teaching process, while others deal with different aspects in education such as IT economics or technology management and operation. In the following sections, advantages and affordances have been categorized, emerging from the results found in the reviewed literature. They have been summarized in Table 1, according to the main stakeholders benefited.

4.1. A wealth of online applications to support education

Cloud computing provides both learners and educational practitioners with a great number and variety of online applications that can be employed to support a wide range of learning scenarios. These applications are usually web-based, accessible anywhere, anytime over the Internet, thus extending the exposure time to learning of students (Wu & Huang, 2011).

Table 1
Benefits and affordances of cloud computing for the main educational stakeholders.

	Educational practitioners	Students	IT staff	Educational institutions
Availability of online applications	New learning scenarios are now feasible. Enabling collaborative pedagogies.	Possibilities to extend learning out of the institution. Easier communication and resource sharing.	Reduced installation and maintenance efforts.	
Flexibility to create learning environments	Package computing environments with all needed resources. Design of complex lab environments for Computer Science disciplines using PaaS or IaaS clouds.	Creation of Personal Learning Environments tailored to student's needs without technical skills. Focus on assignments instead of configuration tasks.	Reduced installation and maintenance efforts.	Promote the reuse of pre-configured environments among teachers, courses or other institutions.
Support for mobile learning	New scenarios available for geolocated or in situ learning.	Easy sharing or synchronization with other devices and institutional learning platforms.		
Computing intensive support	Design of learning scenarios involving heavy simulations (sciences, engineering) or multimedia processing. Access to timely learning analytics.			
Scalability		Perception of stable QoS through time.	Offering services with highly variable demand without investing and managing overprovisioned infrastructures. Development of applications without scale concerns.	Offering services with highly variable demand without investing and managing overprovisioned infrastructures.
Cost savings in hardware			Better utilization and simpler management of consolidated resources.	Smaller upfront investment, costs spread over time and proportional to actual use. Possibility to federate in community clouds.
Cost savings in software		Use the same applications at home without needing to buy a license.		Usage of free or pay-per-use applications instead of buying many licenses (often not really used).

There are many cloud applications (such as Google Apps, Dropbox, etc.) that are already extensively employed in education because they are common-place, user-friendly and inexpensive tools that many students use in their daily life. Besides, it is often cutting-edge software maintained and evolved constantly by specialized providers. High availability, low response times and scalability are other characteristics that these cloud-based applications offer, making them attractive for education. In some cases, however, there are risks involved in performance and reliability (see Section 5.3). Generic software, such as Google Apps for Education[19] or Microsoft Office365[20], offers online productivity applications like word processing, spreadsheets, and presentations that can be used in class (e.g., see Bennett & Pence, 2011; Bhattacharya et al., 2011; Bonham, 2011; Dmitriev, Kononov, Shiriaev, & Malozemov, 2012; Herrick, 2009; Nevin, 2009; Rienzo & Han, 2009; Sultan, 2010). Teachers may give them diverse usages as well. For example, teachers can use Google Spreadsheets to share points to award students for their classroom behavior (Blood, 2011). Both practitioners and students can use a Google or Microsoft email account branded with the institution's domain name (Sclater, 2010b), use YouTube channels to stream video lectures (Dmitriev et al., 2012), or they can be provided with storage from SkyDrive[21] or Dropbox (Lennon, 2012; Siegle, 2010). In an interesting work, Abrams (2012) describes a chemistry lab in which students share their data and results using Dropbox. Students can access and analyze these data and the results can be shared among other students, groups, classes, courses and across different years. They can access data in a convenient way, even from home, overcoming the physical constraints of the faculty and increasing their learning time. Besides, students exploit the built-in collaboration features to contribute to the defined learning objectives. Other examples showing general purpose cloud applications in education are video on demand (VoD) services used to deliver lectures (Rajendran & Veilumuthu, 2011); virtual worlds employed to explore an art museum (Cucinotta et al., 2012); or a VLE integrating different generic cloud applications for foreign language learning (Songbin & Cuizhen, 2012).

The cloud also provides applications conceived originally for domains other than education that can be very useful in specific learning contexts. An example is the cloud-based Customer Relationship Management (CRM) system (Vulic, Barac, & Bogdanovic, 2011) that manages the relationship between the institution's administrative staff and the students. Other examples are a cloud application for civil engineering (AutoCAD WS[22]) used for educational purposes (Lukaric & Korin-Lustig, 2011), or scientific and statistical applications like Scilab[23] and R[24] employed to teach maths and statistics (Chine, 2010). Also, Khmelevsky and Voytenko (2010) report students employing cloud services generally used for professional programming like GitHub[25] and SourceForge[26] as a configuration manager for the source code of the students' projects.

Additionally, there are cloud applications that have been designed for education either with a generic or a specific purpose. Cloud-based VLEs belong to the former category. VLE providers such as Blackboard[27] or Lessons LAMS[28] are now offering outsourced cloud-based e-learning services, benefiting students from ubiquity, scalability and availability capabilities. Similarly, Dutra Piovesan, Hoff do Amaral, Barbosa Arenhardt, and Duarte Medina (2012) show a scenario where students access a cloud instance of Moodle that adapts the content delivered to the student's connection speed in a Computer Architecture course. On the other hand, cloud software for specific educational purposes is introduced by Dinita, Wilson, Winckles, Cirstea, and Jones (2012), where students use NetLab+,[29] a computing environment that provides students with hands-on assignments on computer networks. Other studies show students using dynamic visualization and simulation applications on the cloud to learn geometry and algebra (Stein, Ware, Laboy, & Schaffer, 2013), or specific applications to watch and learn from art works (Liao & Ho, 2011).

A significant number of the reviewed contributions take advantage of the built-in collaboration and communication capabilities present in some of these cloud applications, which is particularly useful for certain pedagogies such as constructivism or collaborative learning (Denton, 2012). For instance, Denton (2012) surveyed the attitude of pre-service teachers towards different collaborative cloud-based tools, like Google Apps, used in class following a constructivist approach. They answered that their understanding of the concepts was enhanced by using these technologies and that they were in favor of using them for teaching in the future. Similar results were found by Yang (2012), who used Google Docs in a blended learning process for the development of collaborative action research in an educational technology course. Another study that points out this advantage is the one by Thomas (2011), which proposes different cloud collaboration tools for teachers. In other contributions (Bhattacharya et al., 2011; Hernandez Rizzardini & Amado, 2012; Ma, Zheng, Ye, & Tong, 2010; Patil, Kulkarni, Negalur, & Pashupatimath, 2011; Tan & Kim, 2011; Wood, 2011), tools such as Google Docs, blogs or wikis are used in diverse disciplines like science and technology, an MBA, courses on e-learning, physics, computer science, and programming, respectively.

4.2. *Flexible creation of learning environments*

The broad degree of configurability of many cloud-based services and resources gives teachers and students new opportunities to create rich environments for teaching and learning. Different cloud services and applications can often be mixed using their available Application Programming Interfaces (APIs) into completely customized learning environments suited to the needs and preferences of students, facilitating the creation of Personal Learning Environments (PLE) (Rizzardini, Linares Roman, Mikroyannidis, & Schmitz, 2012). For example, Casquero, Portillo, Ovelar, Romo, and Benito (2008) allow learners to create a PLE with iGoogle where they integrate gadgets of a variety of external cloud-based services like Google services, Delicious, Flickr, YouTube and blogs for a course of Medicine at the university. A test-bed

[19] http://www.google.com/apps/intl/es/edu/.
[20] http://my.liveatedu.com.
[21] https://skydrive.live.com.
[22] http://www.autocadws.com.
[23] http://www.scilab-enterprises.com/products/scilab/.
[24] http://www.r-project.org.
[25] https://github.com.
[26] http://sourceforge.net/.
[27] https://www.coursesites.com.
[28] http://lessonlams.com.
[29] http://www.netdevgroup.com/products/.

is set up by Rizzardini et al. (2012) with a PLE that integrates different cloud tools like Google Apps, Facebook and mind-mapping applications for pre-service teachers in a course on e-learning. This platform was perceived as useful and encouraging for learning, but it was also noted that students can be overwhelmed until they become acquainted to use it. Other examples and settings of cloud-based PLEs are (Ko & Young, 2011) for lifelong learning; (Liang & Yang, 2011), for primary and junior high school, and (Al-Zoube, 2009) for science education. Cloud-based applications are also proposed for microlearning in short-time learning activities (Li, Liu, Han, & Zhang, 2011). In another scenario, students use different cloud-based predefined applications integrated in a framework (Calvo, O'Rourke, Jones, Yacef, & Reimann, 2011) to learn on academic writing and receive automatic feedback.

Besides, the availability and rapid on-demand provision and release of configurable resources offered by cloud infrastructures give teachers the opportunity to create more complete computing environments of their choice, like virtual desktops for students with pre-established applications, bare virtual machines, preconfigured computer laboratories or development environments. Even though the set-up of the chosen environment can take some effort, once practitioners design and build one environment, it is straightforward to replicate the same environment as many times as required (Vaquero, 2011). The preconfigured environment can also be saved or packaged for later use, for next courses, or for other colleagues (Ivica, Riley, & Shubert, 2009). The infrastructure provisions the required resources in a matter of minutes, fast enough for some learning scenarios, so that they are readily available for the students (Yuan, Cody, & Zhong, 2011). This way, an important amount of time can be employed to the practice at hand rather than concerning about configuration issues (Ivica et al., 2009). Since the IT staff does not have to maintain computers, but just re-instantiate preconfigured images, there is also less management overhead. In this way, technicians can focus on critical business tasks instead of maintenance duties (Aljenaa, Al-Anzi, & Alshayeji, 2011).

Virtual desktop environments with preconfigured software are generally used across different educational disciplines. For instance, Yang, Chang, Chien, and Wang (2011) present its own virtual desktop application, called Dumbogo, on a private cloud based on VMWare, where high school students and teachers can share documents and multimedia resources. The authors state that virtual desktops can be used in blended learning thanks to the ubiquity of cloud computing and because teachers can deliver suitable learning material to their students. Other studies showing flexible configurations of virtual desktops are (Wang, Ye, Chen, & Xu, 2012), which demonstrates the generic use of virtual desktops using Ulteo[30] technology or (Wu & Huang, 2011), where primary school students use their own virtual desktops with installed office software. A virtual desktop prototype is also described by Li, Peng, Zhang, Han, and Yuan (2011), where students access their own virtual machine to discuss the learnt concepts on language with their project team on a bulletin board. The authors argue that the VMs have all the required applications and can be provisioned on-demand in a matter of seconds, so that students can use them immediately. Chine (2010) presents Elastic-R, a preconfigured VM for students with mathematical and statistical tools that can be shared with other educators.

Although computing environments are used in multiple domains, most of the reviewed scenarios that take advantage of the flexibility of cloud computing deal with computer science disciplines for laboratories and assignments. Computer science teachers can preconfigure and provision bare resources to start the assignment from scratch. For instance, Rajaei (2012) proposes to use virtual databases created on Microsoft Windows Azure to learn computer science or AWS VMs to learn on operating systems. As another example, Doelitzscher, Sulistio, Reich, Kuijs, and Wolf (2011) report that students of Business Informatics and Computer Science faculties had two practical, semester-long projects on designing software architectures, evaluating networking and programming techniques. With CloudIA, the implemented private cloud, students could set up and reserve VMs on demand just for the duration of the laboratory or project at hand. Usual errors due to operating system misconfiguration of missing software components were also avoided. In addition, Anton, Anton, and Borangiu (2012) show the case of a private cloud shared by four universities that enables the provision of VMs with preconfigured images launched on demand by trainers or students for courses on computer science. In a different contribution, StarHPC,[31] a package developed by the Massachusetts Institute of Technology (MIT), is described by Ivica et al. (2009). It contains stand-alone VMs with the required development software that can be reused by students in a parallel programming course.

Additionally, since the cloud not only allows to virtualize machines, but also the networking resources that connect them, practitioners have the flexibility to design computing clusters and networks tailored to the requirements of the assignment or lab. For example, Yan (2011) proposes a computer network laboratory on a private cloud where students can configure servers, firewalls and switches to learn about computer networks. Reported advantages include less lab administration costs, and the availability of an open learning environment where students can experiment with fewer constraints.

Many other studies report programming and networking laboratories built flexibly with cloud tools. For example, Gomez-Folgar, Valin, Garcia-Loureiro, Pena, and Zablah (2012) configure virtual clusters based on CloudStack[32] for parallel programming assignments, and Yuan et al. (2011) build an IP telephony lab with call servers on a private cloud. Two different works (Caminero, Robles-Gómez, et al., 2011; Rugelj, Ciglarič, Krevl, Pančur, & Brodnik, 2012) show scenarios where computer networks based on virtualization are used for networking courses. Even further, Yokoyama, Yoshioka, and Shida (2012a, 2012b) utilize edubase Cloud, a private infrastructure to deploy other clouds for courses on cloud computing. It should be noted that these assignments require very specific hardware, software and/or configuration processes, and that the usage of cloud techniques facilitates their setup and replication.

Alternatively, computer science teachers can select public PaaS environments like GAE or Windows Azure for their assignments due to the convenience of employing a ready-to-use development and execution environment. Some examples of assignments employing PaaS tools are (Bhattacharya et al., 2011) and (Hollingsworth & Powell, 2010), both of which describe a programming course where students use GAE to develop applications and servlets. Vaquero (2011) evaluates the performance of students using three different development environments with an increasing degree of underlying abstraction in an overlay networks course. Here, he compares using a traditional environment (Eclipse, Tomcat, etc.) that students had to configure from scratch, a second environment with an EC2-based computer network where students only had to install Tomcat, and a third environment, based on Google App Engine. The results of the experiment

30 https://www.ulteo.com/home/en/ovdi/openvirtualdesktop/.

31 http://star.mit.edu/hpc/.

32 http://cloudstack.apache.org.

showed that a more preconfigured environment maintained students' focus and saved time to students, but this did not necessarily lead to increasing the learning time and an improvement of their average grades. Moreover, teachers should be careful not to oversimplify the complexity of the operating system and software under study.

4.3. Support for mobile learning

The cloud can help to overcome the current limitations in mobile learning (m-learning) regarding the limited processing and storage capabilities of the devices (Chen, Liu, Han, & Xu, 2010), mainly through the affordances of availability of enough computing resources and scalability of the cloud. This way, learning applications can run on students' mobile devices while the heaviest computing tasks take place in the cloud (Chen, Lin, & Zhang, 2011). Students can also use their mobile phones to access, accumulate, share, and synchronize learning contents in the virtually unlimited storage resources that cloud computing provides (Shuai, 2011). As a result, students can use m-learning services and applications that are rich and useful (multimedia, real-time, context-aware, etc.) with the adequate Quality of Service (QoS) and they can access them anywhere any time they need them (Chen et al., 2011), provided they have network connectivity.

Some studies show the capabilities of the cloud to support m-learning services. Cucinotta et al. (2012) show students receiving e-learning contents relevant to their current position (e.g., near historical monuments) on a mobile phone in real time. In this case, real-time response is achieved by enforcing QoS policies at infrastructure level and provisioning the appropriate resources in the cloud. Other students with mobile devices in a computer science course access a cloud-based Moodle instance that delivers learning contents (e.g., smaller files) according to the learner's connection speed (Dutra Piovesan et al., 2012). In another scenario, students learning a language use their mobile phones to acquire context-enriched learning content (in this case, photographs of a Chinese character) (Kovachev, Cao, Klamma, & Jarke, 2011) to obtain the translation provided by an Optical Character Recognition (OCR) system in the cloud and can tag the results for later study. Since students are used to employing different types of devices, they use the cloud as a means to synchronize the learning content among all their heterogeneous devices. Other examples of m-learning services where cloud computing is used are a live video service streamed into mobile devices (Saranya & Vijayalakshmi, 2011), cloud-based mobile applications that provide students with tools for enquiry-based learning in the science field (Quintana, 2012), or a proposal of Augmented Reality (AR) applications for students with Attention Deficit Hyperactive Disorder that require heavy computing processes to be performed in the cloud (Aziz, Aziz, Paul, Yusof, & Noor, 2012). One last example shows instructors posting learning contents on GAE to make them available for an m-learning application (Bai, 2010).

4.4. Computing-intensive support for teaching, learning and evaluation

Sometimes students require computing power for certain educational applications that are difficult or impossible to run on their own computers with usually limited resources or the institution's servers (Zablah, Garcia-Loureiro, Gomez-Folgar, & Pena, 2012). If the student must design an experiment, run some computational task related to the experiment, observe the result, and then possibly redesign the experiment and run new tasks, learning comes from the design or observation activities, and hence the computation activity should be reasonably short. Cloud computing infrastructures can be configured or hired to achieve on-demand capacity to run these applications with the time constraints imposed by the educational setting.

For instance, Chine (2010) provides students with the mathematical and statistical tools, Scilab and R, from the AWS EC2 cloud. These applications require intensive computing for which resources can be obtained from the cloud. In a different scenario (Zablah et al., 2012), students render video editing projects employing Cinelerra, a non-linear video editor. Students create editing projects using Cinelerra in their workstations and upload them to a VM in the cloud where other projects will be queued and rendered in a batch system. In another contribution (Leony, Pardo, Parada, & Delgado Kloos, 2012), a compute-demanding service to deliver recommendations of learning resources is implemented on an Amazon EC2 infrastructure. They used the Hadoop[33] framework to distribute computing workload among different instances in the cloud infrastructure.

The affordances of cloud computing are also harnessed by Lukaric and Korin-Lustig (2011) to support computing-intensive learning scenarios. Here, civil engineering students use AutoCAD WS, a commercial Computer-Aid Design (CAD) application built on the Amazon EC2 and S3[34] cloud that copes with the demanding computing requirements of CAD processing. In addition, Cucinotta et al. (2012) portray a virtual world application based on Open Wonderland[35] for art students interacting in a virtual museum. It is supported on a private cloud with enough computing capabilities to offer soft real-time QoS.

In some educational situations, it would be convenient to know what is happening during the teaching and learning process in order to quickly adapt it to the needs of the students. Learning analytics deals with the interpretation of large amounts of data produced by student activities to evaluate progress, predict performance or detect issues (Ferguson, 2012). The cloud computing model can also be useful to speed up learning analytics processes. This possibility has been studied by Doan, Zhang, Tjhi, and Lee (2011), where cloud computing is used to offer computation and storage for a Hadoop framework that analyzes students' log data to predict their performance. In this case, logs were generated by the university e-learning system during three courses in Computer Science.

4.5. Scalability of learning systems and applications

The demand of computing resources of educational applications varies during a course (there are peaks, especially during enrollment periods, assignment deadlines, before exams, publishing of grades, etc.) (Caminero, Ros, Hernandez, Robles-Gomez, & Pastor, 2011). In a traditional approach, the service is seriourly affected if the demand exceeds the alloted computing resources (Adler, 2011). The scalability

[33] http://hadoop.apache.org.
[34] http://aws.amazon.com/s3/.
[35] http://openwonderland.org.

features of cloud computing enable the adaptation of resources to the changing conditions in order to meet the expected QoS requirements without the need of over-provisioning computing infrastructure (Mousannif, Khalil, & Kotsis, 2012; Rajendran & Veilumuthu, 2011). This is relevant for many learning scenarios, like MOOCs, in which a very large number of students access online courses concurrently and require a large amount of resources to cater for a quick change in demand (Fernández, Peralta, Herrera, & Benítez, 2012).

The reviewed literature shows some scenarios of scalability to provide sustained QoS for a large number of users. In a previously mentioned example (Cucinotta et al., 2012), students use virtual worlds for e-learning supported on a private cloud where QoS control is enforced at IaaS level according to application metrics (e.g., logged users). As the number of logged users increases, the platform calculates the required new resources and renegotiates them with the infrastructure and application provider, thus increasing the number of allowed users.

Other works also take advantage of the scalability of cloud computing to ensure the QoS of learning applications. Rajendran and Veilumuthu (2011) propose using cloud computing to host a video on demand service for learning purposes. Students access streaming video lessons and the virtual infrastructure reacts to changes in the demand to allocate enough computing resources to ensure the necessary capacity and QoS. C-MADAR is proposed by Belahcen, Abik, and Ajhoun (2012), as an e-learning environment they plan to migrate to the cloud to overcome the limitations of the previous in-house e-learning platform regarding scalability. Another work (Sanchez et al., 2012) proposes moving to the cloud certain servers that control remote physical laboratories so that they achieve scalability when there are many laboratories and students trying to use them.

Other studies support the advantages of using cloud development environments to ensure the native scalability of the educational applications deployed with them. In this respect, Zhao, Sun, and Dai (2010) describe the implementation of a mobile application for the communication between teacher and students, where the server-side application was developed with GAE that natively supports features to scale applications according to the increased number of users. GAE is also used by Chaabouni and Laroussi (2012) to build a system to track learners' indicators, and in (Yin, Han, Liu, & Hongyun, 2010) to develop a courseware system because of its scalability and availability. A mobile application for students is presented by Branon, Wolfenstein, and Raasch (2012), whose scalable database is stored in the cloud using Amazon SimpleDB.[36] Also, Liu, Han, Liu, and Jing (2011) propose to develop educational applications (the student learning portfolio system, the distance education platform and a mobile learning platform) in a private cloud by means of AppScale[37] development system.

4.6. Cost savings in hardware

Virtualization, on-demand provisioning and scalability features together with the pay-per-use model of cloud computing are key factors to bring cost savings in hardware for educational institutions. The most straightforward source of savings is the acquisition of hardware itself. Instead of an institution owning expensive, quite often under-utilized resources, these are owned by the cloud provider, and the institution is only charged per use (Laisheng & Zhengxia, 2011; Tout, Sverdlik, & Lawver, 2009). Other significant sources of savings stem from maintenance, telecommunication services, power consumption to run hardware, cooling (Ivica et al., 2009; Sultan, 2010), fire suppression systems or space. Besides, educational organizations are freed from the tasks of operating the infrastructure (Doelitzscher et al., 2011; Sultan, 2010), thus reducing the cost of technical human resources in the institution.

In public clouds, all these expenses are shifted to the cloud provider (Sultan, 2010), who absorbs the costs and spreads them over a long period of time and many other cloud computing customers (Pocatilu, Alecu, & Vetrici, 2010), achieving economies of scale in their deployments. Therefore, the net costs of using public cloud services can be lower than maintaining infrastructures locally by a single educational institution. If the cloud services are used for a relative short time (several weeks, a quarter, a semester), as it is often the case in the educational domain, savings can be even more noticeable (Pocatilu et al., 2010).

Even if institutions do not make use of public clouds, they can also obtain cost savings by using private clouds thanks to virtualization and scalability. Virtualization capabilities in private clouds enable hardware consolidation (Katz, Goldstein, & Yanosky, 2010), centralizing under a common infrastructure resources otherwise spread over often under-utilized servers, even re-using existing hardware (Vouk et al., 2008), and also achieving a more efficient power consumption (Caminero, Robles-Gómez, et al., 2011; Lennon, 2012). Since virtual resources are scalable, the already deployed infrastructure will be more efficiently used (Vouk et al., 2009), because resources can be provisioned when needed and de-provisioned in idle periods.

Other cost saving measures using cloud computing can come from sharing resources from the cloud among different institutions (Tong, Jiang, & Ruan, 2012) in community clouds. In this case, savings come from unifying the purchase, operation and maintenance of hardware and software packages scattered across institutions.

It is also worth noting that moving the computing infrastructure to the cloud, also results in cost savings in the client side. Some authors, such as Aljenaa et al. (2011), mention that generally only a browser and a computer with lower requirements (storage, computing specifications, etc.) are needed by the learner to access cloud services.

An interesting scenario of cost savings using public clouds is (Ivica et al., 2009). Here, the institution hired AWS EC2 Virtual Machines to host their solution, StarHPC. The course lasted two weeks in which ten students were using virtual clusters on the cloud to develop parallel applications. The institution did not have to invest in new machines for this course, which may be under-utilized later. The cloud provider was in charge of maintaining the hardware that supports the VMs, paying for the required licenses, ensuring the availability of the service, etc. This peak period was supported thanks to the scalability of the cloud, acquiring and releasing VMs on demand, and the institution being billed only for the consumed resources. The authors claim that the price of using resources only when they were needed ($0.10/hr/machine as for January 2009) was more affordable than the cost of owning and maintaining traditional in-house computing clusters.

Regarding educational private clouds, a good evidence of cost savings comes from the use of the solution "Virtual Computing Lab"[38] (VCL) (Averitt et al., 2007; Schaffer et al., 2009), developed to build private clouds with virtual laboratories such as VMs with MATLAB or virtual

[36] http://aws.amazon.com/simpledb/.
[37] http://code.google.com/p/appscale/.
[38] https://vcl.ncsu.edu.

clusters of specific nodes for a High Performance Computing (HPC) experiment. Vouk et al. (2009) claim that VCL achieves cost-effectiveness through virtualization. Hardware consolidation through virtualization leads to savings in power consumption and an optimized utilization of the resources by dynamic reallocation (around the 70–80% range) that also yields a better exploitation of the already acquired hardware resources. Besides, management overhead of the IT staff for maintenance tasks is reduced.

Rajendran and Veilumuthu (2011) use a cloud-based VoD service to deliver lectures to learners. The authors estimate around 20–40% of cost savings in infrastructure due to the scalability features of the cloud service versus the traditional hosted model. Also, Chandra and Borah (2012) estimate that the savings of moving to the cloud five generic computers with virtual desktops over a period of three years were $11,900. Different scenarios are described by McDonald et al. (2010), like public academic clouds, private academic clouds and private institutional clouds with an increasing degree of control over the infrastructure but decreasing scalability and cost saving opportunities. A last example explains the cost drivers to deploy a hybrid cloud in an Irish university, mainly because of reduction in power consumption and lower equipment costs (Lennon, 2012).

4.7. Cost savings in software

Institutions may also obtain cost savings by using the diverse cloud applications that can be employed in an educational context. Often cloud tools are available for free (like Google Docs, Dropbox or YouTube) so institutions do no have to implement or pay for them to build their education information systems (Sultan, 2010). Even if these tools are available at a price, the pay-per-use model of cloud computing avoids the waste of under-utilized software, which is often used by just a few learners, even though multiple copies may have been licensed (Guin et al., 2011; Hu, Chen, & Lin, 2011). The pay-per-use model also allows institutions to make use of tools for a short period of time or experimentally (Branon et al., 2012). Students too can benefit from cost savings since they do not need to acquire licenses of certain products because they are available in the cloud for free (Ma et al., 2010) or they can pay for them only when required. In any case, they can use the same applications at home and in class without having to acquire another license.

Cost savings in software derived from the use of the cloud can be illustrated with the case of the University of Wesminster (UK) (Sultan, 2010), where they started using Google Mail and Google Apps as productivity and collaboration applications in 2008. The author states that the cost was zero, while it was estimated that providing the equivalent service on internal systems would have cost around £1,000,000, comprising both the purchase and maintenance of applications and the infrastructure to run them on. License savings are also reported in a case study where simulation and visualization software for geometry and algebra is used from the cloud, optimizing its usage among several schools (Stein et al., 2013). In a different contribution, students of civil engineering use the free-of-charge product, AutoCAD WS, instead of purchasing and installing licenses locally (Lukaric & Korin-Lustig, 2011).

Likewise, software development kits that can be used for educational purposes, especially in computer science subjects, can also be found in the cloud for free (e.g. some flavors of Google App Engine) or at a certain price (e.g., Amazon SimpleDB for cloud database services). For example, Branon et al. (2012) developed an m-learning application to deliver question packs to students using Amazon SimpleDB. They take advantage of the cloud price model and scalability of Amazon since they did not know in advance how the service was going to evolve. The institution payed for the service incrementally as the m-learning application scaled up.

5. Risks of cloud computing for education

Although there are clear advantages in the use of the cloud in education, some risks have also been identified in the reviewed literature. These risks affect differently to the educational stakeholders and should be taken into account before the adoption and during the use of cloud computing in educational settings. This section discusses the main identified risks of using cloud computing in educational scenarios, and proposes some mitigation measures to face them, which are also summarized in Table 2.

5.1. Security and privacy

Protection of sensitive data is key in the educational domain, and there is a special concern about how cloud computing deals with this issue (Bristow, Dodds, Northam, & Plugge, 2010; Johnson et al., 2012). Some contributions (e.g., Pocatilu et al., 2010) have pointed out that cloud computing can be more secure than traditional distributed systems to protect these data. They argue that data is stored in virtual

Table 2
Mitigation measures to face the risks of cloud computing in education.

	Educational practitioners	Students	IT staff	Educational institutions
Security and privacy	Gain awareness of security risks of cloud computing. Avoid unreliable SaaS providers for learning activities.	Gain awareness of safe use of cloud computing services. Avoid unreliable SaaS providers for learning activities.	Audit public cloud security. Set up private or hybrid clouds, to maintain sensible data.	Draw careful contracts with cloud providers. Make sure that cloud providers adhere to privacy laws.
Vendor lock-in			Set up private or hybrid clouds to avoid service discontinuation. Backup sensible information in different providers.	
Performance and reliability		Ensure broadband access to public or institutional cloud providers (if feasible).	Ensure broadband access to public cloud providers (at a cost). Implement load balancing techniques in private clouds.	Negotiate Service Level Agreements with public cloud providers.
Licensing and price models				Study pay-per-use pricing models and ensure they will hold over time. Use of open source applications.

servers unknown to thieves, that compromised services can be replaced faster without major costs or damages, and that security and monitoring are centralized and can be dealt with more effectively. Cloud providers may offer more security measures and expertise than those within educational institutions (McDonald et al., 2010).

However, sensitive data stored in the cloud (for example, students' records or accounts) (Chandra & Borah, 2012) can be maliciously or accidentally leaked or commercialized and, together with identity theft, may lead to cyberbullying or abuse (Weber, 2013). Furthermore, McDonald et al. (2010) claim that current cloud implementations may disregard personal data protection laws that could result in sensitive information leaks. It is not clear for the customer who owns the data, where the servers are located, or the degree of compliance to local legislation (Dong, Han, Liu, & Xu, 2010). Besides, users of cloud computing in education may not be aware of its potential risks (Lennon, 2012; Vishwakarma & Narayanan, 2012). A study conducted among schools in Tallin (Estonia) (Lorenz, Kalde, & Kikkas, 2012) unveiled a lack of awareness of security risks among educational professionals. The IT staff trusted the cloud computing services and most problems were reported to be related to human errors (e.g., unintended file deletion or users not logging out their account) but not to cloud computing itself.

To mitigate the aforementioned security risks, the literature proposes technical, legal and training measures. From the *technical* point of view, using hybrid clouds could be a solution (McDonald et al., 2010; Mircea & Andreescu, 2011; Sclater, 2010a; Weber, 2013): Sensitive and business information could be stored in private clouds (e.g., grades, health data, or disciplinary information), and less relevant data could be hosted on public clouds (e.g., e-mail). In any case, educational institutions should analyze how data is protected in transmission and storage to prevent security attacks such as packet sniffing or traffic analysis (Weber, 2013). Audits and certifications of security should be performed to increase the user's confidence (Fernández et al., 2012). Even though cloud providers have secure infrastructures (Sultan, 2010), institutions should consider using specialized security services like encryption or single sign-on capabilities (McDonald et al., 2010). Contracting more than one cloud provider is recommended (Sclater, 2010a) to host educational services and data to avoid the single point of failure produced by security attacks, especially since these attacts are more frequently targeted at relevant public cloud providers (Tout et al., 2009). Note that most of these technical mitigation measures address security issues caused by the use of cloud computing itself (Subashini & Kavitha, 2011), not because of its application to the educational domain. Nevertheless, some private cloud architectures proposed for educational institutions have been designed with these security challenges in mind. For example, Snow Leopard (Cayirci, Rong, Huiskamp, & Verkoelen, 2009), a private cloud for educational purposes in the military domain, resolves security challenges in its design, including privacy, anonymity and traffic analysis, single point of attack, and single point of failure or Denial of Service (DoS) attacks. Another relevant architecture for educational private clouds, VCL (Vouk et al., 2009), enforces different security measures: isolation of VMs at the infrastructure level, authentication and access permissions to allow a user to create VMs, encrypted access to VMs, and logging and monitoring to identify and prevent misuse.

Within the *legal* domain, Weber (2013) advocates that institutions should analyze their contracts with cloud providers to make sure that they comply with local legislation and institution's policies. Some cloud providers now guarantee compliance with legislation (Sclater, 2010a) but, otherwise, ad-hoc agreements could be reached to prevent these problems (Weber, 2013).

Finally, the *training* approach should aim at educating learners, teachers and administrators to make a safe use of cloud computing. For instance, students should be taught to use cloud services securely, limiting the personal information provided and learning privacy best practices (Weber, 2013). The same contribution recommends that practitioners should also be aware that many cloud applications were not originally designed for educational purposes and security issues were not primary objectives in the design process.

5.2. Vendor lock-in

The lack of interoperability among different cloud providers makes it very difficult, technically or economically, for educational institutions to port virtual machines, data, or services from one cloud to another (Sclater, 2010a). This problem, known as vendor lock-in, is one of the barriers to the general adoption of cloud computing (Armbrust et al., 2010). For instance, since cloud providers may use different formats and metadata to code and describe properties of VMs, it is not straightforward to move a VM from an IaaS cloud provider to another. Applications developed at PaaS level with certain APIs and runtime environments could not be moved to other PaaS providers with different ones. Also, switching from a SaaS provider to another in services such as webmail, could also result in losing invaluable information.

Because of vendor lock-in, institutions are at the mercy of changing price and service conditions or discontinuation of cloud services. In addition, vendor lock-in and cloud service discontinuation together may also lead to irretrievable educational data loss. As an example, Weber (2013) reports that the former Google's online virtual world, Lively, was shut down in 2008. In this case, educational content could have been lost because data was not easily exportable. One solution to this threat, as explained by Weber (2013), would be to sign contracts with several cloud providers to diversify risks, but institutions may find it difficult to manage. However, this would avoid service discontinuation, but not eventual data loss.

According to Aljenaa et al. (2011), private clouds could be less exposed to this risk. Private clouds are owned and managed by the institutions themselves, so they do not depend on a third party to keep offering the cloud services. Nevertheless, changing from one private cloud to another could also result in data or service lock-in because private cloud platforms may not be interoperable.

The technical approach to avoid vendor lock-in is related to achieving software interoperability in one or more layers of cloud services (IaaS, PaaS or SaaS) (McDonald et al., 2010). In this regard, work is underway in different organizations and initiatives such as the Distributed Management Task Force[39] (DMTF) to ensure VM portability across multiple virtualization platforms, DeltaCloud[40] to define REST-based APIs to manage IaaS, or the NIST[41] to establish standardized data formats to enable cloud interoperability at different tiers, among others.

[39] http://dmtf.org/standards/cloud/.
[40] http://deltacloud.apache.org.
[41] http://www.nist.gov/itl/cloud/sajacc.cfm.

5.3. Performance and reliability

Some cloud-based services used in educational contexts, especially those involving interactivity and collaboration, can be very sensitive to network performance and latency. Therefore, broadband connections should be available for users to enjoy an adequate learning experience. For instance, Ivica et al. (2009) note that high throughput and low latency connections are required for learners to access their virtual laboratories on the cloud. This, in turn, poses new threats on the use of cloud computing for education. Since broadband networks such as optical fiber or leased lines are needed (Masud & Huang, 2012), there will be users (e.g. those in deprived areas, without sufficient bandwidth) with difficulties to adopt cloud computing (Bhatia & Lala, 2012; Le Roux & Evans, 2011). On the other hand, hiring more capacity for broadband lines in educational institutions may increase the expenses of communication services compromising the promises of cost savings.

Other performance issues have to be considered. For instance, delays caused by slow deployment or scalability mechanisms in the cloud could result in unacceptable QoS degradation in certain educational scenarios. It could take several minutes to launch a VM in the cloud (Doelitzscher et al., 2011). Albeit a relative short time, it can be too long to bear for a class. Slow scaling can also affect some educational applications whose demand varies heavily during enrollment periods or by assignment deadlines. In order to solve this, load forecast techniques have been proposed to scale resources efficiently in cloud-based e-learning systems (Caminero, Ros, et al., 2011; Koch, Assunção, & Netto, 2012), taking into account education-specific behavioral patterns (e.g., seasons, enrollment periods, etc.).

An additional related risk is the reliability of cloud-based educational services (Tout et al., 2009). Although reliability is one of the most salient features the cloud offers compared to traditional IT infrastructures (Armbrust et al., 2010), relevant providers, such as Google or Amazon, have had some episodes of failures interrupting their services (Sultan, 2010). Educational online services are not as critical as other services such as those related to e-health, but they must be available at least during classes and special periods such as enrollment or grade publications and may impact students' learning and the timely delivery of assignments (Tout et al., 2009).

5.4. Licensing and price models

The lack of maturity of price models in cloud computing can be a threat for the cost-saving benefits it promises for education. This risk is illustrated by Stein et al. (2013) with the following hypothetical scenario. A school district with 10 traditional classrooms and 50 computers in each classroom would require the purchase of 500 software licenses which are probably under-utilized. Provided that classrooms can arrange an adequate schedule, with a cloud-based network license of 50 concurrent users, all the classrooms across the district could be served maximizing the utilization of these licenses and consequently achieving cost savings. In this situation, the software vendor could reduce institution's savings by changing the price of shared licenses, so that the costs were tantamount to traditional local licenses (Stein et al., 2013). In this case, the cost savings case for cloud computing could be arguable. However, it should be noted that some providers are adapting their licensing models into pay-per-use schemes to better suit the cloud model and make it more affordable for organizations (Armbrust et al., 2010). Educational institutions should also take into account licensing prices to establish cost policies, for instance, determining cost limits, preferences on horizontal scaling (i.e., additional computational resources) or vertical scaling (i.e., more powerful computing capabilities) depending on the cost, etc.

Open source applications can also be a solution for this threat (Armbrust et al., 2010). In fact, it is the preferred path followed in many of the reviewed studies, such as R and Scilab (Chine, 2010), Cinelerra (Zablah et al., 2012) or Open Wonderland (Cucinotta et al., 2012).

6. Research issues

The analysis of the literature resulted in the identification of a number of issues the research community is currently focusing on. This section introduces the main research efforts, their limitations and possible future work related with each research issue. Table 3 summarizes these research opportunities, according to the cloud-specific or TEL issues they address.

6.1. Cloud infrastructures for educational institutions

Once have the educational institutions realized the benefits of cloud computing, some of them are interested in moving their systems and services to the cloud (Anton et al., 2012; Bristow et al., 2010; Caminero, Robles-Gómez, et al., 2011; Doelitzscher et al., 2011). Therefore, one of the main challenges is the deployment of cloud infrastructures for educational purposes. Table 4 summarizes the main efforts in this sense and their essential characteristics. In this regard, two main approaches are perceived. On the one hand, there are research works proposing ad-hoc middleware for educational clouds. On the other hand, more recent studies employ existing general-purpose middleware components to build up the educational clouds. In the former group of studies, one of the earliest and most significant contributions is VCL (Averitt et al., 2007; Vouk et al., 2008, 2009). VCL is an ad-hoc middleware to reserve and deliver computational services for education, from single desktops, to clusters of real and virtual servers or high-performance computing (HPC) services. The main application domain of VCL is the university, but it has also been used in K-12 education (Stein et al., 2013). The VCL source code is currently managed by the Apache Software Foundation,[42] and as for 2009, VCL served over 30,000 students and faculty staff. VCL can be considered as a middleware mainly for private clouds, although work is in progress to create and reserve VMs in the Amazon EC2 public cloud. Scalability is handled manually by practitioners or administrators, creating or terminating VMs as the demand varies. Regarding the availability of the infrastructure, automatic failover is possible for certain VMs depending on the hypervisor used.

Another relevant contribution, CloudIA (Doelitzscher et al., 2011), is a project to design and build a private cloud to create on-demand computing resources, and run e-learning applications and collaboration software. It was implemented in the Hochschule Furtwangen University (Germany) and it comprises computing services for education at IaaS, PaaS and SaaS levels. According to private conversation

[42] http://vcl.apache.org.

Table 3
Research issues of cloud computing in education.

	Cloud-specific issues	TEL issues
Cloud infrastructures for educational institutions	Design ad-hoc educational clouds or use generic cloud middleware to set up private clouds. Decide which virtualization level (IaaS, PaaS, SaaS) is adequate. Support automatic scalability. Implement security mechanisms.	Determine actions that teachers and students can perform upon the cloud, and the interfaces for it. Determine needs of SaaS built in educational clouds (e.g. collaboration tools, VLEs). Determine needs on PaaS for specific uses (e.g. simulations).
Easy scheduling and reservation	Expose scheduling and reservation mechanisms through APIs, and develop friendly interfaces on top of them.	Determine user requirements for scheduling and reservation interfaces. Define workflows of typical learning scenarios as a means for automatic scheduling.
Automatic scalability mechanisms	Define forecast models. Implement monitoring and scaling mechanisms for diverse scenarios (e.g., MOOCs). Map high level metrics to infrastructure metrics.	Define high level metrics that practitioners understand and use to specify scalability rules.
Composition of cloud-based learning environments	Design mechanisms that, from a high level specification of computational needs, configure and provision cloud support (SaaS, virtual machines, virtual desktops or virtual networks of machines), and then deploy and scale them as needed.	Adapt languages and editors used for learning design formalization, so that infrastructure needs can be specified in relation to learning activities.
Interoperability of educational clouds	Define standards for operation invocation, virtual machine persistence, among others. Define cloud brokers to achieve load balancing among clouds to meet some QoS.	Define educational abstractions of "Task as a Service" which are independent of the underlying cloud technology.
Architectures to support m-learning	Define architectures for mobile applications that exploit both ubiquitous access and scalability in computation and storage.	Define mobile learning scenarios unconstrained by the device capabilities (e.g. augmented reality).
Other research opportunities	Explore applications to all educational levels (e.g., K-12). Perform evaluations of these innovations in real scenarios with real practitioners. Research if there are pedagogies more suitable for scenarios now feasible with cloud support.	

with the authors, CloudIA is currently running and it is used by around 200 students, with an average of 90 VMs deployed. In its architecture, resource pools are managed by the CloudIA's Cloud Management System (CMS) that enables users to create VMs on demand, even choosing what specific software packages are to be installed on them. At PaaS level, CloudIA provides the Servlet Container Platform (SCP), a programming environment for students with preconfigured tools. At SaaS level, Collabsoft, a software package developed for online collaboration with instant messaging capabilities can be installed in a VM on demand. They also offer virtual storage for students. Since CloudIA has interfaces to the Amazon cloud, VMs can be initiated both in the private and in this public cloud. Finally, the NATO Education and Training Network is presented by Cayirci et al. (2009) to support simulations and training exercises of military services on a community cloud for headquarters, nations and partners.

More recent contributions use existing cloud middleware to build educational cloud infrastructures. For instance, the private cloud built by the Spanish Distance University (UNED) (Caminero, Robles-Gómez, et al., 2011) uses Open Nebula to provide students with access to VMs where they can do their practical exercises. Another example is the community cloud built for four universities in Romania (Anton et al., 2012) on IBM virtualized servers. Here, a VLE allows students to reserve VMs with preloaded software for computer science subjects. Liu et al. (2011) present a test platform using Eucalyputs built for the Capital Normal University of Beijing, upon which they install AppScale at PaaS level for the institution's applications.

It can be observed that, recently, there seems to be a trend to use existing cloud middleware to build educational clouds instead of designing ad-hoc clouds for education, except in specific contexts (see Cayirci et al., 2009), where security is a strong requirement. This can be caused because when ad-hoc cloud infrastructures were designed, there was not any available and full-fledged cloud middleware, such as Open Nebula, Eucalyptus or Amazon Web Services, that now can be used.

Proposals of cloud infrastructures for education using exclusively public cloud services have not been found, since researchers have developed specific cloud middleware and mainly private deployments for educational purposes. Private, community and hybrid clouds are employed across the different studies seemingly because of the need to use already invested hardware infrastructures (Doelitzscher et al., 2011), whereas public cloud services are restricted to situations when the private cloud capacity is overflown (Caminero, Robles-Gómez, et al., 2011) to limit costs. Besides, with private clouds, the institution also exerts total control over the infrastructure and can adapt and tailor their platform to their specific needs (Doelitzscher et al., 2011). Another reason may be that institution's managers perceive that it is more secure to control their own resources in a private cloud (Sclater, 2010a). Even though educational institutions mainly use private or hybrid clouds at the infrastructure level, public cloud applications and software are the most common choice at SaaS level. This may be caused by the widespread use of commercial cloud software by students and practitioners.

Based on these cloud infrastructures, further research should be undertaken to take full advantage from other key capabilities of cloud computing, such as fast automatic scalability or high availability. Other features already found in commercial clouds can be developed on top of ad-hoc educational clouds, such as queuing, load balancing or monitoring services, which will be useful to implement learning services and applications in higher levels of cloud computing (PaaS or SaaS). All these characteristics are relevant so that the use of cloud-based applications does not interrupt or slow down the learning activity. Some of these features are already available in public clouds like AWS, so research efforts could be focused on using public clouds to support educational systems, especially those with a highly variable demand, utilized for a short period of time or with an experimental use. Besides, research effort should be devoted to deploy PaaS environments and SaaS applications on private cloud infrastructures. So far, only a few proposals implement high-level cloud-based applications

Table 4
Cloud infrastructures for educational institutions.

	VCL (Averitt et al., 2007; Vouk et al., 2008, 2009)	CloudIA (Doelitzscher et al., 2011)	NATO Education and Training Network (Cayirci et al., 2009)	UNED (Caminero, Robles-Gómez, et al., 2011)	(Anton et al., 2012)	(Liu et al., 2011)
Deployment model	Private cloud.	Hybrid cloud.	Community cloud.	Private cloud.	Community cloud.	Private cloud.
Education sector/level	Mainly university. Also K-12.	University.	Military.	University.	University.	University.
Level of abstraction	IaaS.	IaaS/PaaS/SaaS.	IaaS/PaaS/SaaS.	IaaS.	IaaS.	IaaS/PaaS.
IaaS services	Creation of customized on-demand VMs, virtual clusters, physical and HPC resources.	Creation of customized on-demand VMs, even with software packages. Monitoring.	Creation of customized on-demand VMs.	Creation of customized on-demand VMs with Open Nebula.	Creation of customized on-demand VMs even with software packages.	Creation of customized on-demand VMs with Eucalyptus.
PaaS services	None.	Servlet Container Platform.	Components to deliver simulations.	None.	None.	AppScale.
SaaS services	None.	Collaborative VLE Storage as a Service (OwnCloud).[a]	Simulations, email, webservers, collaborative workspaces.	None.	None.	It is proposed to migrate the institution's applications.
Scalability	Manually creating more VMs. Future developments to interface with Amazon EC2.	Manually creating VMs either in private or public clouds (Amazon EC2 and S3).	Manually creating more VMs.	Manually creating more VMs. Overflow to public clouds in progress.	Manually creating more VMs. Automated scalability based on service requests.[a]	Manually creating more VMs. Natively at PaaS level.
Availability	Automatic failover of certain VMs.	VMs can be replicated in the private and the AWS cloud.	Not described.	VMs can be replicated in the private cloud (and in the AWS cloud in progress).	Automatic failover of VMs. Backup data center.[a]	Load balancing among application components.
Security	Authentication. VM isolation through OS level firewall or VLANs.	Authentication and SSO using Shibboleth. Federation of educational institutions at SaaS level.	Multi-level security (clearance management). Encryption. Authentication.	Not described.	Custom built IDS, IPS, server security management.[a]	Not described.
Development maturity	Implemented.	Implemented.	Specifications and testbeds.	Partially implemented.	Implemented.	Test platform.
Type of contribution	Research proposal of architecture.	Research proposal of architecture.	Research proposal of architecture.	Integration of existing cloud infrastructures.	Integration of existing cloud infrastructures.	Integration of existing cloud infrastructures.

[a] As reported in private conversation with the authors.

on the institution's infrastructure (mainly VLEs, collaborative tools and virtual storage). Other research can be undertaken to test the affordances of cloud computing for learning analytics, where scalability and compute-intensive capabilities to process massive amounts of data are desirable.

Although some of the mentioned infrastructures, such as CloudIA and VCL, have been widely used in real settings, there has not been a formal evaluation from the viewpoint of the stakeholders (practitioners, students or administrators) or, at least, it has not been reported. This could be a future work for researchers dealing with cloud infrastructures for educational institutions, where characteristics such as flexibility, usability or fitness of response times for educational purposes could be studied.

6.2. Easy scheduling and reservation of computing resources

In educational scenarios, computing resources are often needed for labs or practices and resource reservations need to be made. Cloud computing enables this feature, but the appropriate middleware must allow students or practitioners to schedule and reserve resources on demand conveniently (Dong, Zheng, Yang, Li, & Qiao, 2009).

Some proprietary solutions have been employed for users to request computing resources on an educative private cloud. For instance, Anton et al. (2012) describe the workflow used to approve requests of VMs by practitioners in an IBM private cloud. Nevertheless, middleware designed specifically for education seems to be required. In this regard, in VCL (Vouk et al., 2009), middleware was created to allow users to reserve and schedule computing resources on the cloud via web or through defined APIs. A module called VCL Manager receives user requests and is in charge of resource scheduling, security, monitoring and virtual network management. Node managers handle the local installation of resources and load the corresponding image from a repository. Within the CloudIA platform (Doelitzscher et al., 2011), students in a lab create a VM for their use through a web page where they are authenticated and can load the components needed. The creation of VMs can also be scheduled and reserved in advance. In some cases, APIs are handy to allow VLEs to request computing resources for a certain exercise, such as REST-based APIs developed to reserve VMs for a lab once students access the institution's VLE (Anton et al., 2012).

Not only system administrators but also unskilled users such as students or teachers should be able to schedule or reserve these resources easily (Wiebe & Hudnutt, 2007). Accordingly, usability tests on early interface prototypes have been run on VCL to ensure its suitability for practitioners in K-12 education (Wiebe & Hudnutt, 2007), but it seems that further usability evaluation of these mechanisms should be required.

The reservation and scheduling mechanisms should also take into account that the underlying cloud infrastructure may have limited computing resources, as it is the case in private clouds (Morariu, Morariu, & Borangiu, 2012). Therefore, algorithms have to be designed to optimize the use of resources. For instance, teachers may request reservations of cloud computing resources for labs during several weeks, with varying class durations and start times and therefore a suitable algorithm should schedule the available resources to optimize their utilization. Genetic algorithms are developed by Morariu et al. (2012) and Brzozowska, Greblicki, and Kotowski (2012) that optimize the scheduling of cloud resources under the eventual existence of conflicting requests by teachers. With a similar approach, Koch et al. (2012) propose an architecture for workload-aware dynamic resource allocation in the cloud taking into account educational metrics such as the class schedule (when classes start and end), class profile (type of application and expected workload) and interaction patterns among students and their devices.

As future work, these systems could include other control mechanisms to ensure that departments do not reserve and consume all the available resources, to enforce control policies to limit maximum costs, or to impose constraints depending on the characteristics of the subject. They should also take into account QoS in educative terms (e.g., reserving and scheduling resources that require rapid deployment to use them immediately in the classroom or high computing capabilities to render a computer-intensive learning activity).

6.3. Automatic scalability mechanisms

Scalability at the infrastructure level is a weakness in traditional e-learning systems (Dong, Zheng, Qiao, Shu, & Yang, 2009; Fernández et al., 2012), i.e., when the system receives high workloads, it is difficult to manage and expensive to scale up the resources. Cloud computing can be advantageous to overcome this limitation through its flexible mechanisms for (virtually) infinite scalability, but dynamic scalability is still a challenge in cloud computing (Zhang et al., 2010). If scaling is performed automatically, greater cost savings will be produced and, at the same time, the infrastructure will conform to QoS requirements as the demand varies. In educational settings, when new computing resources are needed during class time, its provision needs to be fast. Automatic scalability is also desirable in scenarios where resources are needed quickly to respond to a sudden demand variation, such as in MOOCs.

In the educational domain, some research efforts have been aimed at defining prediction models to better suit the computing needs of demand. For instance, forecast algorithms have been developed to predict the load of cloud-based e-learning infrastructures and dynamically provision additional resources (Caminero, Ros, et al., 2011). In this case, the algorithms work with infrastructure-level monitored data such as the CPU load and take advantage of the seasonality of demand in education. For instance, the CPU load is higher during the day and increases as exams are closer and decreases later. This contribution proposes studying other low-level parameters to predict the usage like disk I/O, and application-level metrics such as the status of queues or requests per second (Caminero, Ros, et al., 2011). However, new algorithms especially tailored for rapid and unexpected changing conditions are needed, so that they can be applied to the abovementioned scenarios, like massive online courses. For longer-term prediction models, they should also take into account specific characteristics of education, such as the periodic nature of educational events (enrollments, examination periods, etc.).

A different approach to support auto-scaling is followed by Cucinotta et al. (2012) where application metrics are monitored to automatically scale the cloud infrastructure. Here, a maximum number of logged avatars are allowed in a cloud-based virtual world application for educational purposes. Other application parameters can be monitored as well, such as the avatar speed, chatting quality, etc. Upon arriving at the maximum number of avatars, the owner of the service is prompted to allow the increase of computing resources to scale up the infrastructure (CPU share, memory, network bandwidth, etc.) and permit new avatars to enter the virtual world with the same QoS. In this case, the process is semi-automatic so that the SaaS provider has control over the infrastructure costs.

All in all, some issues have to be looked into to solve this research challenge in the near future. First, specific metrics to monitor at application level have to be defined. Currently, most of the metrics monitored are related to IaaS parameters, but other education-related higher-level metrics should be considered, such as the number of concurrent students accessing a MOOC, the bitrate of a video streaming service or the average response time serving learning contents. Higher-level metrics are closer to the educational domain and can be easily interpreted and managed by practitioners.

Secondly, the rules that bind monitoring metrics and specific actions to take at the different levels of cloud computing have to be identified. Education-specific business logic has to be set up to decide how to auto-scale in the events triggered by the monitored metrics. Not only do actions have to be taken at IaaS level (e.g., vertical or horizontal scaling), but also at PaaS or SaaS level. For instance, in a cloud-based simulation application, new instances of a simulation package could be created as the number of users increases at SaaS level, and at the same time, the creation of more VMs at IaaS level could be triggered.

At SaaS level, different computing resources can be automatically scaled in educational settings ranging from the number of video-streaming servers broadcasting lectures or the QoS of a streamed video, to chat rooms, or virtual worlds for students. At PaaS level, resources such as databases or threads in cloud-based programming environments can also be scaled automatically. Rules can be complex considering events at different cloud layers, and could be defined to scale resources from a private to a public cloud or viceversa. They should also take into account other parameters, sometimes education-specific parameters, such as school timetables, enrollment or examination periods, class profile according to computing needs, (see Koch et al., 2012), or others, like the overall cost.

Obviously, actions to allow scalability at different levels of cloud computing depend on the available management primitives, so it may be necessary to develop specific APIs at different cloud tiers to automate cross-level resource scaling.

6.4. Composition of cloud-based learning environments

Another research challenge is the design of cloud-based computing environments for learning. Taking advantage of the flexibility of the cloud, TEL researchers are composing self-contained software packages that can be deployed on the cloud almost automatically and can be used in the classroom. Practitioners can create complex and rich learning environments that students benefit from, without concerning about configuration issues. The computing environments can be deployed only when they are going to be used, therefore using resources efficiently and reducing costs. Previously mentioned contributions such as StarHPC (Ivica et al., 2009) or IP telephony laboratories (Yuan et al., 2011) are good examples of these cloud-based computing environments. While StarHPC provided a self-contained parallel programming environment to install on the cloud, the IP telephony laboratory deployed IP call servers on a private cloud that students can configure.

In more complex collaborative learning scenarios, teachers or instructional designers script in advance the sequence of activities that students must perform, specifying not only constraints such as group formation or time for completion, but also the computational resources needed, as part of what is now called educational orchestration (Prieto, Dlab, Gutiérrez, Abdulwahed, & Balid et al., 2011) by many researchers. Traditionally, these scripts were to be run (i.e. activities enforced, computational resources provided) within a monolithic VLE, but recent research (see Prieto et al., 2013) offers means of deploying scripts into a VLE but integrating SaaS tools from the cloud. Further research could include the provisioning of VMs with stand-alone applications installed and configured on the fly, as specified in the learning script. Stand-alone machines or virtual clusters for Computer Science experiments could also be provisioned based on the educational design specified in a script. As the script also describes group sizes and time constraints, the infrastructure could be reserved and scaled up or down to meet QoS requirements, which could also be defined in the script. Some authors have proposed different approaches for the automatic provision of cloud resources regardless of any specific domain (Rodero-Merino et al., 2010), but TEL researchers would need to find out ways for teachers to express their needs from the infrastructure, means to satisfy them using the cloud, and integrate them with existing educational systems.

On the other hand, the design of PLEs is an opportunity to harness the benefits of cloud computing, especially the great variety and number of cloud applications. Research has been made to use cloud applications to build PLEs for effective learning. The composition of PLEs for mobile devices can be a resultant research line. However, the heterogeneity of cloud tools can be a drawback if the PLE is not designed appropriately increasing its complexity and hindering usability (Rizzardini et al., 2012). Therefore, further research should be carried out to seamlessly integrate heterogeneous cloud tools.

Another open issue deals with the fact that some preconfigured environments can be too complex for teachers to set up, so they are limited for teachers with advanced skills in computers or networks or support from the IT staff is required. Easy-to-use, off-the-shelf solutions are required for rapid deployment by teachers without technical skills.

After implementing these cloud-based learning environments, trials in real settings need to be run to demonstrate that they are useful to improve students' learning. As Vaquero (2011) points out, sometimes preconfigured cloud environments do not result in a students' performance improvement. It should be tested that educators are comfortable with the environment and if it meets some of their everyday educational needs.

6.5. Interoperability of educational clouds

Interoperability among clouds is a desirable characteristic in the educational realm both to avoid vendor lock-in and to interact with other educational platforms and systems. The former is a generic challenge of cloud computing and it is being widely researched, as it was explained in Section 5.2. The latter can be further investigated for specific purposes in education.

Educational clouds scattered along different campuses or premises can provide different online services and computing resources for students. In this scenario, interoperability among clouds is wanted to provide the most suitable educational service or resource or to reallocate e-learning services to foreign clouds. The way these clouds interoperate at this level is an open issue (Bristow et al., 2010). This research challenge could also involve other generic issues such as how to handle security, authentication, load balancing, or QoS management in federated clouds.

Interoperability among educational clouds has been dealt with in similar terms by Yang (2011) and Conghuan and Xiaowen (2011). They propose to accomplish interoperability by means of an integrated framework or, else, cloud brokers, that collect and manage information about the available clouds and the services they provide. This information can be parameters such as QoS, costs, or reliability, but it can also consist of educational information such as the types of e-learning services provided by the federated cloud, or learning metadata of the learning objects delivered. Based on this information, the framework forwards student's service requests to the most suitable educational cloud.

In a different approach, Rajam, Cortez, Vazhenin, and Bhalla (2010) propose to expose cloud-based e-learning components as "Task as a Service" (TaaS) to interoperate among educational clouds. These components could be provided in different clouds as "tasks" (e.g. an online quiz, an examination, or a lecture), that can be composed and reused to provide students with a complete e-learning experience. In this sense, the presentation layer providing interfaces to students could be implemented in a different cloud.

Nevertheless, further work needs to be done on this issue. Most of the presented contributions are theoretical, designs are not complete, and interfaces and interoperability mechanisms have not been specified yet. Besides, no evidence has been found of implementations that can test and validate these proposals.

6.6. Architectures to support m-learning

A number of contributions tap into the affordances of cloud computing for mobile learning, especially scalability, unlimited computing and storage resources and ubiquitous access to enable synchronization capabilities among devices (Kovachev et al., 2011). For instance, the e-learning platform U-SEA (Dutra Piovesan et al., 2012) is composed of a Moodle-based VLE on a private Eucalyptus infrastructure. Some Moodle features were adapted so that different mobile devices can access materials and tools suitable to each device connection speed. Nonetheless, although this approach harnesses the ubiquitous access capabilities of cloud computing, it does not take full advantage of other affordances such as scalability or unlimited storage that could be beneficial for large-scale m-learning systems. Instead, Zhao et al. (2010) and Branon et al. (2012) describe m-learning applications that use Google App Engine and Amazon SimpleDB respectively as cloud-based back-end platforms. This way, they ensure native scalability at application and database level, for a potential high and changing number of learners. Alternatively, storage in the cloud is exploited by Kovachev et al. (2011) to allow students synchronize their learning content among different mobile devices and desktops to learn languages. An evaluation process was carried out and resulted that students provided positive feedback for synchronization of learning content and usage of online learning resources.

As it has been shown, the proposed architectures and applications only take partial advantage of cloud computing affordances, either ubiquitous access, or scalability of virtually unlimited computing and storage resources. Research should be undertaken to draw up a comprehensive architecture for m-learning supported on cloud computing that integrates and takes advantage simultaneously of the abovementioned affordances.

The possibility of supporting m-learning Augmented Reality applications can be another research opportunity, where heavy computing can be required to take place in the cloud (Aziz et al., 2012). However, realistic learning scenarios have to be envisioned and constraints such as limited network connectivity for highly sensitive applications like this one have to be taken into account.

7. Discussion and conclusions

This study has analyzed the most relevant contributions on the use of cloud computing in the educational domain and has found out that the cloud offers characteristics that can be advantageous for education. Some of these advantages, such as cost savings or scalability, can be common to other domains (e.g., commerce, health, etc.), but others are specific to education. For instance, the wide availability of cloud applications with similar functionalities as a service (e.g., consider the great number of wiki or blog providers) has allowed educators to design many TEL innovative scenarios (e.g., Abrams, 2012; Dmitriev et al., 2012; Tan & Kim, 2011; Wood, 2011), which some authors have found to change the way learners acquire new knowledge (Conole, De Laat, Dillon, & Darby, 2008; Saadatmand & Kumpulainen, 2012). In other situations, especially in Computer Science disciplines, IaaS resources come in handy (Anderson, Wilkes, & Young, 2008), for instance, for practitioners to flexibly design laboratories of different complexity on clusters of VMs to provide students with networking or programming environments (e.g., Dinita et al., 2012; Ivica et al., 2009; Vaquero, 2011; Yuan et al., 2011). In this regard, the IEEE/ACM Joint Task Force for Computing Curricula clearly emphasizes that sufficient, up-to-date laboratory infrastructures must be provided by institutions teaching any computers discipline (Shackelford et al., 2006), which can be arranged easily and more efficiently by the use of clouds. Furthermore, the student has more opportunities for self-organized learning, by freely choosing applications and contents from the cloud suited to their learning needs and objectives. In some cases, they even become creators of their own learning environments, mashing-up tools and combining learning contents of their choice (e.g., Casquero et al., 2008; Liang & Yang, 2011; Rizzardini et al., 2012). This fact may push VLEs into the background mainly as single-access-point to learning services and contents and as storage of student's administrative information. In this case, it is likely that VLEs will have to address issues such as interoperability and integration with third-party cloud tools (not only SaaS applications, but also IaaS or PaaS learning components), security (e.g., deciding which data is sent to what cloud service), or uniform QoS management across clouds.

There are many other situations in which cloud computing can enable learning applications otherwise unfeasible or expensive. Simulations or rendering of 3D objects or videos (Zablah et al., 2012) can be parallelized in the cloud; virtual worlds (Cucinotta et al., 2012) are engaging environments that are computationally demanding but can be offered with resources provisioned from the cloud. Similar arguments maintain the use of the cloud to support scenarios intensive in calculations (Chine, 2010), CAD processing (Lukaric & Korin-Lustig, 2011), or real-time AR (Ming, Chen, & Zhang, 2011). Besides, the cloud is an adequate platform for mobile computing, and therefore for m-learning, providing scalable ubiquitous services, device synchronization, and high storage and computing capacity thus saving battery life.

On the other hand, cloud computing brings advantages for educational institutions and their IT staff that can be common to other application domains. In this sense, educational institutions can leverage the cost savings of cloud computing by relying on public clouds or consolidating hardware in private clouds. Public infrastructures can be suitable to host high-end educational services, such as MOOCs, m-learning applications, or learning analytics systems because of the scalability and availability affordances offered. Larger cost savings can be achieved if automatic scalability techniques are implemented, though this requires research on defining educational metrics that drive it, and that are also cost-constrained. Regarding the IT staff, virtualization will help to minimize the operation time, making it possible for technical personnel to focus on core tasks instead of configuration issues.

Despite the described advantages, some risks and limitations have been identified. The cloud raises concerns about privacy and security, especially with sensitive students' data, provider lock-in, performance issues and underdeveloped licensing models. Together with the risks, measures to mitigate them have been proposed across the literature. Some of these risks are not purely technical, but also involve other legal, cultural, or business-related aspects.

This work has also detected the most prominent research challenges that can be advanced by researchers in this field. One of the main research challenges is the design of cloud infrastructures for educational institutions, using whether ad-hoc or existing cloud middleware. Some specific features have to be implemented on these cloud infrastructures. For instance, easy scheduling and reservation mechanisms, to design usable middleware so that educators and learners can reserve cloud resources for assignments and laboratories, optimizing its use at the same time. Other feature to be researched is the design of automatic scalability schemes. Particular educational scenarios such as MOOCs can obtain greater benefits from cloud computing if scalability is performed automatically. Although relevant to other cloud uses, this topic has to be looked into, supported and augmented by educational parameters and metrics to monitor and scale.

Researchers have also to take advantage of the flexibility of cloud computing to facilitate the composition of cloud-based learning environments. Cloud-based tools and bare computing resources can be combined by educators to form new computing environments for learning not feasible before.

A different topic, interoperability among educational clouds, has to be researched as well. Brokerage among different educational clouds or similar mechanisms are required to achieve interoperability at service level among clouds in different campuses or providers. Finally, architectures to support m-learning have to be drawn up. In a scenario of an increasing number of mobile users, the cloud can be a suitable infrastructure to enable scalable, ubiquitous, and computationally powerful m-learning services. Comprehensive architectures that benefit from all these affordances are needed and have to be researched.

Additional comments can be made related to the research work in this field. Despite the main advantages of cloud computing in education are strongly supported by the reviewed literature, we believe that research on this topic may still be immature. Many of the reviewed contributions are shallow or mainly introductory. Contributions are often theoretical, report few implementations to validate their proposals, and there is a lack of proper evaluation in many of them. From the pedagogical point of view, it is also worth noting that little work has been carried out to find new ways to teach and learn with cloud computing (Boyatt & Sinclair, 2012), to adapt cloud computing to new or existing pedagogies except, in some cases, collaborative learning (Denton, 2012), or to evaluate the learning efficacy of this approach. Although some studies point out that cloud computing is a promising paradigm for K-12 education (Johnson et al., 2013), it is noticeable that most of the contributions about this topic deal with deployments in the university domain. All these observations open the way for new research work on this field with many challenging opportunities for TEL researchers.

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