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Engineering Education 5.0: Continuously Evolving Engineering Education*

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This study presents the concept of "Engineering Education 5.0", a future educational paradigm linked to a vision of engineering education characterized by a need for continuous evolution, as a consequence of a challenging quest for a more sustainable and caring future. In a way, this forthcoming evolution emanates from very relevant advances in engineering education achieved in the last decades and from a view inspired by the Sustainable Development Goals, but beyond the Agenda 2030 in terms of temporal framework. Besides, it outruns current emergent approaches and innovation trends, linked to supporting the expansion and application of Industry 4.0 technologies and principles. Engineering Education 5.0 transcends the development and application of technology and enters the realm of ethics and humanism, as key aspects of for a new generation of engineers. Ideally, engineers educated in this novel educational paradigm should be capable of leading and mentoring the approach to technological singularity, which has been defined as a future point in time at which technological growth becomes uncontrollable and irreversible leading to unpredictable impact on human civilization, while ensuring human rights and focusing on the construction of a more sustainable and equitable global society.

Keywords: Engineering Education; Industry 4.0; Engineering Education 5.0; Agenda 2030; Sustainable Development Goals

1. Introduction

Engineering has helped to advance technology for solving societal problems for more than six millennia, if we consider the more technological definition of engineering, although modern engineering emanates from combining science and technology [1]. Since the dawn of history, engineers have helped to construct civilizations and to reshape society, through technological developments progressively bringing well-being and enhanced capabilities to interact with the environment. Pioneering efforts in civil, hydraulic and naval engineering led to the construction of the Egyptian pyramids, to the raise of the lighthouse of Alexandria, to the irrigation systems of ancient cities in India and Egypt, to the first diversion dams in rivers in China and to the domination of the seas and the establishment of commerce routes and cultural development throughout Asia, Europe and Africa.

Progressively, technology education evolved, usually connected to arts and crafts and following a trainer-trainee scheme. However it was not until the second half of the 18th Century that modern engineering education was established, as a consequence of the first industrial revolution, with the foundation of pioneering technical universities. Nowadays, most studies explain the evolution of modern engineering, as the result of four industrial revolutions [2]: the first linked to the invention of steam machines and their application to transport and production; the second resulting from advances in chemistry and electricity, involving also the discovery of new energy sources and transport methods; the third associated to the transition from analogue to digital electronics, often referred to as "digital revolution"; and the ongoing fourth, based on interconnected smart technologies, commonly denominated "Industry 4.0" [3, 4]. Accordingly, it is possible to establish a direct connection between industrial revolutions and derived transformations in modern engineering education, as further explained in Section 2. For example, the concept of "Engineering Education 4.0" has been recently proposed [5], as a reformulation of engineering education to facilitate the uptake and spread of technologies linked to the Industry 4.0 paradigm. Interestingly, the technologies (artificial intelligence, internet of things, additive manufacturing, virtual reality, master-slave schemes for production machines, digital twins. . .), from which the concept Industry 4.0 emanates, have been already researched and applied at technical universities for at least two decades now.

In any case, it is clear that technological revolutions are taking place at an increasingly rapid pace and some authors predict the coming advent of technological singularity, as "*a point at which technological growth becomes uncontrollable and irreversible, resulting in unforeseeable changes to mankind*" [6]. With or without technological singularity, it is clear that our global society is already

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facing relevant challenges and exceptional threats, as the Agenda 2030 and the Sustainable Development Goals put forward [7, 8]. At the same time, concepts such as "Society 5.0", "*a human-centred society that balances economic advancement with the resolution of social problems by a system that highly integrates cyberspace and physical space*" [9] and "Life 3.0", "*human life in the age of artificial intelligence*" [10] have been lately proposed. These concepts are clearly connected to a coming future, in which scientist and engineers will have to develop and mentor important technological advances with a fundamental impact on society and human relationships, as we understand them. We may well be initiating a technological revolution with much deeper implications than those arising from Industry 4.0. In consequence, engineering education should also evolve towards an "Engineering Education 5.0" in the era of Society 5.0.

To the author's best knowledge, the concept of Engineering Education 5.0 is presented for the first time in this study. Such future educational paradigm is linked to a vision of engineering education characterized by a need for continuous evolution in a challenging quest for a sustainable, caring and fascinating future. In a way, this forthcoming evolution emanates from very relevant advances in engineering education achieved in the last decades and from a view of inspired by the Sustainable Development Goals, but beyond the Agenda 2030 in terms of temporal framework. Besides, it goes beyond current emergent approaches linked to supporting the expansion and application of Industry 4.0 technologies and principles. Such application-oriented models are in some cases referred to as Engineering Education 4.0, as previously mentioned [4], and prove interesting. However, the concept of Engineering Education 5.0 is clearly different, as it transcends the development and application of technology and enters the realm of ethics and humanism, as key aspects of for a new generation of engineers. Engineers educated in this novel educational paradigm should be capable of leading and mentoring the approach to technological singularity, while ensuring human rights and focusing on the construction of a more sustainable and equitable global society.

In the following section, a historical development of modern industrial revolutions and related educational engineering transformations is presented, in order to better contextualize Engineering Education 5.0. Afterwards, the most relevant characteristics of the new educational model are proposed, together with possible topics and structures for versatile engineering programmes aimed at promoting dynamism, flexibility, holistic training and personalization, among other relevant aspects. Specific suggestions for implementation, according to modern professional roles of engineers, are also discussed. Finally, very recent and ongoing engineering transformations, which share many of the key features of Engineering Education 5.0, are analysed and connected with a roadmap proposal for effective implementation.

2. Modern Engineering: Industrial and Educational Revolutions

The brief overview of modern industrial revolutions and of related engineering education transformations presented below shows a clear pattern: whenever a scientific-technological revolution takes place, a transformation in engineering education follows, as pattern previously described by other authors [11]. Furthermore, such scientific-technological revolutions take place at an increasingly more rapid pace, as authors predicting the approach to singularity have already highlighted [5]. In addition, the lag between industrial revolutions and engineering education transformative responses decreases, as modern academic institutions see change as an opportunity to learn and improve and, fortunately, are no longer static "temples" of knowledge.

2.1 Overview of Modern Engineering Education Transformations

2.1.1 Engineering Education 1.0

The technological advances of the first industrial revolution made a fundamental impact on production, transport and infrastructures, hence completely changing societies. These revolutions importantly impacted military technology as well. In fact the corps of engineers were fundamental, both in the US Independence War and in the Napoleonic Wars. A new imperialism wave, linked to the expansion of Western powers and Japan in the second half of the 19th Century, was possible due to the technologies from the first industrial revolution (and also complemented by those from the second industrial revolution).

Anyhow, modern engineering education was established as a consequence of the first industrial revolution and in connection with the growing demand of engineers, both as civil servants for designing and developing infrastructures, as mentors of mechanization and production and as technicians for innovating and applying military technology. The foundation of *École Polytechnique*, which gathered some of the most relevant mathematicians and experts in mechanics of that age, supposed a new beginning for engineering education [12]. Even if some technical universities had been already operating for some decades in Prague, Berlin, Istanbul and Budapest, the international impact of *Polytechnique's* model for the systematization of modern engineering education is outstanding. The traditional trainer-trainee model for disseminating technological mastery in workshops was replaced by a systematic knowledge-based approach taught at universities. The "polytechnic" (from *πολύς* "many" and *τέχνη* "art") model rapidly spread, first through continental Europe and then through the US and Britain, and supported the training of technology experts or polytechnic engineers, with a wide background in science and versed in most civil, mechanical, and military technologies [13].

2.1.2 Engineering Education 2.0

The second modern engineering education evolution lasted approximately from 1880 to 1940 and progressed in accordance with the pace established by the second industrial revolution. It was connected to a continuous search for a balance between theoretical and practical aspects of engineering; to a view of technology, arts and crafts as a global unity; to the establishment of chemical and electrical engineering, as independent disciplines; and to the incorporation of the new concepts to engineering education, inspired from the heyday of European physics. The Arts and Crafts movement (around 1880 to 1920) started in Britain and spread throughout Europe and North America, influencing several industries. It emerged as a reaction to the lack of charm and creativity of mass-produced objects and to the alienation of workers, consequence of the technologies and processes from the first industrial revolution [14]. Some connections may be found with contemporary trends, trying to bring together mass-production and mass-personalization.

These decades saw also the flourishment of the Bauhaus, founded in 1919 and lasting until 1933, which reformulated industrial design and architecture and profoundly impacted education, focusing on a holistic conception of professional training, through which trainees acquired technical, social, human and artistic education. Being an art school and focusing on the creation of a "Gesamtkunstwerk" or total work of art, it transcended art and importantly interwove with engineering, whose education helped to transform by influencing many important technical schools, both in Europe and in the US [15].

2.1.3 Engineering Education 3.0

Between the 1950s and 1980s, following the digital revolution, the first programmes in some contemporary engineering disciplines started to appear, including: biomedical engineering, electronics, computer engineering, robotics and mechatronics, to mention some examples of disciplines from engineering, which are now fundamental. This emergence of new topics and programmes reshaped importantly the landscape of engineering and, in turn, motivated the rise of international accreditation agencies, as a way of bringing order to the vast number of programmes arising those decades. This supported the settlement and promotion of common principles for the new disciplines and, at the same time, contributed to the increasing internationalization of programmes and engineering students.

In terms of internationalization, the foundation of the ERASMUS programme in 1987 [16] was a result of this period of changes and contributed to the transition towards more modern student-centred paradigms. Other important advances, performed along these decades, were linked to the incorporation of information technologies to education and management, to laboratory and research practice, to a transition from analogue to digital records and to the implantation of computer-supported quality management systems.

2.1.4 Engineering Education 4.0

The turn of the XXI Century brought a relevant change of focus to higher education in general and to engineering education in particular. The Bologna Declaration (1999) and the consequent process, aimed at the implementation of the European Area of Higher Education [17], contributed to a change of focus from a traditional teacher-centred scheme to a learner-centred approach. Classical master lessons started to be complemented and replaced by more active methodologies. Alongside, since the late 1990s, the CDIO (conceive-design-implement-operate) concept was formulated and deployed in 2000 with the foundation of the International CDIO Initiative. The founders, MIT, KTH, Chalmers and Linköping universities, rapidly established a truly global community, counting now with more than 120 universities worldwide, working towards a common framework for supporting a transition to learner-centred methodologies, in many aspects synergizing with the Bologna process. CDIO relies on active learning methods for helping students acquire technical knowledge, apply it to the engineering of complete products, processes and systems and, hence, develop their professional skills [18].

Through the establishment of the EHEA and the CDIO actions (standards, conferences for sharing good practices, support to new partners) engineering education was reformulated once again. Many other teaching learning experiences, including international makers and design competitions, summer schools, "hackathons", progressively contributed to the valorization of student-centred activities and to the dissemination of CDIO-related methods among all engineering disciplines. Interesting experiences include: the "CAN-SAT" satellite construction challenges (since 1998), the "FIRST Lego League" robotics competitions (since 1998), the "Solar Decathlon" competitions focused on efficient buildings (since 2002), the James Dyson Design Competitions (since 2007) and the "UBORA" medical device design schools (since 2017), to cite some examples. Apart from these, it is necessary to point out the pioneering examples of the "Formula SAE/Student" automotive challenges (dating back to 1981) and the "IARC" competition on aerial robotics (ongoing since 1991).

This systematic promotion of active learning roles, experiences and environments helped to incorporate, to engineering programmes worldwide, the technologies and methods of the "Industry 4.0". Cloud computing, cyberphysical interfaces, internet of things, big data, simulation methods, digital twins, autonomous robots, additive manufacturing, among other, had already been researched at universities at least since the 1990s and well before the official coining of the term "Industry 4.0" in 2011 [3, 4]. Nowadays, these technologies and methods are widely applied in most engineering programmes at all levels.

"Engineering Education 4.0" is, consequently, characterized by student centred methodologies, by a systematic promotion of project-based learning, through which professional skills and transversal outcomes are acquired and put into practice, by an intensive application of technologies from engineering professional practice and by a growing number of connections between training and research.

In addition, other authors have put forward the relevance of e-learning (and b-learning) methods, the interesting employment of e-portfolios, the progressive use of virtual laboratories and the increasing importance of internationalization in engineering education along the last two decades [5]. Other innovations, which can be considered part of the revolutions achieved in the "Engineering Education 4.0" period, are open lectures and massive open online courses [19–21], which have also supported a democratization of education through a more equitable access to knowledge. Making reference to the ground-breaking examples of Wikipedia and of the Khan Academy is necessary.

2.2 The Revolutions Ahead: A View Beyond 2030

In the last five years, the aforementioned innovation trend has lost momentum. For instance, the European convergence has not been yet effectively achieved and the countries from the EU still train engineers through extremely varied programmes, in terms of structure and length, which prevents the interoperability of degrees and the approach towards more universal programmes and, at the same time, limits the swift operation of existing joint degrees.

Besides, even though methodological changes have been progressively incorporated to engineering programmes, to complement the classical master classes, there are still many professors reluctant to change, who believe that the engineers of the future cannot match the excellence of the engineers of the past. In 2020, in the middle of the SARS-CoV-2 outbreak, with most universities worldwide closed and resorting to e-learning methods, too many professors are reluctant to finding and applying innovative assessment methods, different from the traditional written examinations, which generates additional stress and helps to point out the need for evolving engineering education again and continuously.

In addition, the more recent topical changes or incorporations to engineering programmes have been just focused on including minors or electives about innovative technologies from the Industry 4.0 arena. The creation of mini-degrees on internet of things, artificial intelligence and machine learning, big data, cybersecurity, advanced production technologies, among others, is also common. Nevertheless, such recent concern about the specific techniques from Industry 4.0, in a way, diverts the focus from the real challenges ahead and from the Agenda 2030.

Seeing that we are now in a transition from Industry 4.0 towards Society 5.0, possibly approaching technological singularity, and considering the global challenges ahead, a related evolution of engineering education, presented in this study as Engineering Education 5.0, is foreseeable as well. Such evolution should go a step further and, not only focus on the progressive incorporation of new-development technologies, but reassume the quest for global engineers, as proven right in so many intellectual revolutions (Renaissance, Enlightenment, first decades of the XX Century, among others previously mentioned).

To contextualize all the aforementioned evolutions, the timeline of Fig. 1 is prepared. It summarizes historical, scientific-technological and related educational advances, since the first industrial revolution, and presents some predictions and possible directions with year 2050 in the horizon, in connection with the provided explanations and with the establishment of Engineering Education 5.0, whose key features are detailed in the following section.

Fig. 1. Timeline of modern industrial and engineering education revolutions: Key transformations since 1760 to the end of World War II in 1945.

3. Engineering Education 5.0: Key Features

Engineering Education 5.0 should combine the benefits of well-established and validated engineering education models, taking inspiration from the past for constructing the future, while incorporating radically innovative aspects and relying on advanced technologies, as a necessary complement for more effectively and efficiently transform engineering, in order to successfully face global societal and environmental challenges. Inspiring criteria and proposals from well-established accreditation agencies [22], from recent worldwide initiatives focused on educational innovation [18], from professional and research organizations reformulating professional training [23], and from relevant state-of-the-art reports [24, 25] and recent special issues of the International Journal of Engineering Education, have been considered for describing the novel paradigm. Accordingly, Engineering Education 5.0 should be characterized by 16 interwoven key features, listed together for the first time and explained below:

1. **Dynamic and continuously evolving:** In a continuously evolving world, with scientific advances and technological discoveries emerging constantly, engineering programmes should be able to dynamically evolve, so as to

Fig. 1 (*continued*). Timeline of modern industrial and engineering education revolutions: Key transformations since 1950 and current expectations towards 2050.

better adapt to societal needs and human challenges. Nowadays, engineering education institutions in many countries suffer from the bureaucratic burden of verifications, accreditations and reaccreditations, whenever a new engineering programme is proposed or even when minor modifications are thought appropriate. This burden prevents the speed of response to scientific-technological changes and limits the positive impact of advanced research on engineering education, which should incorporate advances, more dynamically, as soon as they are achieved. Continuous accountancy, possibly aided by artificial intelligence tools [26], instead of periodic evaluations and accreditations may be the correct approach thinking beyond 2030. In this way, cost and time efficiency will be also importantly promoted.

2. **Modular and flexible:** Professional roles of engineers (see Section 4 for more details) are also evolving with a progressive blend between professional fields. The frontiers between science, technology and society are also gradu-

ally dissolving, as a consequence of the extremely varied fields of application of modern technologies. One can easily imagine a chemical engineer collaborating with a *nouvelle cuisine* chef, a mechanical engineer supporting the restorers of an art museum, a materials engineer working with designers from the fashion industry or a computer engineer working together with anthropologists and linguists, to cite some examples. Engineering is entering so many areas that engineering education will require more flexible programmes, so as to better respond to the needs of society and the wishes of students. This can be achieved through modular approaches for the implementation of engineering programmes (see also Section 4).

3. **Personalized for joint personal and professional development:** The aforementioned flexibility is clearly aligned with a desire for engineering education personalization, conceiving universities as places that support both the personal and professional development of students, helping them in their path to fulfil their dreams. Accordingly, in a student-centred university, students should also responsibly decide and take a more part in their curricular planning, not just by choosing a degree and a specialization, but by continuously selecting formative modules adapted to their desires, by planning their internationalization strategy from the first years of the degree, by approaching in a more calculated way the enterprises or institutions, in which a co-op or academic external practice can be performed, among others. Mentoring by professors with experience in human resource management and support from more experienced peers, in a *Montessorian* style, should be considered, as part of the transformations required.

4. **Sustainability and solidarity focused:** For decades now, we understand that sustainability must be intrinsic to development. Environmental and social impacts should guide research, innovation and all engineers throughout their professional life. Sudden worldwide emergencies, such as the SARS-CoV-2 outbreak and the related COVID-19 disease, make us aware of our limitations and weaknesses, as global society, and of the need for solving current challenges in a more balanced way than ever before. After some decades of placing perhaps too much faith in radically innovative technologies and of pursuing technological singularity, we should now better understand our boundaries and put the focus on engineering towards sustainability and solidarity, which should be actively developed, as essential learning outcomes in all engineering programmes.

5. **Combining knowledge-based and outcomes-based approaches:** More traditional approaches to engineering education were mainly knowledge-based, while more recent trends have been linked to outcome-based strategies with a focus on professional and soft skills [18, 22]. The future educational models for engineering should make both approaches compatible, not juxtaposed: fundamental scientific and technological knowledge is essential for successful professional practice and for developing effective, efficient and safe engineering systems. However, a focus on professional and soft skills is also crucial for any engineer dealing with complex projects, especially considering that current global challenges and threats require from multidisciplinary teams, adequate communication, creativity, leadership, respect to other people's and partners' opinions and cultures, in order to be solved.

6. **Holistic:** All engineering disciplines are now deeply interconnected, so building down frontiers between traditional engineering fields may be an interesting approach, towards a more holistic and impactful engineering education. In my life I have seen chemical engineers mastering robotics and manufacturing technology, electrical engineers developing methods for calculating gearboxes and mechanical engineers focused on biofabrication and molecular biology, just to cite some close examples. Last decades have seen a progressive specialization of engineering degrees, with super-specialized paths within already specialized programmes of study. Even if specialized engineers are (and will be) needed, it is also true that super-specialization may become a problem of modern engineering, as has already happened in contemporary medicine. The transformative power of engineers relies on their capability of interpreting complex problems as a whole and of interacting with the many different profiles present in multidisciplinary teams. Driving scientific technological research and innovation to success requires also from insights on technology commercialization, entrepreneurship and industrialization. Perhaps it is time to see engineering as an integral entity and to ideate schemes for "universal" engineering programmes (see Section 4), capable of providing students with a comprehensive mastery of engineering fundamentals. Specialization comes always through professional practice and lifelong learning in the adequate moment.

7. **Humanistic:** The engineers of the Renaissance

were capable of modernizing the world through a judicious combination of science and technology, thanks to a deep study of ancient traditions and cultures, and by resorting to a close relationship between technical and fine arts. In many cases, inspiration from nature was also present, in a continuous desire for developing better transport methods, finer instruments, larger buildings, more efficient mechanisms, faster processes and more precise weapons. Such desire to know and the establishment of synergies between different fields of knowledge should inspire us in our transition to Engineering Education 5.0. We must find ways for incorporating social, cultural, historical, anthropological, philosophical, etc., in summary: human aspects, into the engineering programmes, as the problems that engineers approach and solve are always human problems [27]. Resorting to modular and flexible structures can provide a compromise solution for incorporating such human aspects, without affecting to the necessary scientific core and engineering fundamentals, as explained in Section 4.

8. **Guided by ethics:** Ethical issues arise with the development of transforming technologies with the potential for reshaping society. Artificial intelligence, wisely applied, can lead to more efficient and effective products, processes and systems. However, several concerns linked to gender and racial biases observed in AI-based decision-making systems have been already reported [28]. The abilities developed in the decades for reinventing healthcare, from the birth of tissue and genetic engineering to pioneering results linked to biohybrid systems and artificial life, have placed mankind in a position, in which "redesigning" humans and extending life may soon be feasible. These examples help to put forward the urgent need for more actively ensuring that engineering advances are mentored with the highest possible ethical standards [29]. Ethical issues are currently seen as secondary aspects in most engineering programmes, while focusing on the application of standards and regulations is widely spread, which in a way partially compensate the lack of specific courses or teaching-learning activities specially concentrated on ethics. This should be corrected for an adequate implementation of Engineering Education 5.0 and courses on ethics and professional deontology should be part of the core fundamental of any engineering degree.
9. **Collaborative and open source:** Collaboration and knowledge sharing are fundamental for fostering steady scientific technological advances, as shown by current trends in open science and research, including the progressive adoption of FAIR (findable, accessible, interoperable, reusable) data principles for research [30] and the rise of open publishing schemes. The engineering universities of the future will benefit from increased collaboration through innovative schemes, both in research and training tasks, and from sharing knowledge, for instance by means of open source teaching-learning materials, which will support a more equitable access to higher education. Collaboration between groups of students in international design experiences and courses, international hackathons and student competitions for jointly approaching complex problems, e-twinning schemes for establishing global classrooms, are some options towards more collaborative universities. The sharing of their results as open source technologies has the potential to facilitate the desired educational transformations. In fact, some of the most interesting technologies recently developed and widely used in engineering education, already rely on open-source schemes, like the Arduino and Bitalino electronic boards, the Tensor Flow open-source machine learning framework or the Taiga.io environment as open source project management platform, among others.
10. **Involving international experiences:** Deeply linked to collaboration, internationalization of engineering universities, through the experiences of their professors, researchers and students, is necessary for constructing a global society capable of facing the complex uncertainties ahead. The extraordinary results of the ERASMUS programme along its history have led to the creation of the more recent ERASMUS+, through which the programme structures international collaboration well beyond the borders of the EU and the European Area of Higher Education. These pioneering examples, which share several key features of Engineering Education 5.0, are further discussed in Section 5. Through internationalization and collaboration, engineering students become more prepared for large scale projects, understand the potential of diverse, international and multicultural teams for achieving creative engineering solutions and experience more enjoyable or even fascinating professional developments, while hopefully trying to create better conditions for our global society.
11. **Including external academic internships:** Promotion of professional and research skills can

be straightforwardly achieved through enhanced collaboration between academia and industry. External academic internships should be a relevant part of any engineering programme (in some countries it is even compulsory for decades now) as such internships help students to deploy their knowledge in real work environments and with an adequate mentorship. Such internships should be correctly organized and students should be continuously supported by professional development mentors, with experience in human resources management, for increasing the degree of personalization in higher technical education. Assessment of the external academic internships should take into account the input from the professional mentors, working with the students in the external industrial or research environments, but also the self-reflections of students regarding the development of their professional skills. Mentors from academic institutions should supervise the correct implication of the external partners with the students and the formative value of the proposed external internships.

12. **Supported by project-based learning activities hybridized with service learning:** The relevance of project-based learning experiences for achieving ABET professional skills and as a central element of the CDIO model, which is reinventing engineering education, is beyond doubt [18, 22]. Towards the future, it is necessary to further increase the social impact of already excellent project-based learning experiences and PBL-supported educational schemes. This can be done through a hybridation between project-based learning and service-learning [31], starting from real, relevant and unsolved societal problems, which receive a concrete answer in the form of a project, product, process or system. The development of such "PBL-SL" experiences in international contexts can be truly transformative and help to rethink, not just engineering education, but also several industries [32].
13. **Technology-supported and artificial intelligence-aided:** New opportunities for more effective and efficient teaching-learning methods and processes arise thanks to the support of technology. In the last decades, we have experienced how capstone projects, final degree theses and project-based learning initiatives in general, have benefited from a widespread incorporation, to the teaching-learning process, of: computer-aided design, engineering & manufacturing technologies, simulation resources, rapid prototyping and rapid tooling machines, low-cost and open source electronic boards, just to cite some examples. At the same time, artificial intelligence (AI) has the potential of transforming universities, helping us reach an AI-aided engineering education, in which many processes may be optimized and automated and purposeless bureaucracy converted into useful information for continuous quality improvements [26]. Technology-supported and AI-aided engineering degrees may even go in the direction of a more equitable access to engineering education, if technologies are sensibly interwoven with contents and applied throughout the teaching-learning processes at universities.
14. **Oriented to lifelong learning:** Lifelong learning has been put forward as a key outcome of modern engineering programmes, at least since the 1990s [33]. Once again, considering that technological revolutions take place at an increasingly rapid pace, which directly impacts on the roles of engineers in society, learning to learn will be progressively more and more relevant. Such ability should be actively promoted in engineering programmes through strategies involving: increased collaboration between academia and industry [34], establishing university-community research and training partnerships, providing continuing education for adult learning, developing mechanisms to recognize the outcomes of learning in different contexts, in connection to more flexible approaches to higher education, among others, as previously detailed [35].
15. **Enjoyable for enhanced results:** Neuroscientists have demonstrated that enjoyable learning produces enhanced results, especially when resorting to "learning through play" strategies, which should be conceived and implemented to be: joyful, meaningful, socially iterative and actively engaging [36]. All this applies to engineering education as well, as several studies have also verified [37]. In fact, the true essence of university can only be achieved, when students and professors learn together and inspire each other in mutually enriching and joyful experiences, as any professor who has learned from his/her students may agree. In addition, learning through play is also connected to more holistic learning experiences, hence supporting other key aspects of Engineering Education 5.0 previously described.
16. **Equitable, aimed at "engineering education for all":** The challenges of our global society cannot be solved without applying the "leave no one behind" motto. In fact, leaving no one behind is the central promise of the 2030

> Agenda and of the Sustainable Development Goals (SDGs) [7-8]. Understanding that engineers play a fundamental role for achieving such SDGs and that talent is equally distributed (although opportunity is not), it is compulsory to work towards an equitable access to engineering education, following "engineering education for all" principles [38]. Excellent initiatives and global movements (Khan Academy, MOOCs, open source software & hardware movements [19–21]) have already demonstrated that the dream of an equitable engineering education is possibly. To face the challenges ahead, we rely on the best possible trained engineers for further developing and mentoring the technological advances that are reshaping the present. The gathering of genius and motivation can no longer be hindered by reasons linked to social status, race, religion, political opinions, sex or sexual orientation and a more equitable access to engineering education should be supported, so as to construct Engineering Education 5.0 and, through it, transform the world [38].

Enlightening engineering education to incorporate all the aforementioned essential features, towards Engineering Education 5.0, is challenging and requires time and collaborative efforts, as even the characteristics of educators may need rethinking. Probably the traditional knowledge-generator/knowledge-transmitter role of engineering educators will further co-exist with the more recent role of learning facilitator and mentor (even if the figure of mentor dates back to ancient times). Besides, new roles and types of interactions with students will prevail, especially if online methods demonstrate effectiveness and efficiency, and appear, once artificial intelligence and robots are broadly incorporated to higher education. This may progressively transform educators into designers of learning experiences and managers of information and tasks. Anyway, the proposed universal structure for engineering degrees according to modern engineering roles, further described in Section 4, and the results from some pioneering experiences, presented in Section 5, which share many of the above described key characteristics, may help to guide such transition.

4. Universal Engineering Programme Structure for Contemporary and Future Engineering Roles

In order to promote the 16 key features of Engineering Education 5.0, together with the required pedagogical evolution, it is necessary to transform the structures and contents of engineering programmes and, almost certainly, the structures and processes of academic institutions (as further detailed in Section 5). Regarding the structure and contents of engineering programmes, a proposal for universal engineering programme structure, considering contemporary and future engineering roles, is described below and schematically illustrated in Figs. 2 and 3.

Summarizing, a whole 6-year programme, based on a 4-year bachelor's degree plus a 2-year master's degree, can very adequately provide students with fundamental scientific technological knowledge, specialized professional and transversal skills, necessary ethical values, and even give them important opportunities for personalization and professional planning. This can be achieved through modularity, through collaboration with other programmes, universities and institutions, through the promotion of international mobility and external internships and through a more flexible understanding of all the possible types of experiences that contribute to a holistic training of engineers. In fact, engineering students may benefit from all areas of knowledge schematically presented in Fig. 2a.

Considering the proposed general structure towards a universal Bachelor's Degree in Engineering, as schematically presented in Fig. 2b, it is important to highlight the following aspects: 60 credits, according to the European Credit Transfer System (1 ECTS corresponds to between 25–30 hours of student dedication), are devoted to engineering fundamentals during the first two years of studies. 60 ECTS credits are dedicated to the promotion of transversal and professional skills also during the first two years, including: compulsory courses or activities focused on ethics and professional deontology; participation in student competitions, hackathons and capstone or CDIO experiences, as a way for acquiring and deploying leadership, creativity, teamwork and communication skills; internships in research groups or enterprises, as preliminary introduction to the working experience; collaboration with student associations and other project-based learning and service learning experiences. Along the third and fourth years of studies 60 ECTS credits are focused on specialized engineering fields (mechanical, chemical, industrial, materials, aeronautics, naval, agricultural, biomedical, civil, ICT) and 60 ECTS credits allow students to flexibly organize and personalized their degree. These 60 credits for personal curricular planning may be taken from any field of knowledge, help to achieve a more in depth knowledge of engineering fundamentals and of concepts of the chosen specialization, allow for the study of a second specialization or additionally contribute to

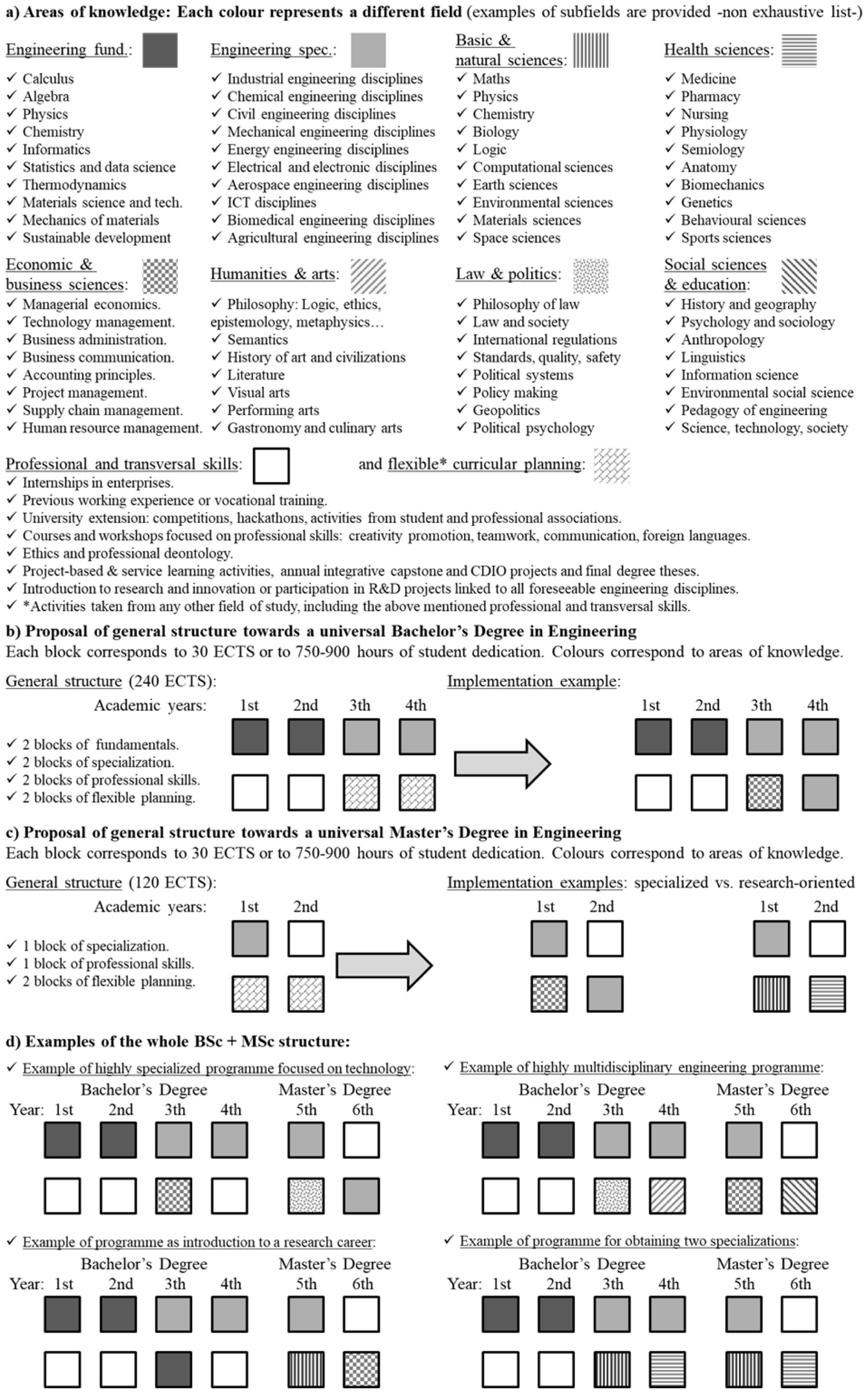

Fig. 2. Schematic construction of a universal engineering programme: (a) Areas of knowledge. Proposal of general structure for: (b) bachelor's and (c) master's degrees in engineering. (d) Implementation examples considering the complete bachelor's plus master's structure.

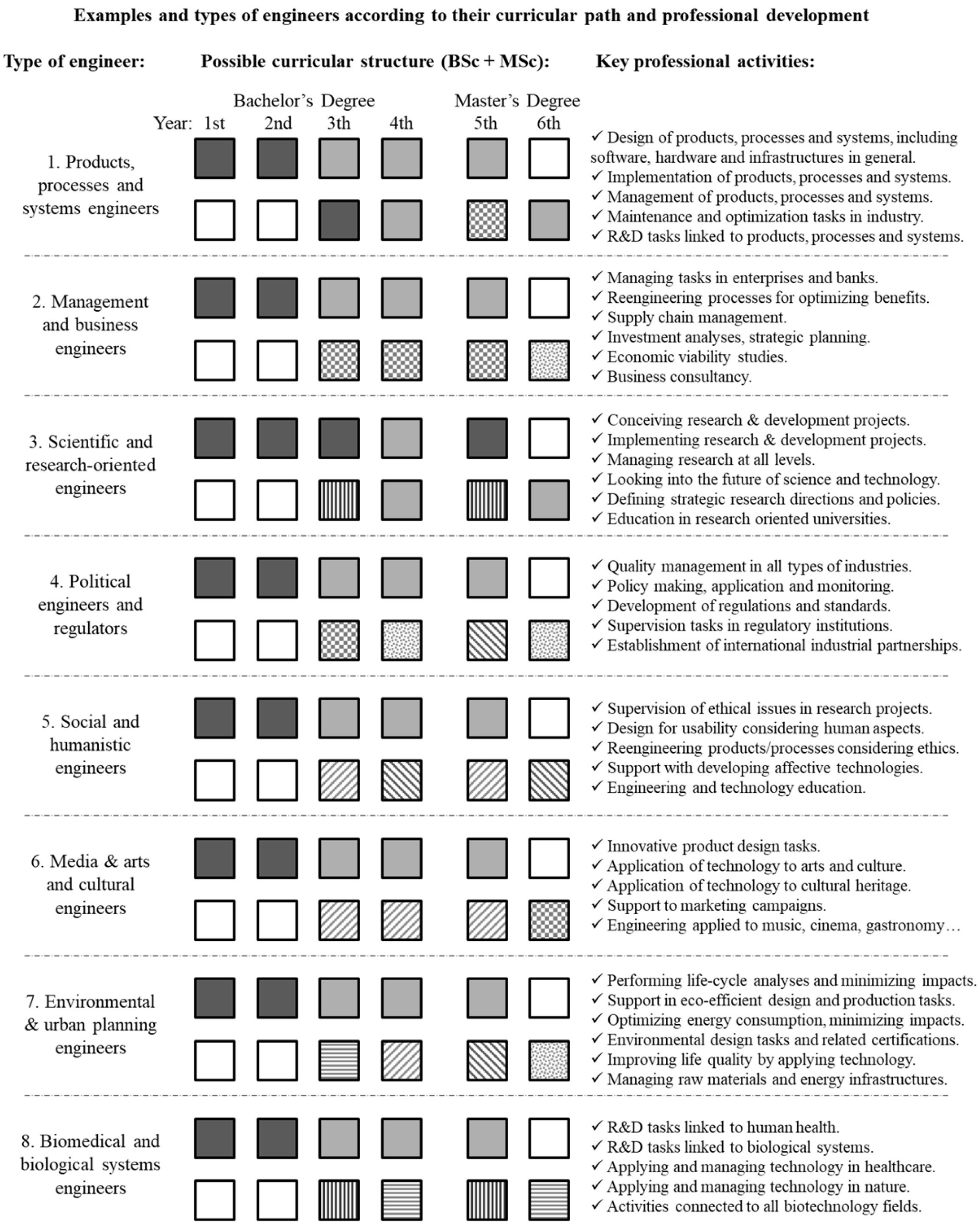

Fig. 3. Examples of programmes based on the proposed universal structure and types of engineers according to their curricular path and professional development.

promote the acquisition of personal and professional skills. A 15-ECTS to 30-ECTS final degree thesis connected to the chosen specialization(s) is also part of the 60 ECTS block for personalized curricular planning.

Taking into account the proposed general structure towards a universal Master's Degree in Engineering, as schematically shown in Fig. 2c, it is necessary to mention the following: 30 credits are devoted to specialized engineering topics, in the area of knowledge of the Master's degree, during the first year. 30 credits along the second year are dedicated to the promotion of professional and transversal skills. Along the two courses, 60 credits are conceived for personalizing the Master's degree, from which 15 to 30 ECTS are linked to a final degree thesis again in the specialized area of knowledge of the degree.

The proposed general structures towards universal Bachelor's and Master's degrees in Engineering can dynamically evolve, combine necessary basic engineering fundamentals with a focus on required professional and transversal skills, should promote the personalization of engineering education and may lead either to very specialized or to highly multidisciplinary engineers.

However, the true potential and versatility of these structures will only be deployed if the two levels are combined and implemented as a whole 6-year training programme. A complete 6-year programme allows for providing vast knowledge of engineering, which can be complemented with in depth specialization in desired topics, enriched through the incorporation of humanities and social sciences, focused on the development of professional skills and supported by international and practical experiences.

In terms of the duration of the studies, a 6-year bachelor's plus master's degree structure (4 + 2) is already common in countries well known for their training of engineers, including: Russia, China, India, Japan, Spain and Turkey, even if it is not yet the most common duration in the European Area of higher Education or in the US, which typically resort to 3 +2 schemes.

The versatility of the proposed structure is illustrated in Fig. 2d and Fig. 3. Fig. 2d provides examples of adaptation of the general structure to different alternatives, some more holistic, some more specialized, typically for technology developers and researchers. Even the training of engineers for obtaining two specializations is possible. In the case of Fig. 3, examples of programmes, based on the proposed universal structure and on the possible types of engineers according to their curricular path and professional development, are presented. These examples consider different types of engineers, the possible curricular structure more adequate for them and the usual professional activities they may perform, on the basis of the training received.

In fact, the search for versatile engineering programmes, which also give students possibilities for personalization, is a very relevant current trend, as has been put forward by some very interesting programmes worldwide, selected as reference educational innovation programmes in the MIT-NEET report [25]. At the same time, the holistic vocation, which should also characterize Engineering Education 5.0, has been previously highlighted as necessary for XXI Century engineering education, which also should benefit from interaction with all key stakeholders to promote students' multidisciplinary abilities and global view [24].

It is interesting to mention that the increasing connection between engineering disciplines may contribute to a progressive dissolution of borders between the classical specializations of the programmes of studies. Probably, structuring programmes according to the modern professional roles of engineers, which are more stable than the continuously evolving and nascent engineering majors, as proposed here, may be an adequate solution for constructing versatile, dynamic and universal engineering programmes. Nowadays, the professional roles of engineers go well beyond the more classical roles of "product engineers", "process engineers" and "management engineers" [39], as engineering increasingly affects are larger number of sectors, not just industry, and helps to reshape society in all its aspects.

Current and near-future professional roles of engineers, to which the proposed general structure is particularized in Fig. 3, include, among others:

1. **Products, processes and systems engineers:** The classical role focused on designing, implementing, maintaining and managing products, processes and engineering systems and infrastructures in general, as well as related R&D tasks, which requires both fundamental and specialized engineering knowledge.
2. **Management and business engineers:** Dealing with managing responsibilities in companies, with process reengineering and with strategic planning, tasks benefiting from combining knowledge from engineering, economics and business sciences, as well as an understanding of applicable law and politics.
3. **Scientific and research-oriented engineers:** Engineers as research, development and innovation mentors, dealing with R&D activities at all levels and looking into the future of science and technology, for helping with its construction, all of which requires a combination of vast engineering knowledge and of both basic and applied sciences.
4. **Political engineers and regulators:** Focusing on the creation, application and supervision of technical standards, quality management procedures and science- and technology-related policies, which requires from a very broad training, with technical studies complemented with humanities, social sciences, economics, politics and law.
5. **Social and humanistic engineers:** Technical professionals with a deep understanding of social and human aspects of science and technology, hence especially suited for supervising the ethical aspects of technology development projects and for supporting design for usability methods and the development of affective technologies.

6. **Media & arts and cultural engineers:** Professionals with an understanding of basic and applied engineering disciplines and with a background in humanities and arts, which proves interesting for applying technology to innovative products, to arts and culture, to the protection of cultural heritage and to areas including music, cinema and gastronomy.
7. **Environmental and urban planning engineers:** Occupied with the design, construction and management of future human environments, including space colonies, placing environmental sustainability, optimal management of resources, comfort and usability in the forefront, which requires a multidisciplinary training in technology, natural sciences, policy making and law, complemented by humanities, social sciences and even art.
8. **Biomedical and biological systems engineers:** Engineers devoted to fostering scientific technological developments in all types of biotechnology (blue, green, red, white) and dealing with the approach to the biohybrid engineering systems of the future, which requires knowledge from basic and applied engineering disciplines, but also important background in natural, biological and basic sciences, as needed for interacting with healthcare professionals, biologists and scientists.

Once the general programme structure, the contents and some possible implementations for the promotion of Engineering Education 5.0 have been presented and discussed, the following section concentrates on analysing inspiring experiences and proposing a plan of action for the construction of this novel archetype for higher technical education.

5. Constructing Engineering Education 5.0: Inspiring Experiences And Actuation Roadmap

Some recent inspiring experiences share may of the key features of Engineering Education 5.0 and contribute to rethinking the structure and content of engineering programmes, as well as the structure and processes of institutions concerned with engineering education. Describing some of them may help to propose an actuation roadmap for construction Engineering Education 5.0, as detailed below.

5.1 The Pioneering Case of Pan-European Universities

The idea of creating university consortia or federated universities to achieve an adequate critical mass and more comprehensive infrastructures for carrying out large scale research projects and, hence, attract investments for R&D and promote public-private partnerships, is not new. For instance, in 1991 in Paris, a set of technical universities associated for creating "*Grandes écoles d'ingénieurs de Paris*", which were renamed as "ParisTech" in 1999. In 2007 its status changed to a "public establishment for scientific cooperation", which in many ways acts as a super university, with intimate collaborations both in research and education. Also in Holland, the 3TU federation of technical universities was founded in 2007 and renamed to 4TU in 2016, with a similar orientation to that of ParisTech. However, the impact of such national consortia is very limited, if compared with the transformative potential of international, multidisciplinary and transsectoral consortia, especially as regards the training of global engineers.

In Europe, the establishment of international consortia of universities has important social and political implications and may constitute a fundamental strategy to further vertebrate the European Union. In 2017, during the 30th anniversary of the Erasmus project, Erasmus+ launched a special programme, the "European Universities Alliance", to create around 20 transnational European "super campuses", which should be already operative in 2024. These pan-European universities will share students and professors and arrange international programmes of study, along which students will be able to study in several countries without the need for recognitions.

Flexibility, personalization and internationalization, some of the key characteristics of Engineering Education 5.0, will be importantly fostered through this exciting initiative. The first selection of 17 pan-European universities alliances has been already done and it may help several technical universities to complement their topics with those from social sciences and humanities, so as to promote a more holistic training for the engineers of the future.

In a way, this and similar initiatives may compensate the current topical limitations of technical universities (both in terms of research and training). Perhaps the model of the classical technical universities, focused just on engineering, should be reformulated and evolve towards more multidisciplinary schemes. A good start may be the establishment of long-term interuniversity collaborations for training and research in strategic areas. To mention a pioneering example, the MIT-Harvard Program in Health Sciences and Technology dates back to 1970 as a fruitful and inspiring collaboration. More recently, Humanitas University and Politecnico di Milano have joined forces for a highly innovative programme, the MEDTECH Degree Programme, which provides 6 years of training to deliver graduates in medicine and in biomedical engineering at the same time. This constitutes another example of how more flexible and collaborative training schemes may lead to valuable professionals with skills for the engineering roles of the future.

5.2 Other Initiatives from the EACEA

The "Education, Audiovisual and Culture Executive Agency" (EACEA) of the European Commission supports projects and activities in the fields of education, sport, cultural and creative sectors. Several EACEA's programmes focus on international partnerships and on the promotion of international mobility of students and staff. Fostering solidarity and supporting humanitarian actions are also within EACEA's key tasks.

Of special relevance to higher education, ERASMUS+ transcends the initial vision of the ERASMUS programme (founded in 1987) as EU student exchange facilitator. In ERASMUS+, subprogrammes such as KA107 offer student and staff mobility between EU and partner countries. Since 2014, this has helped to establish educational collaborations and to implement innovative higher education programmes (i.e., ERASMUS Mundus Joint Master Degrees) and courses, in which most countries of the world have already taken part.

Apart from support to student and staff mobility and to the creation of programmes and courses with an international component, the EU Commission, through EACEA, also supports capacity building in higher education, which is of special relevance for engineering studies, due to the necessary practical component of engineers for their professional development. Software and hardware resources, well-equipped laboratories, materials and consumables, are required for an adequate training in modern engineering education, if highly-rewarding project based learning strategies are to be used. Among pioneering capacity building projects in higher education, supported by the EU, it is important to highlight: the ALIEN (Active Learning in Engineering Education) project, aimed at implementing high quality PBL approaches across Europe and Asia, and the ABEM (African Biomedical Engineering Mobility) project, focused on translating the philosophy of the ERASMUS programme to African countries in the field of biomedical engineering. Such transformations, achieved through international collaboration for increased learning, share many of Engineering Education 5.0 principles and show the path to renewing engineering education with a focus on solidarity and sustainability.

5.3 Global Learning and Innovation Communities

Considering that the establishment of international universities is challenging and will require time and considerable political and economical efforts, another option for constructing highly beneficial learning environments may be through the collaborative efforts of international innovation communities, in many cases connected to the makers' movement. These communities are often arranged as non-profit international associations or as social enterprises and emerge from international R&D projects, thanks to partners with the wish to further work together. In addition, these innovation-fostering associations normally operate online, benefit from the use of e-platforms or online infrastructures and involve public and private partners, both from academia and industry, which provides an excellent substrate, not just for innovation, but also for training purposes. Their international and multidisciplinary nature, their connection to open-science and technology movements, their appreciation of change as driver of innovation, are among the aspects that help to promote the dynamism of the learning environments and training events organized within these innovation communities: international design competitions, hackathons and intensive training weeks, summer courses, short-term visits between members, research-oriented theses, among others.

To cite a recent example, the UBORA community is fostering a change of paradigm in the biomedical industry, towards more equitable healthcare technologies through a fostering of open source medical devices. In connection with such essential objective, several training initiatives, including international competitions and express-CDIO experiences, are developed on an annual basis [40]. Besides, UBORA training materials (recorded lessons, presentations, case studies share through a medical device "Wikipedia") are made freely available (please see: https://platform.ubora-biomedical.org/).

Besides, several online maker spaces and tinkering websites are helping educators to use extremely varied hands-on experiences for teaching technology at all levels [41], even reformulating the pedagogical strategy and contents of uncountable university courses. Websites like Thingiverse, GrabCAD, Shapeways, MyMiniFactory, 3DExport, among others, are reshaping the way product engineering is approached and taught. Open source CAD files, open source software, open source hardware (i.e., BITalino and Arduino boards, Prusa 3D printers) and freely shared training resources are completely aligned with a more equitable access to high-quality technology education.

Furthermore, it is important to highlight that these communities are making technology education (and STEAM in general) more attractive high-school students, as the "eCraft2Learn" project has helped to put forward, and constructing a path toward more gender-equal technology education [42]. All these efforts may help to compensate for the current lack of technological vocations and support the training of a new generation of engineers, in accordance with Engineering Education 5.0 principles.

5.4 Hybrid Training Programmes Involving Academia and Industry

Interesting proposals to evolve engineering education are being also developed by the European Institute of Innovation & Technology (EIT), with a clear focus on innovation and entrepreneurship. The EIT is an independent body of the European Union set up in 2008 to deliver innovation across Europe. It brings together entrepreneurs, innovators, academia and students to train a new generation of entrepreneurs, to deliver innovative products and processes to society and to power start-ups. It constitutes the largest community of innovators in Europe and counts with involvement of universities, research centres and companies for innovating in sectors including health, ICT, manufacturing, raw materials, food, energy, climate and urban mobility.

As regards higher education, EIT is supporting remarkable engineering education programmes in Europe by awarding the "EIT label" to programmes of excellence. These programmes should be capable of integrating business, education and research and of transmitting students a passion for innovation and entrepreneurship. EIT has already a well-established set of Master and PhD programmes, highly connected to topics of Industry 4.0, but also focusing on internationalization and holistic education, as students from EIT programmes typically live through 2 to 4 mobilities among programme partners (universities, research centres and enterprises from several EU members and partner countries worldwide). These programmes demonstrate how international public-private partnerships may contribute to training engineers with highly demanded skills, such as creativity, leadership, entrepreneurial view, appetite for innovation and international orientation, all of which connects with Engineering Education 5.0 views.

5.5 Actuation Roadmap

Regarding a possible actuation roadmap, it is interesting to plan the transition to Engineering Education 5.0 in two stages. The first stage corresponds to the next 5 years and the proposed actuations, some of which are listed below, are very straightforward measures to support the key features of the new educational paradigm. The design and implementation of such short-term actuations, in fact, depends only on the will of change of professors, deans, rectors and of effectively involving students in the change wave.

Once the benefits of the proposed evolution are demonstrated, through the initial direct actuations and related pilot studies, the second stage, corresponding to the period 2026–2030, can be approached. Carrying out the related medium-term actions will require from the implication of a wider set of key stakeholders, including policy makers, funding bodies and sponsors, research institutions, companies, employers' associations, professional guilds and representatives from citizens, among others, so as to promote impacts and construct a sustainable continuous evolution trend. Some of the actuations that can be considered for the two mentioned stages are listed below as illustrative example.

Proposed actuations for the period 2021–2025:

- All teaching resources and lessons are made open and freely shared through online infrastructures contributing to "engineering education for all" principles.
- Ethics and professional deontology are progressively incorporated to all engineering programmes, first as minors and electives, then as necessary complement to majors.
- Humanities and social sciences courses are progressively incorporated to engineering studies, initially as electives, and valued as relevant for the success of engineers.
- Makers' events, hackathons, international design competitions and summer schools are considered eligible for credits, as part of the eligible curricular planning activities. This contributes to making education more enjoyable, international and collaborative.
- Self-directed learning is promoted, as a way of underpinning the relevance of lifelong learning. Students are motivated and mentored to get involved in their curricular planning.
- Service-learning partnerships with the third sector are established, as a way of transforming highly rewarding project-based learning activities and making them even more holistic, while working towards solidarity and equity.
- Entrepreneurial and technology commercialization experiences become progressively eligible for credits, again as part of curricular planning options.
- Pilot studies related to all the points above to develop best practices guidelines.
- Meetings between educators, students, accredita-

tion bodies, certification agencies and professional guilds help analyse Engineering Education 5.0, its possible impacts, the viability of implementation according to proposed structure and to modern engineering.

Proposed actuations for the period 2026–2030:

- Previously detailed pan-EU universities grow, most technical universities adhere to several consortia and this transformation inspires similar schemes worldwide, as a way of promoting the international and multicultural component of a new generation of engineers.
- Strategic public-private partnerships are constructed for the development of joint engineering programmes, with schemes similar to the detailed EIT labelled programmes, so that multidisciplinary and transsectoral programmes constitute the norm, not the exception.
- The research and internationalization strategies at universities are developed together with their educational models. Research groups cooperate with educational innovation groups and perform joint projects, through which research and training are further interwoven.
- Accreditation processes are reformulated and their bureaucracy minimized, as a necessary consequence of a desire for dynamism and flexibility, counting with the support of artificial intelligence methods already under development.
- Universal engineering programmes are progressively established worldwide following schemes similar the ones proposed here and focusing on the promotion of as many features of Engineering Education 5.0 as possible.
- Engineering itself evolves in consequence, from the traditional definition by ECPD, predecessor of ABET: "*The creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behaviour under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property*", towards a more global concept connected to modern roles of engineers and to current and forthcoming global challenges. In this new world engineering may be defined as: "The development and application of scientific and technical knowledge to the discovery, creation and mentoring of technologies, capable of transforming human societies and environments, for increased well-being and life quality and, hence, necessarily following sustainability and equity principles".

6. Conclusions

The magnitude of human challenges and threats ahead requires from transformations in engineering education, which should go well beyond the current trend of innovating for supporting the expansion and impact of Industry 4.0 and related technologies. In a sense, several engineering education evolutions have been consequence of industrial advances, with universities and educators acting, in many cases, in a too reactive way. We are on the verge of unprecedented changes, which will be accelerated thanks to the increasing pace of scientific and technological discoveries. At the same time, we are facing already the dramatic effects of the unsustainable growth from last decades and we now understand that our faith in science and technology can be rapidly washed away by unexpected natural outbreaks. Besides, important ethical issues are continuously arising, with several innovative technologies daily invading our privacy, dealing with our data and programmed with intrinsic social, gender and racial biases, which is alarming.

Consequently, in order to train a new generation of engineers, capable of leading and mentoring the next technological advances and their application towards a more equitable and sustainable world, a reformulation of engineering education is urgent. This reformulation should chorally integrate the views of the key societal stakeholders, including: professional associations, engineering institutions, representatives from the industry, policy makers, accreditation boards, organizations from the third sector, students, educators and their representatives. Accordingly, this study presents Engineering Education 5.0 as a personal vision supported by evidence for the desired educational transformation. The key features of such evolution, an analysis of possible structures for engineering degrees capable of supporting this transition, in accordance with modern professional roles of engineers, and some pioneering cases of educational experiences, which share many of the characteristics desired for the future of engineering education, have been analyzed and discussed. An intention of generating future constructive debates and international and multidisciplinary collaborations, so as to guide the mentioned educational renovation towards a fascinating future, has driven the whole study. The author would be delighted to discuss with colleagues about Engineering Education 5.0 and to arrange a working group for defining and supporting future implementation actions.

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purposes. The image of the Watt machine was taken from Wikipedia's "Watt steam engine" article. It was shared by Nicolás Pérez under CC BY-SA 3.0 license. The description is as follows: *"A beam engine of the Watt type, built by D. Napier and Son (London) in 1859. It was one of the first beam engines installed in Spain. It drove the coining presses of the Royal Spanish Mint until the end of the 19th century. In 1910 it was donated to the Higher Technical School of Industrial Engineering of Madrid (part of the UPM) and installed in its lobby"*.

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