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RESEARCH ARTICLE

Simulation-based mathematical learning for higher education students from heterogeneous backgrounds

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ABSTRACT
This paper explores the use of simulation-based training for mathematical learning in undergraduate and graduate mathematics, science, and engineering courses. Simulation-based training offers the advantages of active learning and inquiry-based learning techniques. Furthermore, it provides extensive flexibility, ranging from user-level usage of simulations to the modification or creation of new possibilities by the student, thus engaging different cognitive levels to achieve the learning objectives. This is particularly interesting in groups consisting of students from diverse backgrounds and levels, due to factors such as their international origin or varying prior education, especially in interdisciplinary Master's degree programmes. Additionally, in online or blended environments (which have become widespread during the last years), simulation-based learning has the advantage of granting students a certain degree of autonomy, which can, to some extent, compensate for the absence of the instructor's physical presence.

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Higher education; mathematical e-learning; simulation-based education; cognitive levels; online education

1. Introduction

Internet-related technologies, in particular the World Wide Web, are changing the way higher education is delivered to the new generations of students in the science, technology, engineering and mathematics area of knowledge (Juan et al., 2008; Uhomoibhi et al., 2019). These technologies allow students who are physically located in different regions of the world to follow the same course online. Thus, education is becoming a global activity: a course provided by an instructor at Boston University can easily be joined by students located in China, Brazil, or Germany. Students worldwide feel nowadays that this global experience might benefit their careers, and thus the number of students registering in such global courses has been increasingly growing during the last decade.

This is particularly the case in master's (MSc) and doctoral (PhD) programmes within scientific or technological areas (Owens & Hite, 2020). Despite the clear benefits that this worldwide educational experience can bring to students, institutions, and instructors (Allan et al., 2019; Juan et al., 2011), it also raises new challenges (Cherner et al., 2019; Goodman, 2020). In particular, the fact that a course might be joined by students from different countries and cultures, each of them with its own education system, increases the heterogeneity of the public which an instructor has to address (Carli et al., 2019). Along with the globalisation effect described above, there is another dimension that is contributing to the increase in the heterogeneity of backgrounds in all university courses: the increasing interest in acquiring an interdisciplinary education. In fact, today's job market is increasingly dynamic, which means that most workers need to be trained in different and interdisciplinary skills that must be continuously updated as new technologies appear (Eberhard et al., 2017). This holds for undergraduate courses, but even more so for MSc or PhD courses, as the students have completed different previous degrees before accessing these levels. Thus, it is not surprising today to have an MSc course on civil engineering, computer programming, operations management, or data analytics in which one can find international students with very different backgrounds ranging from mathematics to industrial engineering, computer science, or management degrees. For this reason, this paper focuses mainly on MSc and PhD courses, given the heterogeneity of academic backgrounds these students may have, although most of the content applies to undergraduate courses as well.

Hence, both the globalisation effect and the need for interdisciplinary training with content that requires continuous updating, make the instructor's task even more challenging: instructors of MSc and PhD courses have now to provide advanced training to students who show a high degree of heterogeneity

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regarding their academic and cultural backgrounds, as well as their professional orientation. Gender is also a source of heterogeneity that goes beyond the scope of this paper but is analysed in (Ooms et al., 2019). Furthermore, the second quarter of 2020 saw the onset of the COVID-19 pandemic in most countries, leading to a generalised lockdown situation and the immediate need for universities to switch to online or blended teaching. This is leading to a very different landscape in university education, including some consequences such as a greater internationalisation of students.

This paper analyses the existing literature on the use of simulation in online and blended higher education, discusses how simulation can efficiently be used in these environments, and proposes a series of best practices regarding the use of simulation-based tools for higher education. These contributions are based on our own experiences at five different universities both in Europe and the USA.

The paper is structured as follows: Section 2 describes the university educational landscape prior to the COVID-19 pandemic, paying attention to the penetration level of online education, the identified hindrances that online education poses, the internationalisation of tertiary education, and new trends towards a more heterogeneous education. Section 3 gives a short review of simulation-based education, identified as a powerful tool in online and blended environments in studies involving mathematical content, highlighting the capability of simulation-based learning to adapt to students from different backgrounds. A series of recommendations are given in Section 4 to favour the successful transition to online education. Finally, some final remarks are given in Section 5.

2. Old and new higher education landscape

In this section, we will record some relevant circumstances and features of higher education before 2020, which conform the background against the new educational landscape triggered by the COVID-19 pandemic.

2.1. On-campus vs. online education

Some years ago, it was possible to distinguish between traditional on-campus universities and pure online universities. Today, however, in most advanced countries it has become almost impossible to find on-campus universities that do not make intensive use of online platforms (learning management systems) such as Moodle (https://moodle.org/) or Blackboard (https://www.blackboard.com). Likewise, with the globalisation of higher education, it is becoming increasingly difficult to find on-campus universities that do not offer some of their courses and degrees in an online or blended format. There are examples of pure online and traditional on-campus universities that make intensive use of learning management systems. Some examples of pure online universities are Universitat Oberta de Catalunya in Spain (www.uoc.edu) or Universidade Aberta in Portugal (www.univ-ab.pt). Others, however, are traditional "on campus" universities that are quickly adopting a blended-learning model, like the Autonomous University of Barcelona in Spain (www.uab.cat), the University College Dublin in Ireland, or the Euncet Business School (www.euncet.es), also in Spain. Notice the diversity of degrees with mathematics-related courses are included in these universities, ranging from MSc and PhD programmes in computational engineering, applied mathematics, data science, to MSc/PhD programmes in logistics & supply chain management, aeronautical management, network and information technologies, or business administration.

As far as STEM subjects are concerned, (MSc programmes on Engineering and Technology, Computer Science and Information Technology, Natural Sciences and Mathematics), the number of online or blended master's degrees (vs. on-campus) was still relatively low before the COVID-19 pandemic, averaging 12% in USA and 6% in Europe in 2019, and now reaching 21% in USA and 9% in Europe in 2023 (see Figure 1).

Currently, there is a range of course types that can be distinguished:

- Fully on-campus: These courses are conducted entirely face-to-face, although it is common for these courses to be supplemented by online resources and virtual learning platforms.
- Blended (fixed format): Some activities are conducted face-to-face for all students, while other activities are online for everyone.
- Blended (flexible format): Students have the option to choose whether to attend certain sessions or activities in person or online.
- Fully online: These courses are conducted entirely through digital platforms, with no on-campus meetings or activities.

Also, within all online or blended courses, activities can be synchronous (in real-time, with instructor and students present simultaneously) or asynchronous (with students accessing and completing activities at their own pace). Virtual learning environments are valuable resources to take into account, even though they are not the only means for online teaching.

It should be noted that the blended flexible format became widespread during the COVID-19 pandemic. This approach emerged as a practical solution to accommodate the diverse needs and preferences of students during these challenging times. Learners were provided with the choice to attend sessions either

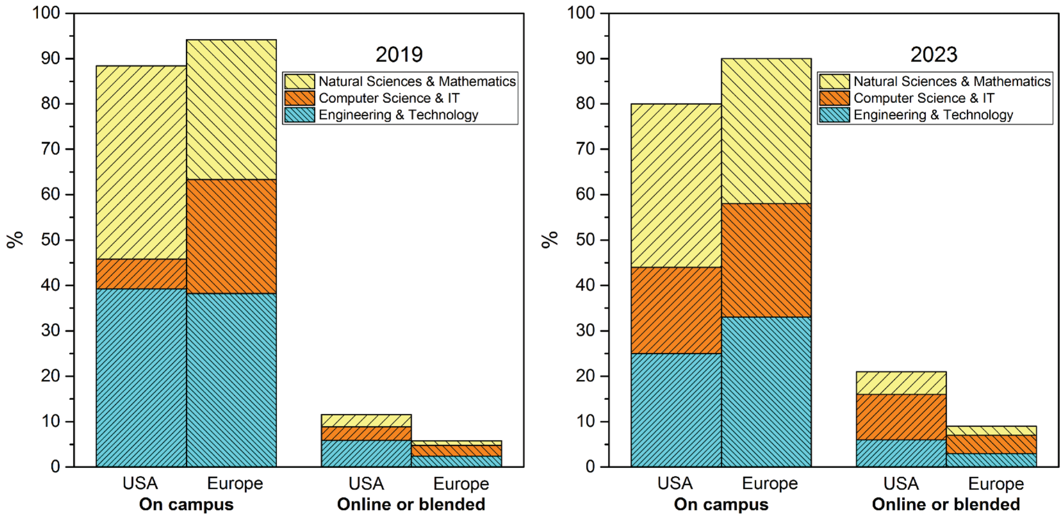

Figure 1. Number of on-campus, online and blended STEM Master's degrees in USA and Europe in 2019 and in 2023. (source: https://www.mastersportal.com/).

on-campus or online, or students were divided into on-campus and online groups, in order to reduce the number of students present on the premises. The pandemic has acted as a catalyst for the adoption of this approach, but it continues to grow in popularity even after the pandemic has subsided, as it combines the benefits of traditional classroom instruction with digital learning opportunities.

Below are some examples of online programmes, offered by traditionally on-campus universities, which are related to data analytics, engineering, business or computer science, and include mathematical content. Most of these programmes are also offered "on campus" for local students:

- Online Master of Science in Analytics, offered by Georgia Tech (www.gatech.edu). It can be completed in one or two years, and it includes courses on statistics, operations research, computing, and business.
- Applied Mathematics Master's Degree, offered by Columbia University (https://engineering.columbia.edu). It is an interdisciplinary master's programme including courses on algorithms, industrial economics, operations research, optimisation, probability and statistics, stochastic models, etc.
- Online Master of Science in Applied Business Analytics offered by Boston University, Metropolitan College (https://www.bu.edu/met/). The programme includes courses on foundations of business analytics, marketing analytics, web analytics, and enterprise risk analytics.
- Master of Science in Applied and Computational Mathematics, offered by Johns Hopkins University (https://ep.jhu.edu). This master's programme includes courses on information technology and computation, OR, probability and statistics, and simulation & modelling.
- Online Master of Information and Data Science, offered by University of California, Berkeley (https://www.ischool.berkeley.edu). This master's programme includes courses on data engineering, data mining, data visualisation, statistical analysis, and machine learning.
- Online Master in Computational Engineering and Mathematics, jointly offered by Rovira & Virgili University and the Universitat Oberta de Catalunya (www.uoc.edu). It includes courses on computer simulation, metaheuristic optimisation, operations research, big data, and multivariate statistics.

2.2. Digital skills in potential students

Online education is in need of several requisites to be used effectively. Even in countries with enough technology levels, the usage of online education resources is hindered by the lack of digital skills in some parts of the population. According to the *Digital Economy and Society Index* (DESI) report, published annually by the European Commission (https://digital-strategy.ec.europa.eu/en/library/), only 58% of the European population possesses at least basic software skills, which are needed to take advantage of the available online education possibilities. The figure goes up if we consider particular demographic groups. "80% of young individuals (16–24), 84% of individuals with formal education, 68% of employed or self-employed people, and 87% of students have at least basic digital skills", but it still leaves behind a significant group who cannot benefit from online education opportunities.

This suggests the importance of strengthening basic digital skills in school and academic curricula.

Figure 2 shows the evolution of the percentage of European citizens who have taken an online course,

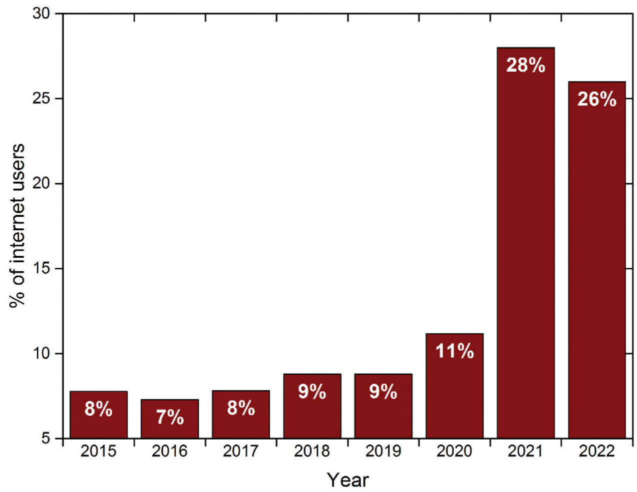

Figure 2. Percentage of EU citizens who have taken an online course. Source: DESI report (up to 2020) and Eurostat (2021 and 2022).

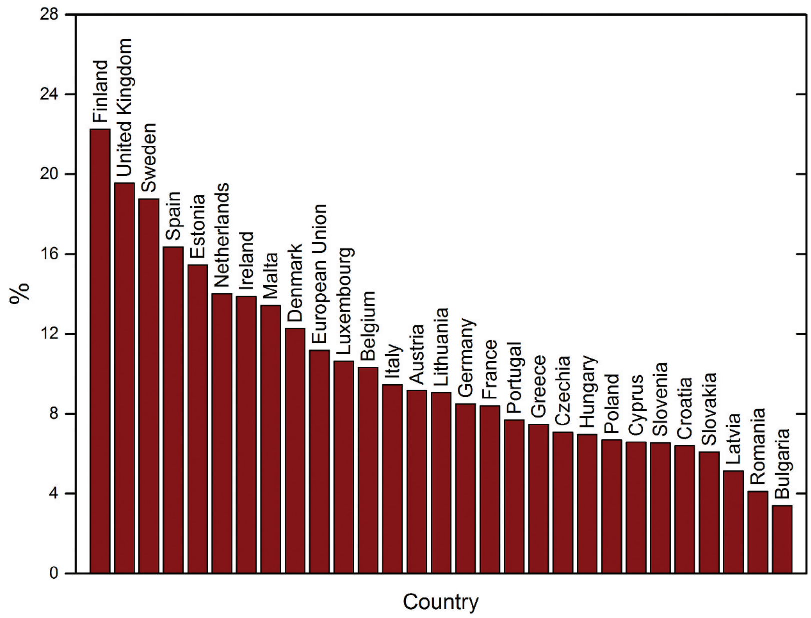

Figure 3. Percentage of EU citizens who have taken an online course by country (source: DESI report).

being just below 9% in 2019, and rising dramatically to 28% after the pandemic, as shown in the graph. Splitting by country in 2020 (Figure 3), the highest scoring countries in Europe are Finland (where 22% of people have taken an online course) and the UK (20%), followed by Sweden and Spain, but there are also countries scoring as low as 4%.

2.3. Heterogeneous backgrounds of students

In the following, the acronym STEM will be used to refer to knowledge areas related to science, technology, engineering and mathematics within Higher Education. In the context of this paper, we will focus on undergraduate or graduate courses that incorporate the study and usage of mathematics.

In the past, before globalisation and the interdisciplinary effects appeared, students in most MSc and PhD degrees were relatively homogeneous in academic backgrounds, cultural characteristics, age, programming capabilities, and communication skills. This homogeneity has practically disappeared in most advanced programmes, and now the situation is noticeably different. Interdisciplinary aspects have been incorporated in many curricula, especially in STEM courses. In the past, a typical student was completing a BSc degree in a particular discipline (e.g., Mathematics), and then a MSc and even a PhD in the same discipline. Nowadays, however, it is quite frequent that a student completes a BSc degree in Mathematics (for instance), an MSc degree in Computer Science, and a PhD in Business Analytics. This is partly favoured by a growth in the number of available programmes, and also in the requirements of a dynamic (ever-changing) job market, where new professional needs appear as new technologies and social concerns emerge (Finch et al., 2016).

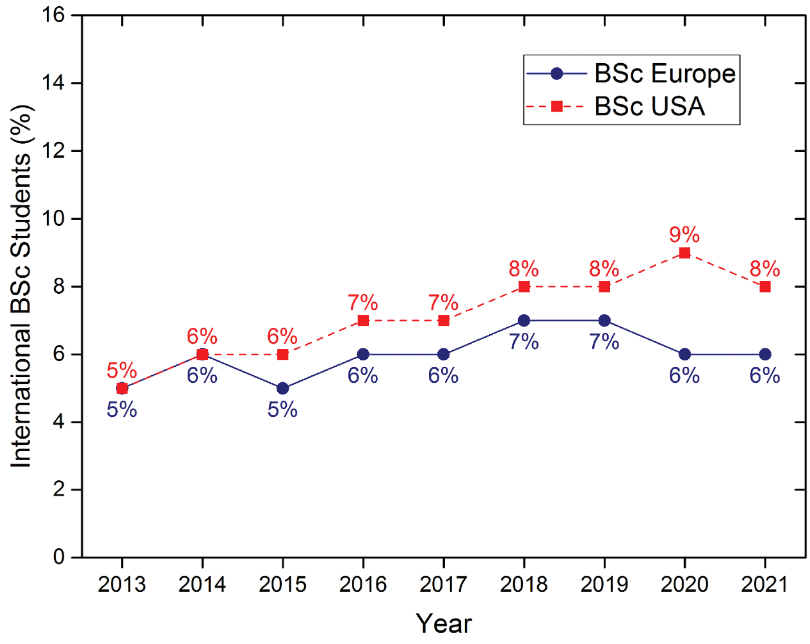

Figure 4. Time evolution of international BSc students in USA and Europe (source: Eurostat and IPEDS).

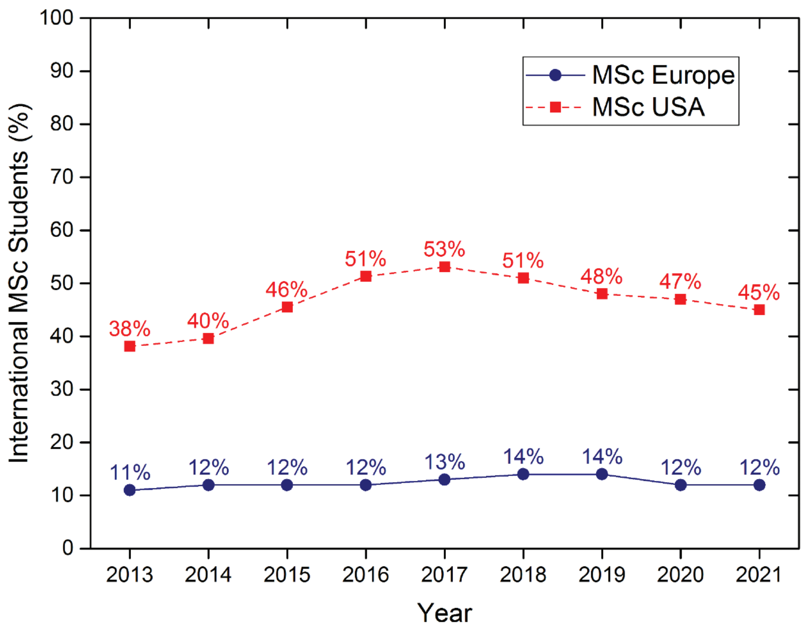

Figure 5. Time evolution of international MSc students in USA and Europe (source: Eurostat and IPEDS).

Figures 4, 5 , and 6 show the evolution of the percentage of international students in Europe and the United States of America from 2013 to 2021 based on data from Eurostat (Statistical Office of the European Union) and IPEDS (U.S. Department of Education, National Center for Education Statistics, Integrated Postsecondary Education Data System). The number of international BSc students suggests a slow but steady trend. Also we have to bear in mind that a percentage point increase means an important number of students in absolute figures. So, even though the figures are nearly constant in most cases, and slightly decreasing after the pandemic, the number of international students is fairly high for PhD and Master's degrees. Especially in the USA, the figures are near 50% for these levels.

A relevant consequence of a larger internationalisation level is the increasing heterogeneity of students, both in online and face-to-face training. Mathematical content is taught in different ways in aspects stressed or the levels of depth attained. Also, students that have been trained in dissimilar cultural environments may present their own learning structures and styles. This may pose an enormous challenge to educators when designing courses with common learning objectives.

We propose to analyse of the use of simulation to take care of this, as simulation-based learning activities can be tackled in different and flexible ways.

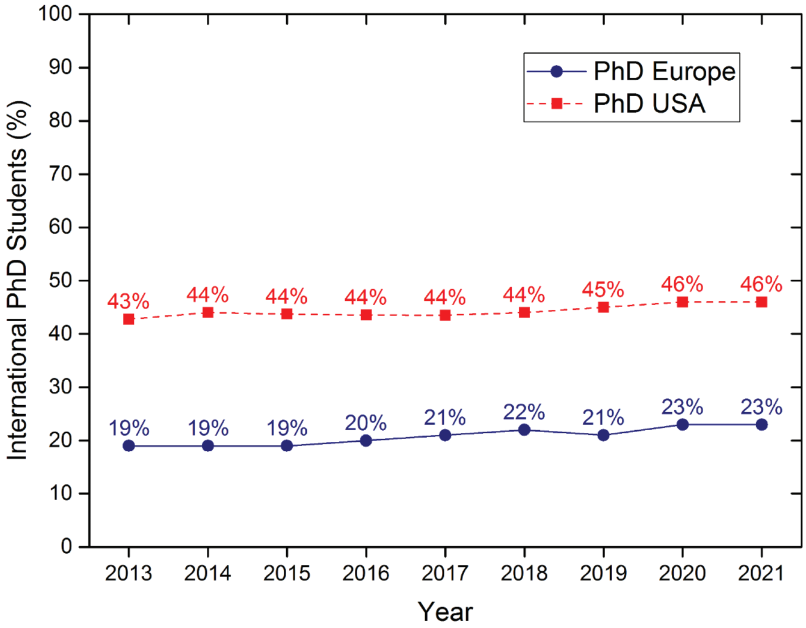

Figure 6. Time evolution of international PhD students in USA and Europe (source: Eurostat and IPEDS).

One more source of heterogeneity in students is the increase of online courses, as mentioned in 2.1. Many of these students follow the usual pathway of university study, while others may be involved in lifelong learning initiatives, now available to more people than ever before. This brings considerable diversity of students to online courses. Some students may be working professionals who already have a significant amount of experience while others may be more traditional students who will be looking for their first job after graduation.

3. A review on simulation-based education

In this section, we provide a selection of publications that focus on simulation-based education in the Internet age, especially in subjects with mathematical content. These publications deal with the topic of simulation from an educational point of view. The review also provides a contextual framework for the remaining sections of the paper and illustrates how other academics and practitioners have considered similar issues.

3.1. *Usage of simulation for educational purposes*

Chang et al. (2009) develop a flexible web-based simulation game called SIMPLE (Simulations of Production and Logistics Environment), which can be adapted to various teaching stages and decision-science courses such as production management, inventory control, and horizontal cooperation in a supply chain. The purpose of this environment was to increase the effectiveness of the teaching, specifically in relation to emerging production paradigms. Vlachopoulos and Makri (2017) later support this purpose and show that simulations actually have a very positive impact on the learning goals of courses offered by higher education institutions. Recently, Lohmann et al. (2019) show that online business simulations provide an authentic team-based learning environment. Tobail et al. (2011) discuss the importance of web-based simulation technologies as an educational tool in teaching a supply chain management course. The authors develop an interactive web-based supply chain management game that students at different locations can play with and share their experiences. Authors believe that web-based capabilities encourage collaboration and group work among students. Beckem and Watkins (2012) provide empirical evidence of the benefits associated with employing a "digital-media simulation" to immerse students in highly-realistic settings with interactive video characters. Their results show the ability of simulations to both increase students' engagement and promote deeper learning. Snider and Balakrishnan (2013) discuss the usage of web-based simulations to facilitate experiential learning of operations management concepts. The authors also provide recommendations on how to use simulation software. These recommendations are based on their long-term experience employing simulation in education. They include evidence that the majority of students desired more experiential learning opportunities. The study also shows that the benefit of simulation on students' learning experience might vary depending on the type of course, i.e., undergraduate or graduate. Lovelace et al. (2016) explore the utility of web-based simulations and find they are an effective way to develop critical thinking skills. In order to do so, the authors test two longer strategy-focused simulations and one shorter leadership-and-teamwork-focused one. Also, simulation-based training has been identified as a significant learning experience, as discussed in Campos et al. (2020), where the authors provide a comprehensive review of simulation-based education in both online and face-to-face formats, also referring to several other relevant studies in this area.

Simulation-based education is particularly well suited for online or blended learning environments, as it allows a hands-off teaching approach, where the instructor provides room for students to explore and draw conclusions on their own without physical presence.

Considering that any online environment needs to provide a means for the instructor and student to communicate, the instructor serves as a guide or facilitator, supporting students through the learning activities rather than directly providing all the information. Thus, students can engage with the simulation-based interface and ask for the instructor's feedback when needed. This is especially suitable for synchronous online education, where instructors and students can communicate in real-time. Asynchronous activities, on the other hand, provide students with more flexibility to experiment freely, while they can still request the instructor's assistance even if responses are not immediate.

3.2. Contributions of simulation to the learning process

Simulation-based education provides an adequate environment for experiential learning that, as indicated by Chang et al. (2009) can be adapted to different teaching stages. When dealing with heterogeneous backgrounds, these aspects become especially appealing, allowing each student to adapt the learning process to their own needs without interfering with the course dynamics.

In order to understand how simulation-based education can be advantageous in the context of heterogeneous students, let us review Bloom's taxonomy, which was first introduced in the seminal work Bloom et al. (1956). Bloom's Taxonomy is a hierarchical structure that classifies cognitive levels involved in learning, ranging from basic to advanced levels. In recent decades, this concept has been and continues to be further elaborated by revised versions of Bloom's taxonomy and other alternatives such as the taxonomies of Marzano, SOLO, Fink or Shulman, as reviewed in Irvine (2017). Also, Lau et al. (2018) make use of revised Bloom's taxonomy to assess and improve the acquisition of learning objectives in university courses.

By engaging learners across multiple levels of cognition, simulation-based education can promote deeper understanding and mastery of complex concepts and skills.

Specifically, at lower cognitive levels simulation can act as a black box, the student being unaware of its internal workings, and only interacting with it in an input-output manner (see Figure 7) This can be enough to allow the student to gauge how the variation of different parameters affects the results, and thus gain a deeper understanding of the situation.

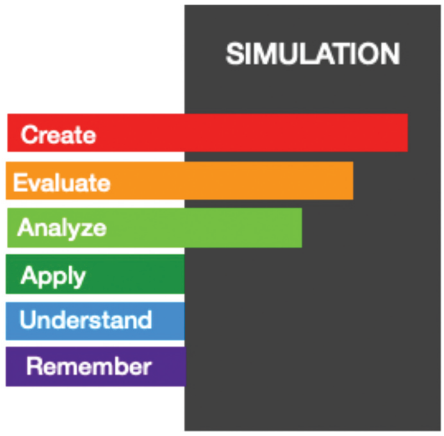

Figure 7. Interaction of Bloom's cognitive levels with simulations.

However, as students cognition levels increase, students can engage with the internal operation of the simulation to greater and greater extents. To facilitate this, it is beneficial that the functioning of the simulation is accessible and does not require advanced programming knowledge. With some understanding of the coding and the support of the instructor, some of the students may want to introduce changes allowing them to simulate other situations slightly different from the original one. This is particularly useful with a heterogeneous set of students, as optimal learning takes place when activities are appropriately levelled for the student. If the level of the activity is too low, it may lead to boredom and disengagement, whereas if the level is too high, the student may struggle to do the activity which can bring frustration and also disengagement. The use of simulation in this way allows enough flexibility to promote learning in students with different kinds of abilities, backgrounds, and learning styles.

For undergraduate students, more likely to operate at lower-level cognitive levels, simulation can be useful to get started with complex concepts, as it will allow them to visualise and experiment with the subject matter, whether face-to-face or online, before going into more technical detail.

On the other hand, MSc students will come from different academic and geographic backgrounds, and consequently, they may or may not have skills in computer science and programming. Actually, it is increasingly frequent to have in the same MSc course students with high mathematical knowledge or analytic capacities and students with a lower maths background but excellent programming or technological skills. Therefore, simulation can be presented to students either as a ready-to-use interface or as a computer code written in some of these programming languages. Those students with some knowledge of computer science may want to inspect how the code works to a greater or lesser extent (in addition to making use of the simulation), whereas other students may prefer to simply use the interface without going into more depth.

For students coming from Computer Science, but also for those coming from Engineering or Mathematics backgrounds, some degree of understanding of the simulation would be desirable. Going one step further, if possible, the students themselves may learn how to build the simulation, or how to modify or adapt it to different situations or mathematical models. Nevertheless, those students not proficient enough to achieve this can equally benefit from the usage of the simulation interface.

Therefore, in order to address different levels of students' knowledge, several levels of depth can be established when working with simulation, namely:

(1) Experiment with ready-made simulations,
(2) Understand the algorithm and/or computer code,
(3) Modify the code to address other problems or models,
(4) Build their own simulations.

It is worth noting how simulation models developed by students can contribute to their learning process. This is a special case of simulation-based learning, with multiple benefits for the students, as they can experiment with their own simulation models with a deeper understanding of the mechanics behind the observed results. This is especially interesting for students coming from different training backgrounds and nationalities, a situation that requires introducing some flexibility in the learning environment. Fonseca et al. (2009) introduce different examples of universities that make use of the Internet to deliver simulation courses online. The authors discuss several course designs as well as some of the main difficulties associated with these courses. They propose an intensive use of computer simulation software, collaborative e-learning practices, and professional-oriented approaches as strategies to increase students motivation for simulation topics. Grasas et al. (2013) describe an online course named Modeling and Simulation in Operations Research and its components that is taught at the Universitat Oberta de Catalunya, which is a fully online university offering degrees in several fields including Computer Engineering, Business Administration and Management, and Information and Communication Sciences. Pidd et al. (2010) describe an inter-university initiative in the UK to teach Operational Research (OR) to PhD students. Students highlighted the benefits that this initiative brought to them in terms of expanding their network of contacts. They also valued the inclusion of case studies and practical applications of the OR methods, including simulation.

Balci et al. (2013) acknowledge the growing number of undergraduate and graduate-level online courses and provide guidelines for developing a high-quality online simulation course.

3.3. Challenges of simulation-based learning

Teaching subjects with mathematical content becomes especially challenging in the online format due to the need for graphical support when interacting with students (Goodman, 2020), which has raised the interest in simulation and serious games as a way to promote students' interaction with a realistic training environment. Also, the pandemic has unveiled several challenges at both educational and assessment levels.

Simulation-based learning may also present some disadvantages. The most common limitations mentioned in the literature are that specific training might be needed by teachers and students, and the risk of unstructured knowledge if the students do not receive appropriate guidance. This might be the reason for some reluctance to its implementation as a learning method, aggravated by the difficulty of assessing its specific contribution to the learning process (de la Torre et al. 2021; Hauge & Riedel, 2012; Keskitalo, 2011; Ören et al. 2017).

Nevertheless, adequate scaffolding may help reduce this risk (Chernikova et al., 2020). Scaffolding is a teaching strategy where the instructor guides students by providing cues or suggestions when they encounter difficulties. This helps learners build upon their existing knowledge and connect new ideas with those they already understand. Instructors can therefore tailor their assistance to the individual needs of each student, gradually withdrawing their support as the learners become more proficient and confident in their abilities. When applied to simulation-based learning, scaffolding may provide students with the necessary support to navigate complex concepts and connect ideas in the intended way to reach their learning objectives. Scaffolding is also possible in online environments, as long as there is a means of communication between the instructor and learners.

Despite these limitations, simulation (both as a tool and as a study subject) has shown an outstanding evolution (maybe even a revolution) during the last decades. Figure 8 presents the number of articles that include the terms "simulation education" and "analytics education" over the last decade in Google Scholar. From 2010 to 2019, the number of articles concerning "analytics education" increased from 9 to 158. As for "simulation education", there were about 1,100 articles that include this term in 2019. The field of online education also shows a dramatic increase over the last decade.

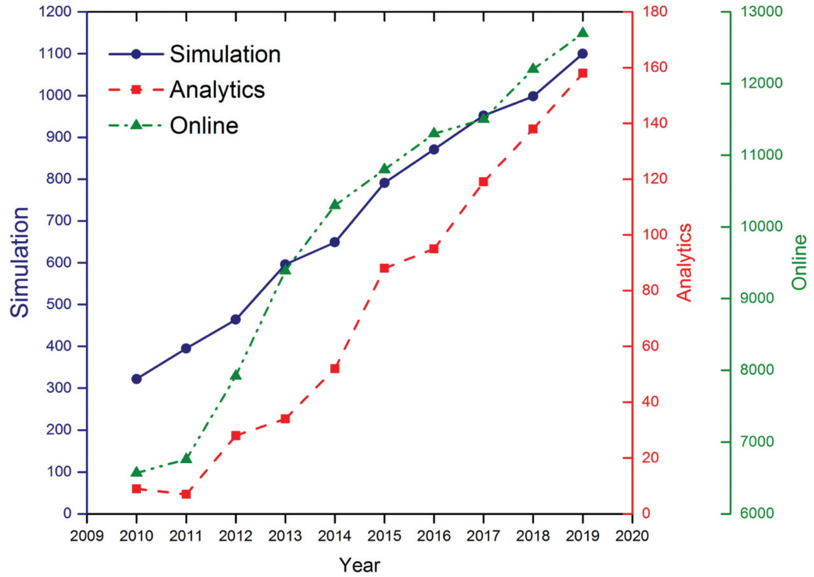

Figure 8. Evolution of the number of articles that include the terms "online education", "analytics education" and "simulation education" on Google Scholar.

4. Best practices for simulation-based mathematical education

Online or blended learning environments present a number of challenges that need to be addressed (Jaradat & Ajlouni, 2021; Simamora, 2020), namely limited interaction, limited attention span, distractions, feelings of isolation or poor time management. Also, the lack of digital skills (see 2.2) can be a serious drawback.

In order to minimise the issues generated by the rapid shift to online or blended environments in Higher Education, we have deployed a series of strategies and best practices. When combined, these strategies have shown to be an effective tool for enhancing the quality of online and blended-learning courses involving simulation and analytics concepts. These best practices are described next:

- Use easy-to-learn simulation software (Rakić et al., 2020): similarly, the use of modern simulation software, such as Simio, Arena, Anylogic, Simul8, ExtendSim, Witness, Flexim, etc., can allow for rapid deployment and testing of models. This, in turn, can facilitate that the student focuses on relevant modelling and simulation concepts instead of investing time in learning more complex environments.
- Use easy-to-learn scientific programming languages (Ozgur et al., 2017): for courses with students that might not have a solid background in computer science, the use of modern and easy-to-learn programming languages such as Python or Julia should reduce the learning curve when compared with other more traditional languages such as C/C++ or even Java.
- Employ easy-to-learn modelling and optimisation software (Tan et al., 2019): modelling and optimisation software has also evolved quite quickly during the last years, and nowadays one can rely on open and easy-to-use tools such as Open Solver for Excel, or on academic versions of commercial solvers such as Cplex, Gurobi, LINGO, etc.
- Use easy-to-learn statistical and data analysis environments (Jena, 2019; McNamara, 2018): open statistical software such as R can be a powerful tool but also one with a steeper learning curve when compared to commercial software such as SPSS, Minitab, Tableau, or SAS. Still, the use of graphical interfaces such as R Commander can make the tool more appealing for the general user.
- Employ easy-to-learn maths environments (Caridade et al., 2015), such as Matlab, Maple, Mathematica, Mathcad, etc., which are also extremely powerful.
- Promote the use of online collaborative tools (Koranteng et al., 2020), such as Overleaf for Latex or Google Docs for traditional word processor files.
- Promote teamwork while completing homework activities (Dellatola et al., 2020; Hesse et al., 2015), especially for activities regarding complex problem solving, where interdisciplinary teams, analytic thinking, and discussion of ideas might be necessary elements in obtaining an efficient solution.
- Recommend appropriate videos (Moghavvemi et al., 2018): nowadays, YouTube has become a very valuable source of excellent videos for self-learning, including videos on many programming languages, statistical and simulation software, mathematical concepts, modelling and

solving using optimisation software, real-life applications of simulation and analytics in different fields, etc.

- Consider embedding videos into the lecture notes that describe the use of specific software or that guide the students on the completion of a task in a step-by-step manner.

Although these practices are also suitable for a face-to-face learning environment, they are especially relevant to address some of the challenges of online education. Shared learning environments help reduce isolation feelings. Easy-to-use material takes care of students with poor digital skills, while not hindering the rest. Also, this easy use allows the learner to make small but continuous progress, thus keeping them motivated. In addition, simulation allows the student to actively engage with software, helping reduce distractions and increasing the attention span.

The use of these resources allow for the creation of a wide variety of simulations. Given the simple learning curve of the software, students can rapidly advance through the cognitive levels mentioned in Section 3.2, even those without a strong background in computer science. This approach allows for a more comprehensive utilisation of simulation-based learning, encouraging students to not only use the simulation as a black box but also interact at a higher level, modifying or creating their own simulations.

5. Conclusions

Learning and comprehending mathematical concepts is always challenging, particularly at the university level for both graduate and undergraduate students enrolled in mathematically-oriented courses such as sciences, engineering, business, and more. Simulation-based education offers a potential solution to this challenge by providing an active learning method that enables students to experiment with the software, leading to a more tangible understanding of abstract concepts through visualisation and interaction. Students who engage in simulation-based activities can better connect abstract mathematical concepts to real-world applications, which is essential for subjects like engineering, business, and science. This learning method also fosters critical thinking and problem-solving skills.

The COVID-19 pandemic and the internet have changed the way universities approach education, as well as the traits that define the typical student. In the first place, the transition from traditional face-to-face courses to online or blended courses has been boosted, creating a variety of graduate and undergraduate courses available to students around the world. On the other hand, there is an increasing heterogeneity among student populations due to factors such as internationalisation and interdisciplinarity of higher education courses. The very existence of online courses also contributes to this heterogeneity, as a broader range of students can be reached.

These circumstances make simulation-based education particularly useful for learning mathematical concepts. For online or blended courses, a hands-off approach allows students to explore and draw conclusions in a flexible way, even without the physical presence of an instructor, although interacting with them to the extent necessary. Furthermore, for students from heterogeneous backgrounds, whether online or face-to-face, simulation-based learning can accommodate varying levels of depth, according to their previous skills or the knowledge area they come from. Namely, at a more basic level, students can use the simulation as a black box, in an input-output manner, varying parameters and observing the results. Further, at higher cognitive levels and for those who have adequate skills, students can modify the code to simulate different situations, or they can even create their own simulations.

Different types of software have been identified as particularly suitable for this approach, as they are easy to learn and do not require a very high level of knowledge. These features fit the purpose as some students will require more time and experiments than others, without impacting the overall course progress, so that all students can eventually reach the learning objectives.

We consider different ways to extend this work: *(i)* to analyse the medium-term effect of the pandemic on the shift of higher education towards an online mode; *(ii)* in particular, how simulation is being increasingly used to enrich online training environments, especially those with international and heterogeneous students; and *(iii)* the different speeds at which different countries and universities are embracing these methodologies and technologies.

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