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

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Abstract—This paper reviews the scientific literature on the use and research of cloud computing in education. The objective is two-fold: to categorize the specific advantages and risks of using cloud computing in the educational realm, and to put forward the open research challenges in this domain. Following a systematic review methodology, 124 works are included in this review. These works support the main identified advantages, such as the great number and variety of online applications to support education, the flexibility to create learning environments, support for m-learning services, support for scalable and computer-intensive processes, and cost savings in hardware and software. However, practitioners and institutions should also take into account other risks and limitations, such as privacy and security issues, vendor lock-in, performance, and licensing issues. Research challenges include the design of cloud infrastructures for educational institutions, mechanisms for easy scheduling and reservation of computing resources, automatic scalability, composition of cloud-based learning environments, interoperability of educational clouds, and cloud-based architectures to support m-learning.

Index Terms—Computer Uses in Education, Distributed Systems, Introductory and Survey

1 Introduction

Cloud computing [1] is a distributed computing paradigm that enables access to virtualized resources including computers, networks, storage, development platforms or applications. These resources can be unilaterally requested, provisioned and configured by the user with 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 usage is measured in the cloud to control and optimize their use 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 run-of-the-mill 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[4] or Microsoft Azure[5] [2]. 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 educational realm, cloud computing has also been identified as a key trend [3] that enables access to online services anywhere and promises scalability, enhanced availability and cost savings [4]. These are desirable properties to provide e-learning services, especially in scenarios where these services are compute-intensive (virtual worlds, simulations, video streaming, etc) or are offered in a high scale as in MOOCs (Massive Online Open Courses). The cloud can provide students and teachers with tools to deploy computing resources on-demand for classes 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 laboratories rapidly [5]. 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) [6]. Other affordances of cloud computing may yield new learning scenarios where ubiquity, advanced online tools and collaboration come together to create innovative ways of education.

The adoption of cloud computing in education has come hand in hand with an important research effort. There are a great number of research contributions that approach the topic from different perspectives trying to take advantage of the benefits of cloud computing in the educative realm considering the needs of institutions, educators or technical staff. However, these heterogeneous contributions have not yet been the subject of a systematic review that assesses the real advantages and limitations of cloud in education and provides a coherent picture of the current research challenges in this domain. Such a review could help practitioners and educational institutions to identify specific opportunities and benefits of using the cloud in their domain, and allow Technolo-

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[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

gy-Enhanced Learning (TEL) researchers to focus their efforts on solving the main issues and challenges.

Therefore, the objective of this paper is to conduct a state-of-the-art review of cloud computing in education following the methodology proposed in [7] to determine the advantages, risks and current research challenges of cloud computing for education. The systematic review will also illustrate these issues with relevant learning scenarios found across the literature.

This paper is thus structured as follows. Section 2 will give some background information on cloud computing, characteristics, services and deployment models. Section 3 will explain the methodology followed to carry out this review. The main benefits and affordances of cloud computing for education will be detailed in Section 4, as well as its related risks in Section 5. The main research challenges will be identified in Section 6. Discussion will follow in Section 7, and the main conclusions and future lines of work will be laid out in Section 8.

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 [8].

Cloud computing services are typically categorized into three main types [1], [9]: At the lowest level of abstraction, we can find *Infrastructure as a Service* (IaaS), which provides the consumer with processing, storage, networking, and other computing resources on demand, for instance, under the abstraction of a Virtual Machine. An example of IaaS is Amazon EC2[8], which provides VMs on demand. Eucalyptus[9] and OpenStack[10] are both examples of open source middleware that organizations can use to build their own infrastructures to provide IaaS services. The following level, *Platform as a Service* (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. Examples of PaaS are Google App Engine[11] and Microsoft Windows Azure. Finally, *Softtware as a Service* (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. Examples of SaaS software are Google Docs[12], Salesforce.com, or Dropbox.

All these services can be offered by a cloud provider according to different deployment models [1]. If the cloud infrastructure is provisioned for the use by the general public, we find *public clouds*. 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 cloud infrastructure is a combination of two or more different cloud infrastructures (public, private, or community).

The analysed literature uses a mix of these services and deployments, showing diverse proposals where cloud computing can benefit education, which will be the subject of our following study.

3 Review Methodology

The methodological guidelines suggested by Kitchenham [7] for literature reviews in software engineering were followed to conduct this state-of-the-art. In this way, a literature search was performed in December 2012, using the following databases: 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"). Only primary studies contained in journals (as well as articles in press), conference proceedings, books and white papers were included. Besides, additional studies from specific conferences on cloud computing and education (WCLOUD[13] and LTEC[14]) were also included. A total of 326 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 derived from other more relevant study by the same 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, 108 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 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 related studies emerged from the analysed bibliography. This set of 79 new studies followed a new iteration of quality assessment. There were 16 additional studies that passed the second quality assessment and went through another data extraction process.

In summary, 405 studies were considered for this review, of which 124 passed the selection process. Fig. 1 summarizes some bibliometric data of the 124 studies of

[8] http://aws.amazon.com/ec2/
[9] http://www.eucalyptus.com
[10] http://www.openstack.org
[11] https://appengine.google.com
[12] http://docs.google.com
[13] http://ceur-ws.org/Vol-945/
[14] http://ltec.usal.es

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 synthesis of the 124 results was performed. 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. However, not all these studies have been cited in the present state-of-the-art because other studies supported more strongly the presented arguments.

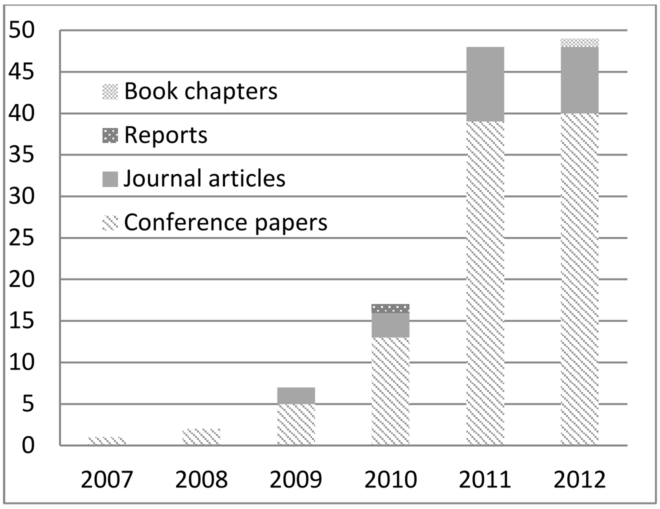

Fig. 1. Bibliometric data of the 124 selected studies organized by year, number and type of publication.

4 Benefits and Affordances of Cloud Computing for Education

Learners, practitioners, educational institutions, and the IT personnel can benefit from using cloud computing. Following, advantages and affordances have been categorized, summarizing and emerging from the aspects found in the reviewed literature.

4.1 A wealth of online applications to support education

Cloud computing provides both learners and 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 [10].

There are many cloud applications (such as Google Apps, Dropbox, etc.) that are already extensively employed in education because they are common-place, uncomplicated 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. For instance, generic software, such as Google Apps for Education[15] or Microsoft Office 365[16], offers online productivity applications like word processing, spreadsheets and presentations that can be used in class [11], [12], [2]. 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 [13]. Both practitioners and students can use a Google or Microsoft email account branded with the institution's domain name [14], use YouTube channels to stream video lectures [11], or they can be provided with storage from SkyDrive[17] or Dropbox [15]. An interesting work [16] describes a chemistry lab in which students share their results using Dropbox. Students can access and analyse 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 their homes, 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 educations can be found in [17] where they use video on demand (VoD) services to deliver lectures, and in [18], using virtual worlds to explore an art museum.

The cloud also provides applications conceived originally for domains different from education that can be very useful in specific learning contexts. An example is the cloud-based Customer Relationship Management (CRM) system [19] that manages the relationship between the institution and the students allowing high availability and security. Other examples are a cloud application for civil engineering (AutoCAD WS[18]) used for educational purposes [20], or scientific and statistical applications like Scilab[19] and R[20] employed to teach maths and statistics [5]. Also, in [21] they report students employing cloud services generally used for professional programming like GitHub[21] and SourceForge[22] as a configuration manager for the source code of the students' projects.

Additionally, there are cloud applications that have been conceived for education either with a generic or a specific purpose. Cloud-based VLEs belong to the former category. VLE providers such as Blackboard[23] or Lessons LAMS[24] are now offering outsourced cloud-based e-learning services, benefiting students from improved and personalized functionalities. Along the same lines, [22] shows 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

[15] http://www.google.com/apps/intl/es/edu/
[16] http://my.liveatedu.com
[17] https://skydrive.live.com
[18] http://www.autocadws.com
[19] http://www.scilab-enterprises.com/products/scilab/
[20] http://www.r-project.org
[21] https://github.com
[22] http://sourceforge.net/
[23] https://www.coursesites.com
[24] http://lessonlams.com

course. On the other hand, cloud software for specific educational purposes is shown in [23], where students use NetLab+[25], 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 [24], or specific applications to watch and learn from art works [25].

A significant number of the reviewed contributions takes advantage of the built-in collaboration and communication capabilities present in some of these cloud applications. This is particularly useful for certain pedagogies such as constructivism or collaborative learning [26]. For instance, [26] 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 favour of using them for teaching in the future. Similar results were found in [27], where Google Docs was used 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 [28], proposing different cloud collaboration tools for teachers. In other contributions [29], [30], [31], [32], [33], [12], 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.

It may be argued that the built-in collaboration features of certain cloud tools are not native characteristics of cloud computing itself, since traditional, non-cloud web applications may also have these collaboration features. However, cloud computing adds certain characteristics such as scalability, accessibility and high availability that enhance the user's collaborative experience.

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 be mixed using their APIs into completely customized learning environments suited to the needs and preferences of students, facilitating the creation of Personal Learning Environments (PLE) [34]. For example, in [35] learners 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 is set up in [34] 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 of cloud-based PLEs can be found in [36] for lifelong learning; [37], for primary and junior high school, and [38] for science education, where different environmetns are implemented using tools like Google Docs, Youtube, Facebook, instant messaging, to-do lists or mind-mapping tools.

Besides, the availability and rapid on-demand provision and release of configurable resources offered by cloud infrastructures empower teachers to create 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 preparation to set up 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 [39]. The preconfigured environment can also be saved or packaged for later use, for next courses, or for other colleagues [40]. 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 [41]. This way, an important amount of time can be employed to the practice at hand rather than concerning about configuration issues [40]. Since the IT staff does not have to maintain computers, but just re-instantiate preconfigured images, there is also less management overhead. These technicians can focus on critical business tasks instead of maintenance duties [42].

Virtual desktop environments with preconfigured software are generally used across different educational disciplines. For instance, [43] presents 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 flexibile configurations of virtual desktops are [44], which demonstrates the generic use of virtual desktops using Ulteo[26] technology or [10], where primary school students use their own virtual desktops with installed office software. A virtual desktop prototype is also shown in [45], 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. In [5], the authors present 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, a contribution proposes [46] to use virtual databases created on Microsoft Windows Azure to

[25] http://www.netdevgroup.com/products/

[26] https://www.ulteo.com/home/en/ovdi/openvirtualdesktop/

learn computer science or AWS VMs to learn on operating systems. As another example, [47] reports 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, [48] shows the case of a private cloud shared by four universities that enables the provision of VMs with preconfigured images created on demand by students for courses on computer science. In a different contribution, StarHPC[27] is built in [40], a package developed by the Massachusetts Institute of Technology (MIT). It contains stand-alone VMs with the required development software that can be reused among 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 completely tailored to the requirements of the assignment or lab. For example, [49] proposes a computer network lab on a private cloud where students can configure servers, firewalls and switches to learn about computer networks. Clear advantages were reported such as less lab administration costs, higher lab accessibility and the availability of an open lab learning environment where students can experiment with fewer constraints.

Many other studies report programming and networking laboratories built flexibly with cloud tools. For example, [50] configure virtual clusters based on CloudStack[28] for parallel programming assignments, and in [41] they build an IP telephony lab with call servers on a private cloud. Two different works [51], [52] show scenarios where computer networks based on virtualization are used for networking courses. It should be noted that these assignments require very specific hardware, software and/or configuration processes, as well as the usage of cloud techniques facilitates their set-up and replication.

Alternatively, computer science teachers can select public PaaS environments like Google App Engine or Windows Azure for their assignments due to the convenience of employing a ready-to-use development environment. Some examples of assignments employing PaaS tools are [12] and [53], that describe a programming course where students use Google App Engine to develop applications and servlets. In [39], the authors evaluate the performance of students using three different development environments with an increasing degree of underlying abstraction in an overlay networks course. Here, they compare using a traditional environment (Eclipse, Tomcat,..) 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 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.

[27] http://star.mit.edu/hpc/
[28] http://cloudstack.apache.org

4.3 Support for mobile learning

The cloud can help to overcome the current limitations in mobile learning regarding the limited processing and storage capabilities of the devices [54], 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 [55]. 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 [56]. 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 QoS and they can access them anywhere any time they need them [55], provided they have network connectivity.

Some studies show the capabilities of the cloud to support m-learning services. In [18], the authors 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 [22]. 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) [57] to obtain the translation provided by an Optical Character Recognition (OCR) 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 [58], cloud-based mobile applications that provide students with tools for enquiry-based learning in the science field [59] 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 [60].

4.4 Computing-intensive support for teaching, learning and evaluation

Sometimes students require computing power for certain educative applications that are difficult or impossible to run on their own computers or the institution's servers [61]. If the student must design an experiment, run some computational task related to the experiment, observe the result, and then possibly re-design 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 constrains imposed by the educational setting .

For instance, in [5] they provide 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 scalability. In a different scenario [61], 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 virtual machine in the cloud where other projects will be queued and rendered in a batch system. In another contribution, a compute-demanding service to deliver recommendations of learning resources is implemented on an Amazon EC2 infratructure [62]. They used the Hadoop[29] framework to distribute computing workload among different instances in a cloud infrastructure.

The affordances of cloud computing are also shown in [20] to support computing-intensive learning scenarios. Here, civil engineering students use AutoCAD WS, a commercial CAD application built on the Amazon EC2 and S3[30] cloud that copes with the demanding computing requirements of CAD processing. In addition, [18] portrays a virtual world application based on Open Wonderland[31] 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 [3]. The cloud computing model can also be useful to speed up learning analytics processes. This possibility has been studied in [63], where cloud computing is used to offer computation and storage for a Hadoop framework that analyzes students' log data to extract their sessions and 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, assigment deadlines, before exams, publishing of grades…) [64]. In a traditional approach, if the demand exceeds the allotted computing resources, the service is seriously affected [65]. The scalability features of cloud computing enables the adaptation of resources to the changing conditions in order to meet the expected Quality of Service (QoS) requirements without the need of over-provisioning computing infrastructure [17]. 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 [66].

The reviewed literature shows some scenarios of scalabiltiy to provide sustained QoS for larger number of users. In the example mentioned earlier [18], students use virtual worlds for e-learning. This soft real-time application is 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. In [17], the authors 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 demand to allocate enough computing resources to ensure the necessary capacity and QoS. C-MADAR is proposed in [67], 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 [68] 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, [69] describes the implementation of a mobile application for the communication between teacher and students where the server-side application was developed with Google App Engine that natively supports features to scale applications according to the increased number of users. A mobile application for students is presented in [70] whose scalable database is stored in the cloud using Amazon SimpleDB[32]. Also, [71] proposes 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[33] 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 underutilized resources, these are owned by the cloud provider, and the institution is only charged per

[29] http:// hadoop.apache.org
[30] http://aws.amazon.com/s3/
[31] http://openwonderland.org
[32] http://aws.amazon.com/simpledb/
[33] http://code.google.com/p/appscale/

use [72], [73]. Other significant sources of savings stem from maintenance, telecommunication services, power consumption to run hardware, cooling [2], [40], fire suppression systems or space. Besides, educational organizations are freed from the tasks of operating the infrastructure [47], [2], thus reducing the cost of technical human resources in the institution.

In public clouds, all these expenses are shifted to the cloud provider [2], who absorbs the costs and spreads them over a long period of time and many other cloud computing customers [74], 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 education domain, savings can be even more noticeable [74].

Even if institutions do not 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 [75], centralizing under a common infrastructure resources otherwise spread over often underutilized servers, even re-using existing hardware [76], and also achieving a more efficient power consumption [15], [51]. Since virtual resources are scalable, the already deployed infrastructure will be more efficiently used [77], because resources can be provisioned when needed and deprovisioned in idle periods.

Other cost saving measures using cloud computing can come from sharing resources from the cloud among different institutions [78] 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, like [79], 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 can be found in [40]. Here, the institution hired AWS EC2 Virtual Machines to host their solution StarHPC. The course lasted two weeks and 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 underutilized 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"[34] (VCL), developed by North Carolina State University to build private clouds with virtual laboratories such as VMs with MATLAB or virtual clusters of specific nodes for a High Performance Computing (HPC) experiment. Vouk et al. [77] claim that VCL achieves cost-efectiveness 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.

Another study [17] uses a cloud-based Video on Demand (VoD) service to deliver lectures to learners based on a prepared time-table. 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, [80] estimates that the savings of moving to the cloud 5 generic computers with virtual desktops over a period of 3 years were $11,900. Different scenarios are described in [4], 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 [15].

4.7 Cost savings in software

Institutions may also obtain cost savings by using the diverse cloud applications that can be used 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 [2]. 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 [81], [82]. This charging model also allows institutions to make use of tools for a short period of time or experimentally [70]. Students too can benefit from cost savings not needing to acquire licenses of certain products because they are available in the cloud for free [29] or pay for them only when required.

Cost savings in software derived from the use of the cloud can be illustrated with the case of the University of Wesminster (UK) [2], where they started using Google Mail and Google Apps as productivity and collaboration applications in 2008. The authors state 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

[34] https://vcl.ncsu.edu

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 [24]. In a different contribution, students of civil engineering use the free-of-charge product, AutoCAD WS, instead of purchasing and installing licenses locally [20].

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. limited flavors of Google App Engine) or at a certain price (e.g., Amazon SimpleDB for cloud database services). For example, in [70], they developed an m-learning application to deliver question packs to students using Amazon SimpleDB. They take advantage of the cloud price model and scalabiliy 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, as discussed next. They should be taken into account before the adoption and during the use of cloud computing in educational settings.

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 [3]. Some contributions [74] 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 servers unkwown to a thief, 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 [4].

However, sensitive data stored in the cloud (for example, students' records or accounts) [80] can be maliciously or accidentally leaked or commercialized and, together with identity theft, may lead to cyberbullying or abuse [83]. Besides, some works [4] 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 [84]. Besides, users of cloud computing in education may not be aware of its potential risks [15], [85]. A study conducted among schools in Tallin (Estonia) [86] 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 [4], [6], [87], [83]: Sensitive and business information could be stored in private clouds (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 analyse how data is protected in transmission and storage to prevent security attacks such as packet sniffing or traffic analysis [83]. Audits and certifications of security should be performed to increase the user's confidence [66]. Even though cloud providers have secure infrastructures [2], institutions should consider using specialized security services like encryption or single sign on capabilities [4]. Contracting more than one cloud provider is recommended [6] 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 [72].

Some private cloud architectures proposed for educational institutions have been designed with these security challenges in mind. For example, Snow Leopard [88], 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 DoS attacks. Other relevant architecture for educational private clouds, VCL [77], 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, [83] 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 to legislation [6] but, otherwise, ad-hoc agreements could be reached to prevent such problems [83].

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 [83]. 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 at 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 switch virtual machines, data, or services from one cloud to another [6]. This problem, known as vendor lock-in, is one of the barriers to the general adoption of cloud computing [89]. For instance, since cloud providers 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 programming APIs and runtime environments cannot 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, [83] 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 in [83], 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 [42], 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. However, 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) [4]. In this regard, work is underway in different organizations and initiatives such as the Distributed Management Task Force[35] (DMTF) to ensure VM portability across multiple virtualization platforms, DeltaCloud[36] to define REST-based APIs to manage IaaS, or the NIST[37] to establish standardized data formats to enable cloud interoperability at different tiers.

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, [40] notes 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 fiber optic or leased lines are needed [90], there will be users, e.g. those in deprived areas, without sufficient bandwith, which hinders the adoption of cloud computing [91]. 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. For instance, it could take several minutes to launch a VM in the cloud [47]. 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 [64], taking into account education-specific behavioural patterns (seasons, enrollment periods, etc).

An additional related risk is the reliability of cloud-based educational services [72]. Although reliability is one of the most salient features the cloud offers compared to traditional IT infrastructures [89], relevant providers, such as Google or Amazon, have had some episodes of failures interrupting their services [2]. 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 enrolment or grade publications and may impact students' learning and the timely delivery of assignments [72].

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. The following hypothetical scenario is presented in [24], illustrating this risk. A school district with 10 traditional classrooms and 50 computers in each classroom would require the purchase of 500 software licenses which are underutilized. 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 [24]. 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 [89]. 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 [89], and indeed it is the preferred path followed in many of the reviewed studies. In fact, open source solutions such as R and Scilab [5], Cinelerra [61] or Open Wonderland [18] have been employed in some studies thus avoiding this risk.

6 RESEARCH ISSUES

The analysis of the literature resulted in the identification

[35] http://dmtf.org/standards/cloud/
[36] http://deltacloud.apache.org
[37] http://www.nist.gov/itl/cloud/sajacc.cfm

TABLE 1
PRIVATE CLOUDS FOR EDUCATIONAL INSTITUTIONS

	VCL [76], [77]	**CloudIA [47]**	**UNED [51]**	**[48]**	**[92]**	**NATO Education and Training Network [88]**
Deployment model	Private cloud	Hybrid cloud	Private cloud	Community cloud	Private cloud	Community cloud
Education sector/level	Mainly University. Also K-12	University	University	University	University	Military
Level of abstraction	IaaS	IaaS/PaaS/SaaS	IaaS	IaaS	IaaS/PaaS	IaaS/PaaS/SaaS
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 with Open Nebula	Creation of customized on-demand VMs even with software packages.	Creation of customized on-demand VMs with Eucalyptus	Creation of customized on-demand VMs.
PaaS services	None	Servlet Container Platform	None	None	AppScale	Components to deliver simulations
SaaS services	None	Collaborative VLE Storage as a Service (OwnCloud) (*)	None	None	It is proposed to migrate the institution's applications	Simulations, email, webservers, collaborative workspaces
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. Overflow to public clouds in progress	Manually creating more VMs. Automated scalability based on service requests (*)	Manually creating more VMs. Natively at PaaS level	Manually creating more VMs.
Availability	Automatic failover of VMs	VMs can be replicated in the private and the AWS cloud.	VMs can be replicated in the private cloud (and in the AWS cloud in progress)	Automatic failover of VMs Backup data center (*)	Load balancing among application components	Not described
Security	Authentication VM isolation through OS level firewall or VLANs.	Authentication and SSO using Shibboleth. Federation of educational institutions at SaaS level	Not described	Custom built IDS, IPS, server security management. (*)	Not described	Multi-level security (clearance management). Encryption. Authentication
Development maturity	Implemented	Implemented	Partially implemented	Implemented	Test platform	Specifications and testbeds

(*) As reported in private conversation with the authors

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.

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 [47], [48], [51]. Therefore, one of the main challenges is the deployment of cloud infrastructures for educational purposes. Table 1 summarizes the main research efforts and their essential characteristics.

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 [47], whereas public cloud services are restricted to situations when the private cloud capacity is overflown [51] 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 [47]. Another reason may be that institution's managers perceive that it is more secure to control their own resources in a private cloud [6]. Nevertheless, it has been observed in our study that educational institutions use mainly private or hybrid clouds at the infrastructure level, but instead 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. It is also noticeable that most of the contributions about this topic deal with deployments in the university domain. As a caution, note that these conclusions can be biased because many selected studies come from university research.

One of the earliest and most significant contributions is VCL [76], [77]. VCL is an implemented cloud-based architecture 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 [24]. The VCL source code is currently managed by the Apache

Software Foundation[38], 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 [47], is a project to build a private cloud to create on-demand computing resources, and run e-learning applications and on-demand 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 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 pre-configured 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 public clouds, VMs can be initiated both in the private and in the Amazon cloud.

Other relevant contribution presented in Table 1 is the private cloud built by the Spanish Distance University (UNED) [51] using 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 [48]. Here, a VLE is used that connects to IaaS services to allow students to reserve VMs with pre-loaded software for computer science subjects. In [92], a test platform using Eucalyputs is built for the Capital Normal University of Beijing, upon which they install AppScale at PaaS level for the institution's applications. Finally, the NATO Education and Training Network is presented in [88] to support simulations and training exercises of military services on a community cloud for headquarters, nations and partners.

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 can be developed on cloud infrastructures, 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 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 schedule 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.

Some proprietary solutions have been employed for users to request computing resources on an educative private cloud. For instance, [48] describes 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 [77], 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 [47], 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 APIs developed to reserve VMs for a lab once students access the institution's VLE [48].

Not only system administrators but also unskilled users such as students or teachers should be able to schedule or reserve these resources easily [93]. Accordingly, usability tests on early interface prototypes have been run on VCL to ensure its suitability for practitioners in K-12 education [93], but it seems that further usability evaluation of these mechanisms should be required.

The reservation and scheduling mechanisms should

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

also take into account that the underlying cloud infrastructure may have limited computing resources, as it is the case in private clouds [94]. 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. A genetic algorithm is developed in [94] that optimizes the schedule of cloud resources under the eventual existence of conflicting requests by teachers.

As future work, these systems could include other control mechanisms to ensure that departments do not reserve and consume all the resources available, or implement control policies to limit maximum costs. 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

Traditional e-learning systems are weak on scalability at the infrastructure level [66], 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 mechanims for (virtually) infinite scalability, but dynamic scalability is still a challenge in cloud computing [9]. 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, the provision of new resources needs to be fast. Automatic scalability is also desirable in scenarios where resources are needed quickly to respond to a rapid 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 [64]. 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 decreseases 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. However, new algorithms especially tailored for rapid and unexpected changing conditions are needed, so that they can be applied to 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 in [18] where application metrics are monitored to automatically scale the cloud infranstructure. Here, a maximum number of logged avatars is 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 bandwith, 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. 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, trigger the creation of more VMs at IaaS level.

At SaaS level, different computing resources can be automatically scaled in educational settings ranging from the number of videostreaming servers broadcasting lectures or the QoS of a streamed video, to chats or virtual worlds for students. At PaaS level, resources such as databases or threads in cloud-based programming environments can also be scaled on demand. Rules can be complex considering events at different cloud layers. They should also take into account other parameters, sometimes education-specific parameters, such as school timetables, enrollment or examination periods, or others, like the overall cost. Rules should also be defined to scale resources from a private to a public cloud of viceversa.

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 for educational purposes 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 [40] or IP telephony laboratories [41] 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 constrains such as group formation or time for completion, but also the computational resources needed, as part of what is now called educational orchestration [95] by many researchers. Traditionally, these scripts were to be run (i.e. activities enforced, computational resources provided) within a monolithic VLE, but recent research [96] 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 constrains, the infrastructure could be reserved and scaled up or down to meet QoS requirements, which could also be defined in the script. Researchers here need to find out ways for teachers to express their needs from the infrastructure, and means to satisfy them using the cloud.

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 [34]. 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 a [39] points out, sometimes pre-configured cloud environments do not result in a students' performance improvement. It should be checked that educators are comfortable with the environment and, whether 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 issue 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. 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 in [97] and [98]. 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 differente approach, [99] proposes 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 loosely coupled model, the presentation layer providing interfaces to students could be implemented in a different cloud.

Nevertheless, further work can be done on this issue. Most of the presented contributions are theoretical, designs are not complete, and interfaces and interoperability mechanisms have not been specificed 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 [57]. For instance, the e-learning platform U-SEA [22] is composed of a Moodle-based VLE on a private Eucalyptus infrastructure. Some Moodle features were adapted so that different 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 applications. Instead, [69] and [70] 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 in [57] 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 of the cloud.

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 [60]. 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

Educational practitioners have been using SaaS to support their educational settings even before the term cloud computing was coined. A variety of applications offered from web servers that replace traditional installed software have became commonplace because they are free, constantly maintained by providers, and they require just a browser on the client side, while computation and storage is on the provider's side. Many applications also come with appealing collaboration features. The wide diversity of providers offering similar functionalities (consider, for example, the myriad of wiki or blog providers) has allowed educators to design many TEL innovative scenarios. A significant number of the contributions included in this review (e.g., [11], [16], [30], [32]) report using the cloud mostly as SaaS tools.

However, this is not everything cloud computing can offer practitioners. In many cases, practitioners may need software for their students to use in assignments or practices. Applications can be pre-installed in VMs and used by students on demand (e.g., [5], [20]). In other situations, especially in Computer Science disciplines, IaaS itself comes in handy, for instance, when practitioners flexibly design laboratories of different complexity on clusters of VMs to provide students with networking or programming environments (e.g., [23], [39], [40], [41]). Since it is very likely that practitioners will keep using the cloud to enrich their labs with tools and virtual infrastructures, it is very important that the reservation, configuration and deployment of these computing resources are easy and intuitive enough for a non-technical practitioner to deal with it [77].

Moreover, learners benefit from cloud computing by using applications suited to their learning needs and objectives. In some cases, they even become creators of their own PLE, mashing-up tools and combining learning contents of their choice (e.g., [35], [34], [37]). 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 scenario, 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 (deciding which data is sent to what cloud service), or uniform QoS management across clouds.

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 virtual unlimited scalability and availability affordances offered. Larger cost savings can be achieved if automatic scalability measures are implemented, though this requires research on defining educational metrics that drive the automatic scalability, and that are also cost-constrained. Besides, interoperability issues will have to be solved to avoid vendor lock-in. However, management, security and scalability of services are more difficult to handle if several clouds are involved. On the other hand, private clouds can hold more sensitive information and host applications where a tighter control of the underlying virtual infrastructure is required, but a previous sizing study and resource sharing policies are required in private clouds. In this deployment model, interoperability is also an issue to ensure efficient communication among clouds in different premises or campuses and to offload services to public clouds, in which case, the definition of rules and policies to decide what to deliver to public clouds becomes a new concern.

Another relevant actor making TEL happen, the IT staff, will take advantage with cloud computing of a platform to render all kind of scalable services. It will be especially beneficial for computer-supported learning tasks that can be parallelized (e.g., simulations, rendering [61], or data crunching [62]) or that are compute-intensive per se (e.g., virtual worlds [18], calculations [5], or CAD processing [20]). Virtualization will help to minimize the operation time, making it possible for technical personnel to focus on core tasks instead of configuration issues.

Computer Science seems a discipline where the use of cloud computing can be especially helpful. Cloud computing can be applied in subjects that require assignments that use computer laboratories, such as operating systems, computer networks, or programming. Higher education and, above all, University, can benefit the most from the use of complex computational learning environments provided from the cloud, because students usually have the technical skills required to use them effectively. Future research should provide improved cloud infrastructures and services that not only involve efficiency and cost savings for educational institutions, but also prove their efficacy to improve learning.

This study has analyzed the most relevant contributions on the use of cloud computing in the educational domain. The cloud offers some characteristics that can be advantageous for education, such as scalability, flexibility and cost reduction. Besides, in the last years, this topic is having growing importance in research as the great and increasing number of publications shows. However, to the best of our knowledge, no previous reviews have been found summarizing the specific benefits, risks, and most promising research challenges of cloud computing for education.

Among the benefits for education, we can find the great number of existing online applications that can be used, both generic and education-specific, especially those with built-in collaborative features. Cloud computing enables practitioners to create complex computing learning environments on demand tailored to the learning objectives. Besides, as the number of mobile devices increases, the cloud is an adequate platform for m-learning, providing scalable ubiquitous services, high storage capacity and enabling device synchronization. Cloud computing is notably a suitable paradigm for e-learning services that require high computing processing (e.g., virtual worlds, simulations or data crunching) or whose demand varies (e.g., MOOCs, VLEs or enrollment systems). Although the driving force of adopting cloud computing in institutions may be cost savings, interesting cases were analyzed where cloud computing can support and enhance the teaching and learning processes. Learners can use engaging cloud applications and tools as end-users to improve their learning. Practitioners can be end-users of these applications as well, and besides they have the possibility of creating powerful and flexible computing environments tailored to the learning objectives.

Nevertheless, risks and limitations have been identified. The cloud raises concern about privacy and security, especially with sensitive students' data, provider lock-in, performance issues and underdeveloped licensing models. Together with the idenfitied risks, measures to mitigate them proposed across the literature were also shown.

One of the important outcomes of this work has been to detect the most prominent research challenges that can be advanced by researchers in this field. They can be summarized as follows:

Cloud infrastructures for educational institutions: The design of suitable cloud platforms that flexibly support educational services is required. Many of the other research issues must also be addressed to propose attractive infrastructures.

Easy schedule and reservation of computing resources: Usable middleware must be designed so that educators and learners can reserve and schedule cloud resources for assignments and laboratories.

Automatic scalability mechanisms: 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 investigated, supported and augmented by specific educational metrics.

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. The creation, integration, and deployment of cloud learning environments is a massive research challenge. Thorough evaluation on the effect of these new environments on students and teachers' performance has to be carried out as well.

Interoperability of educational clouds: Brokerage among different educational clouds or similar mechanisms to achieve interoperability at service level.

Architectures to support m-learning: 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.

All in all, although the main advantages of cloud computing in education are strongly supported by the reviewed literature, we believe that research on this topic is still immature. Many of the reviewed contributions are theoretical, shallow, or mainly introductory and lack of proper evaluation, thus making cloud computing an attractive field of study for TEL researchers.

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