Euro-CASE

The European Council of Academies of Applied Sciences, Technologies and Engineering

Euro-CASE ENGINEERING EDUCATION PLATFORM

Discourses on the Future of Engineering Education in Europe

Paris, October 2020

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About the Euro-CASE

The European Council of Academies of Applied Sciences, Technologies and Engineering is an independent non-profit organisation of national academies of Engineering, Applied Sciences and Technology from 23 European countries. It was founded in 1992 upon French initiative by the members of CADAS (Conseil pour les Applications de l'Académie des Sciences). Euro-CASE acts as a permanent forum for exchange and consultation between European Institutions, Industry and Research.

Through its Member academies, Euro-CASE has access to top expertise (around 6,000 experts) and provides impartial, independent and balanced advice on technological issues with a clear European dimension to European Institutions, national Governments, companies and organisations.

The mission of Euro-CASE is to pursue, encourage and maintain excellence in the fields of engineering, applied sciences and technology, and promote their science, art and practice for the benefit of the citizens of Europe. In pursuit of this mission the objectives of Euro-CASE are:

- Maintain a leadership role in promoting attention to excellence in applied sciences and engineering and to related issues of key importance to Europe,
- Ensure that the societal impact of technological change is given proper attention with full consideration of environmental and sustainability aspects,
- Provide impartial, independent and balanced advice on engineering and applied science issues that affect Europe and its people to the European Commission and Parliament, and other European institutions,
- Promote the importance of applied sciences and engineering throughout Europe and to develop greater public understanding and interest,
- Attract young Europeans into careers in applied sciences and engineering in order to ensure future technological progress in Europe,
- Draw on the experience and best practices of the national academies of engineering and applied sciences in Europe, developing appropriate,
- Information networks.

The secretariat is based in Paris, hosted by the National Academy of Technologies of France in the Grand Palais des Champs Elysées.

Euro-CASE Committee on Engineering Education

Euro-CASE Committee on Engineering Education is an ad-hoc working group of 11 Euro-CASE member academies, which expressed interest in active participation in the operation of the Committee, appointed by the Euro-CASE Executive Committee and approved by the Euro-CASE Board at its meeting held in Lyngby, Copenhagen, Denmark, on November 15 2016.

On November 15 2016, the Euro-CASE Board fully approved the program proposed by the Platform's Chairman.

This report represents a joint research result with equal contributions from each Committee member.

Committee members:

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We are thankful for the support of the KIT-IPEK – Institute of Product Engineering, Karlsruhe Institute for Technology, TU Wien – Vienna University of Technology, UBelg – University of Belgrade, UCL – University College London, and Dassault Systèmes SE for their hospitality, for presentation of their research and working activities in the field of engineering education, openness and readiness to share their findings and practical experiences with the Committee, and on technical assistance in organization of physical working meetings.

We are also thankful to the staff of Euro-CASE Office in Paris, in particular to Nadia Pipunić, Euro-CASE Executive Assistant, and Yves Caristan, Euro-CASE Secretary General. Yves Caristan significantly contributed to Committee work activities and the development of this report, by being present at all physical and online working meetings of the Committee.

Executive summary

The Euro-CASE Committee on Engineering Education was tasked with examining the needs of engineering in relation to the education of future engineers in Europe. The Committee examined a wide range of literature, experiences from universities in different countries and information from the national Academies and the engineering industry and synthesised all of these through deep discussions within the committee and with specific entities in academia and industry who had been identified as having particularly relevant experience in the topic.

The findings of the committee are comprehensive and show the importance of considering the education, as well as the training, of future engineers to be a multifaceted endeavour that needs to bring together all stakeholders in the future European society in a combined endeavour. These findings can be summarised as a set of recommendations for universities, the national Academies, Professional Institutions, the education sector as a whole, and individual companies within the engineering industry.

What engineering is: Principally, Engineering is the utilisation of ingenuity to make innovations happen for the benefit of society and the planet. Therefore it is essential that the education of engineers inspires and encourages the development of ingenuity – without this, the innovations will not happen, and society will not benefit from its engineers. Of course, engineers need to be trained in the scientific theories and methods that underpin the practice of engineering, but the Committee heard many times throughout its deliberations that although this theoretical base is absolutely necessary, it is by no means sufficient to create a true engineer for the future. Engineering is crucial to the innovation required by society. Innovation is not just the introduction of new ideas – it is the successful adoption of those new ideas, and this needs to be engineered as much as the generation and development of the ideas themselves. Without engineers, innovations will not happen, so it is necessary that engineers are well-versed in how to innovate, in the full sense of this term, for the benefit of society. These innovations will also enable industry – in whatever form it will take in the future - play its part in creating and sustaining a prosperous society.

Fundamental concepts of engineering: Engineering is much more than just the application of physics and mathematics. The fundamental concepts that underpin engineering, and to which those theories are applied, are enshrined in Engineering Design, the Engineering Method, and the way of thinking enshrined in the Engineering Habits of Mind. These lead into the development of Engineering Sciences and how these are encapsulated in the dual nature of engineering – that it is, on the one hand, about thinking, doing and making, and on the other by discovery through experiential learning. What needs to be learnt in order to be an Engineer is the combination of all of these fundamental concepts. In the European context, additionally it is necessary for engineers to embrace the various European dimensions – the European Universities Initiative, the European Commission – so that the preparation for sustainable employment, the preparation of engineers for life as active citizens within democratic societies, their personal development to become better citizens, and of course the democratic mission of higher education in Europe as endorsed by the Council of Europe.

Engineers and society: In addition, it is necessary for engineers to appreciate and understand their place in society, in the application of science to society for the sustainable benefit of both people and planet. Above all else, the future engineer needs to be a responsible servant of society – to do no harm as a first principle – and to use their ingenuity in the understanding of society and its needs in the present and future. Without such understanding, engineering, at best, will create indifferent outcomes, and, at worst, could do harm. Understanding, and acting on, this responsibility is a severe requirement for all engineers and brings with it implications for engineering education. The development of appropriate Learning Analytics is necessary in order to monitor progress in educating engineers to be more effective in relation to society as well as to the application of science.

Drivers for change in Engineering Education: The key driver for change in engineering education is the need for competent engineers who can play their full role as members of society. At present all too often engineers satisfy the competence requirement only in relation to the technical aspects of their engineering, but do not measure up so well to the requirements of society. To change this, and enable engineering to make a full contribution to the enhancement of society, it is necessary to reform the way in which engineers are educated and trained. The Committee found that this would require the incorporation of a variety of skills not typically covered in engineering education at present, including so-called 'soft skills', the ability to communicate, understanding of the social sciences and the contribution of the arts and humanities to creating a more equitable and just society.

Engineers and education: It is clear that there is an urgent need for reform of the engineering education sector, not least to take advantage of new and ongoing educational developments, such as digitalisation, MOOCs and so on. It is therefore incumbent on the education sector to ensure that engineers are able to communicate with and understand people outside the immediate circle of their discipline, who speak a different language or who have not benefitted from the high level of educational attainment that characterises engineers. This means that the education of engineers must include such so-called 'soft skills' that pervade all aspects of the learning of engineering, including the learning of theory and theoretical principles. The Committee considered when, during the education of an engineer, such learning should take place. A number of models were considered – for example, specific courses within earlier or later parts of the university curriculum, in industrial practice, embedding these skills and practices within the basic engineering learning throughout the programme, or examining the pre-university education and how this could help or hinder such a requirement. The Committee considered, for example, the 'habits of mind' of engineers, and how this had been introduced to younger school students as a general method for thinking about problems, so that students would be better prepared for the engineering education at university. This seemed to be a successful and practical approach, although implementation within an already tight educational curriculum (and one that often has significant political involvement over its content) could require engineering ingenuity at its best. The new curriculum should address 7 major themes in addition to the theory and practice of engineering techniques: (1) the ubiquity of knowledge and the paradigm shift for learning, (2) Grand Societal Challenges, (3) Market forces and integration of engineering with the economy, (4) Inclusiveness and Openness to access, (5) the contestability of markets and funding, (6) Globalisation of action radius and (7) Digital Technologies and teaching innovation. This transformation must be done with the full involvement of Schools, Universities, the national Academies, Professional Institutions, Certification bodies, Government bodies and the engineering industry as a whole. This is not, and it cannot be, simply a question of demanding that universities incorporate everything in their curricula.

Transformation pathway: The Transformation Pathway incorporates Schools, Universities, the Labour Market, the Engineering Industry, Professional Institutions, Certification Bodies, and Governments as a complex system. This means that all points within the education of an engineer, and not just those within the university sector, need to be involved in creating a comprehensive engineering education, which starts long before university and continues throughout the professional career. Achieving this requires all parts of transformation pathway to come together to produce this coherent educational programme. This complex system must be in good health in order to enable engineering to deliver its responsibilities to society, in the form of mission-driven research directed towards the achievement of the UN Sustainable Development Goals, the development of the Labour Market and the future of work and its role in society, including how labour will need to be divided in an age of intelligent systems and technologies, the development of continuous lifelong learning and of course the crucial ability to learn how to learn. From this, the transformation pathway will be able to deliver engineers well-versed in the skills and practice of entrepreneurship.

Inclusion and Diversity in Engineering: The Committee was not surprised that the number of women in the engineering sector is shockingly low throughout the pathway – from choices of science subjects at school, through entry onto engineering programmes at university and onto their employment in industry. This needs to be remedied, and the committee considered what measures might need to be taken to resolve this issue. The conclusion was that this lies within the education of people in general to embrace engineering habits of mind, but also, on the part of industry and universities, the improved communication to people in general, including politicians, parents and other members of the non-engineering public, about what engineering is and what skills society needs its engineers to have, is essential.

Next steps

It is therefore urgent to start the process of examining the education pathway for engineers in this holistic way, and the Committee recommends a strong and disciplined approach to this examination so that the inevitable revisions needed in the education of engineers will be appropriate, timely and comprehensively able to create a new generation of engineers for society. The approach recommended in this report for the creation of the required transformation pathway is to:

1. Consider the role of engineers and society's requirements for their contribution to society;
2. Explore where the present engineering education system does – and where it does not – meet those requirements;
3. Create a set of requirements for education to meet those holistic requirements;
4. Evaluate how these requirements could be met by a suitably deep and holistic education programme throughout the education system (including in industry);
5. Implement these programmes and evaluate their success, adjusting where necessary;
6. Ensuring that the model can be understood sufficiently to be translated to other environments – much can be learnt from implementations in different countries and education systems for example;
7. Incorporate an inclusive review of the outcomes so that the system can evolve, be sustainable and of benefit to future society and the planet.

' No profession unleashes the spirit of innovation like engineering. From research to real-world applications, engineers constantly discover how to improve our lives by ***creating bold new solutions that connect science to life*** *in unexpected, forward-thinking ways. Few professions turn so many ideas into so many realities. Few have such a direct and positive effect on people's everyday lives. We are counting on engineers and their imaginations to help us meet the needs of the 21st century.*

...

Engineering is vital to successful, sustainable civilization. So much rests on the shoulders of future generations of engineers that ***we must give them the best possible foundation*** *to their professional lives.'*

Achieving excellence in engineering education: the ingredients of successful change

The Royal Academy of Engineering (RAEng), UK, 2012

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Part I

Introduction

'*The best investment in our future is the investment in our people. Skills and education drive Europe's competitiveness and innovation. But Europe is not yet fully ready. I will ensure that we use all the tools and funds at our disposal to redress this balance.*'

Ursula von der Leyen

President of the European Commission
Political guidelines for the next European Commission
2019-2024

About the Euro-CASE Engineering Education Platform: Engineering is the use of ingenuity to make innovations happen. Turning knowledge and innovation into the key enablers for the future economic development of Europe, especially its industry, requires various European stakeholders to focus explicitly, holistically and rapidly on engineering – its present as well as its future. In this context, engineering education gains a special, generic significance. Motivated by these facts, Euro-CASE has launched an internal project entitled the Euro-CASE Engineering Education Platform. The implementation of this project has been entrusted to the Euro-CASE Committee for Engineering Education.

The Euro-CASE Engineering Education Platform is designed as a continuous research and analytical activity focused on engineering and STEM education in Europe and the production of a new generation of technology leaders.

The first strategic goal of the Platform is to permanently observe and analyse the situation in the education sector on a holistic and systemic basis while taking into account:

a. the needs of society, especially the economy, industry, as well as the great social challenges of Europe,

b. the current needs of the profession and related reform processes in the sector of engineering and STEM education,

c. the needs of policy and decision-making in public administration, and

d. the dynamic processes in the sphere of business and labour market.

The labour market and the education system are two highly intertwined systems, with a strong mutual impact. Mass cybernetisation and the world gradually entering the Second Machine Age [1], i.e. the age of artificial intelligence, smart machines and robots, are leading the global economy into a new phase of development based on a new division of labour. At this time, however, labour is divided between humans and machines: the socialisation of technology is melding what was previously thought to be the interfaces between people and technology into one single system. To respond effectively to their professional life challenges, a new generation of engineers must therefore possess new literacy skills: fundamental, technical and humanistic, which will enable them to embrace the second machine age and find opportunities, rather than threats. Europe needs 'Robot-Proof' engineers – engineers who are able to respond to the needs of society to which even the most sophisticated smart machine cannot[2,3]. However, Europe also needs engineers who understand the social context – engineers with social intelligence, trained to be active citizens, active participants in political life. Engineers who possess technical excellence, ability to think critically, attitude and empathy. Modern engineers are thinkers as much as they are doers. This ideal is not easy to achieve. But it is not a matter of choice. It is a question of the existential imperative of a globalised world ruled by fierce competition. Therefore, the second strategic goal of the Platform is to innovate the education process by:

a. monitor the progress of research in the field of pedagogy and cognitive aspects of the education process,

b. do research in the field of curricular strategies, and

c. innovate the education process through the application of new learning methods and new digital technologies of organisation and monitoring of the learning process, both in the classroom and outside.

The Euro-CASE Engineering Education Platform has the ambition to become one of the leading fora for a wide range of topics related to engineering and STEM education in Europe. Euro-CASE is a community of 24 national Academies of applied sciences, technology and engineering sciences in Europe, with over 6,000 members who are national leaders in the field of engineering and STEM, and includes experienced professors who have built their professional careers in engineering education either as researchers in laboratories, senior managers at universities and institutes, or, often, as high public officials. This scope and diversity of expertise concentrated in one place is a unique resource in Europe, and acts as a guarantor of the success of the Euro-CASE Engineering Education Platform in its intention to contribute to a constructive dialogue on the future of engineering and STEM education in Europe.

Priorities: Analysing the current state of engineering in Europe and worldwide, the Euro-CASE Committee on Engineering Education has identified two sets of priorities:

a. strategic, or general priorities, which require a broader time frame for the research and a broader social dialogue between different

1 Brynjolfsson, E. and McAfee, A. (2014). "The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies", New York: W. W. Norton & Company. ISBN: 0393241254.

2 The new mode of education of engineers which nurture our species' unique traits of creativity and flexibility, and prepares graduates to successfully compete in a labour market in which brilliant machines work alongside human professionals. More details in: Aoun J. E., (2017) Robot-Proof: Higher Education in the Age of Artificial Intelligence, The MIT Press, Cambridge, Massachusetts, ISBN-10: 9780262037280

3 Siemens Podcast Network, Developing Robot-Proof Engineers in the Classroom https://blogs.sw.siemens.com/podcasts/innovation-in-the-classroom/developing-robot-proof-engineers-in-the-classroom/

stakeholders in their search for adequate solutions and satisfactory compromises, and

b. immediate priorities, which are related to the ongoing processes in the implementation of the current policies in the education and other related spheres of social life in Europe, and which all demand an immediate and agile reaction.

The first set of priorities is classified into five clusters of topics, highly relevant for the future of engineering:

a. **Engineering and knowledge economy:** What is the position of engineering and what role does it have, and should it have, in the transformation processes of building a knowledge-based economy? This is especially important in the domain of digital transformation of European industry and development of the next generation of manufacturing that will enable reindustrialisation of European economic space on socially, economically and environmentally sustainable foundations? What is the specific role of engineering and engineering education in the context of one of Europe's highest political priorities: the European Industrial Renaissance? Europe's industrial future depends on engineering, but this in turn depends equally on the sector's large-scale presence, and the talents and creative potential of European engineers: so how will Europe ensure that the talents and creative potential of future generations of engineers are realised?

b. **Interaction between engineering and science:** What is the intrinsic nature of the interaction between modern engineering and science and what is the role of engineering in the conversion of ideas and inventions ('scientific knowledge') into immediately useful knowledge ('productive knowledge') or innovation, which we interpret as successful products or services? What are engineering sciences and what is the relationship between engineering sciences, technology, and the applied and natural sciences? What is the interaction between modern engineering and social sciences, humanities, the arts, and culture, and what is the position and role of modern engineering in the so-called third culture? How to establish a bridge between engineering and philosophy? How to harmonise the overall space of engineering, determined by the (quasi-)dichotomous partition of engineering into, on one side, a science (a corpus of creative engineering – engineering sciences), and, on the other, engineering as a profession (a corpus of analytical engineering), and especially, the interaction between these two seemingly distinct poles?

c. **Interaction between engineering and people:** How does engineering manage its interactions with people? As a servant of society that desperately needs sustainable development, engineering needs to create new opportunities for people now in a way that leaves realistic opportunities for future generations to be able to meet their future needs (even though we do not know what these might be). The melding of technology with people, through making better interfaces, including physical, virtual, cognitive, intelligent and cybernetic processes, is a primary issue for engineering at this time. This places a whole new emphasis on this relationship: beyond just enabling people to operate or live with technology, this means creating new symbiotic relationships between people and technology. We call this the fifth industrial revolution: the socialisation of technology. The socialisation of technology requires engineers to create the technology with people at the centre of their thinking, right at the start of the creative process, rather than as something outside the actual engineering challenge, to be thought about later. This in turn will require new engineers who are empathic towards the people – engineers who understand not only what people need, but how they think and consider their alternatives for attaining a better quality of life in the future as individuals and as a society.

d. **Engineering and innovation ecosystem:** What place and what role does modern engineering play (and what role should it play) in the development processes of the innovation and entrepreneurial ecosystem of Europe? The answer to this question needs to take into account the domain of R&D-based innovations (both radical / disruptive and incremental / sustaining innovations) as well as the often neglected domain of so-called non-R&D-based innovation (meaning three manifestations: technology adoption, imitation and minor modification, and innovative marketing)? Is the innovation process possible without engineering and is the university sector able to accomplish its third mission of entrepreneurial university and entrepreneurial science without engineering?

e. **Transformation of the engineering education sector:** What are the implications of all the above for the engineering education, who are the key drivers of reform changes in the time horizon of 10, 20 or 50 years? In fact, it is a fundamental issue for the production of European engineers for the 21st century. What are the key drivers, challenges and barriers of the reform processes of the European system of engineering education, and what are the specifics of the above in relation to the ongoing transformation processes of the European Higher Education Area (EHEA) aimed at strengthening the university sector's third mission and knowledge capitalisation (academic entrepreneurship, entrepreneurial university and entrepreneurial science)? Then, what substantial contributions can engineering education make in the context of the European Universities Initiative, as well as many other relevant topics and priorities such as those contained in the Yerevan Ministerial Communiqué (for example, pedagogical innovation in student-centred learning environments) and the implementation of the Bologna process[4] in general? Or UN Sustainable Development Goals and initiatives related to that platform such as 'WFEO Engineering 2030 Strategic Plan', produced by the World Federation of Engineering Organization [5] ? Then, a very general question concerning the position of European engineering in a global context: Can European engineering education meet not only European, but above all, global challenges? Well, perhaps the most significant issue / challenge / dilemma facing universities in the 21st century: the university at the crossroads between 'humanism and the market' and the search for viable answers to the long-standing controversy over useful knowledge (and usefulness of useless knowledge) as well as position of engineering in that context.

The complexity of these five clusters of issues, which are strategic for European engineering, imposes the need to initiate a broader long-term social dialogue, with the aim of thoughtfully reaching answers relevant to the future of engineering in Europe through the consensus of various

[4] The European Higher Education Area in 2018: Bologna Process Implementation Report. Luxembourg: Publications Office of the European Union, ISBN 978-92-9492-740-8, doi:10.2797/265898.

[5] World Federation of Engineering Organizations (WFEO), (2018) Engineering 2030 - A Plan to advance the achievement of the UN Sustainable Development Goals through engineering, http://www.wfeo.org/wp-content/uploads/un/WFEO-ENgg-Plan_final.pdf

stakeholders and perhaps launching a broader reform process related to the need to build a new identity and a role for contemporary engineering in Europe enframed within what might be called the 'European Engineering Renaissance'. Such a dialogue, regardless of its long timeline, should be accompanied by a parallel production of concrete solutions at both the policy level and the level of practical implementation of the policies. This is necessary so that the overall process will be productive, essentially transformative, and have an evolutionary character with a positive gradient of change.

In this context, the Euro-CASE Committee on Engineering Education is interested and open to establishing cooperation and partnerships with the national academies of science and engineering, and with specialised institutions or associations active in the field of engineering and STEM education, such as LERU[6], CASEAR[7]; SEFI[8], EUA[9], and others, then specialised working groups such as CAETS Discussion Group on Engineering Education[10], and institutions such as the EIT[11] that carry out their work activities in domain of education within the so-called Knowledge Triangle. Also, the Euro-CASE Committee for Engineering Education is interested in cooperation on these issues with the European Commission bodies that are directly or indirectly involved in engineering education and engineering in general, including innovation, industrial development and the like, where some form of scientific / engineering advice can be relevant to policy-making activities.

Notwithstanding the need for long term strategic thinking about engineering and its ongoing and future role in European society, we also need to take care about the situation now. Issues relevant at present for engineering in Europe, predominantly focused on engineering education and the reform processes taking place in the sector, are a top priority of this report. These are discussed in Part II of this report, through an analysis of engineering in a broader context spanning the progress of engineering over its historical timeline, its relationship to science, economics and society, to topics related to university reform, especially where this affects and is affected by the engineering education sector.

Further, this report discusses a selected group of the most significant challenges (Part III) and a set of selected topics related to systemic issues of transformative processes (Part IV) in the sector of engineering education in Europe.

The report's target audience: The report is intended for the professional community engaged in research in the field of pedagogy, methodology, technology and education practice in general, in particular engineering and STEM education, then for universities, associations and other stakeholders working professionally in engineering and STEM education, or are professionally interested in the subject (labour market, for example).

In addition, this material is relevant to the policy-making sector, the European Commission and other regulatory bodies at the EU level, or equivalent regulatory bodies at the level of EU member countries. Consequently, this

[6] The League of European Research Universities (LERU), is an association of some of the most renowned research universities in Europe. Founded in 2002, as a partnership of 12 leading research universities, the League expanded its membership to 23 universities in 2017.

[7] Conference of European Schools for Advanced Engineering Education and Research (CESAER), founded in 1990, is the European non-profit association that unites 53 leading universities of science & technology from 25 countries.

[8] The European Society for Engineering Education (SEFI), is an international association of more than 300 members: Higher engineering institutions, professional societies, student associations, students, academic staff, engineers and companies. Active since 1973.

[9] The European University Association (EUA), represents more than 800 universities and national rectors' conferences in 48 European countries. EUA was formed in 2001. EUA plays a crucial role in the Bologna Process and in influencing EU policies on higher education, research and innovation. EUA fully upholds the values and principles enshrined in the Magna Charta Universitatum.

[10] Council of Academies of Engineering and Technological Sciences (CAETS), founded in 1978 as an organization of national engineering and technological sciences academies. CAETS membership spans 30 countries distributed across six continents of the world.

[11] The European Institute of Innovation & Technology (EIT) is an independent body of the European Union set up in 2008 to deliver innovation across Europe. The EIT brings together leading business, education and research organisations to form dynamic cross-border partnerships.

report can be considered as a kind of public, informal evidence-based scientific advice for engineering and STEM education in Europe.

Finally, this report is of importance to the engineering industry itself. The education of engineers is of primary importance to the future of engineering in Europe and it is clear that industry needs to play a part in the reforms being considered in this report. Defining how this role should be designed and operated, and how industry and the education sector could work together to create a strong future for engineering, are two core elements of the thinking needed in industry in the coming years.

In addition to the aforementioned audiences, and equally important, this report is intended for the Euro-CASE member academies and their working bodies dealing with the topic of engineering education.

Approach: The report is based on a systematic analysis of the relevant literature in the field of engineering and STEM education. In the first phase, the collection and systematisation of extensive written literature was carried out, starting from scientific papers, books, position papers, reports, ... to policy documents, relevant to higher education in general, and especially engineering and STEM education. In the second phase, analytical and added-value activities were conducted with the aim of formulating responses to the selected topics and a set of related questions.

In addition to the above, the Report is largely based on the extensive experience and expertise of Committee members and accompanying working teams who actively participated in the work of the Euro-CASE Committee on Engineering Education.

From the methodological point of view, SCRUM and Soft Systems Methodologies were used in the activities of analysis of collected data and added value activities.

Work activities included one-day or two-day physical work meetings, both closed and open. As a rule, open meetings were organised with the host Academy and some of the representative universities in its immediate vicinity (University of Belgrade, Faculty of Mechanical Engineering; Institute of Product Engineering (IPEK), Karlsruhe Institute of Technology (KIT); University College London (UCL), Faculty of Engineering Sciences; Vienna University of Technology, TU Wien), or local industrial enterprises, for example, Dassault Systèmes SE, a large software company which is one of the leading European and world manufacturers of specialised engineering design tools and whose business portfolio also includes activities of non-formal engineering education through Dassault Systèmes 3DEXPERIENCE Edu Academy.

The chronology of physical working meetings:

1. Belgrade, September 13-14 2017 - Academy of Engineering Sciences of Serbia (AESS) and University of Belgrade, Faculty of Mechanical Engineering;
2. Paris, March 6-7 2018 - National Academy of Technologies of France (NATF);
3. Karlsruhe, September 13-14 2018 - National Academy of Science and Engineering (acatech) and Institute for Technology (KIT), Institute of Product Engineering (KIT-IPEK);
4. London, March, 19-20 2019 - The Royal Academy of Engineering (RAEng) and University College London (UCL), Faculty of Engineering Sciences;
5. Vienna, October 10-11 2019 - Austrian Academy of Sciences (ÖAW) and Vienna University of Technology, TU Wien.

Part II

General observations

Key points

- The industrial economy and engineering are co-evolutionary systems. Industrial economy defines the essence of the identity of modern engineering and all aspects of its extensive interaction with society. Without engineering, there can be no industrial economy, no prosperity, nor wellbeing.
- Through the consistent application of the engineering method, engineering creates its own knowledge that differs from the knowledge of the world of science. This is the knowledge we call the engineering sciences.
- From the perspective of engineering education, perhaps the most rational solution to bridge the existing gap between STEM and STS is by extending STEM into a sTEmS composite, which would be shaped that way to effectively integrate an aggregate of social sciences, humanities and culture / art into the STEM framework.
- Engineers are true masters of innovations. They turn ideas and scientific inventions into products and businesses. If we want innovative engineers we must educate them to be innovators.

'*Engineering is not only instrumental to other human ends, it is in itself an existentially meaningful activity. Engineering possess inherent or intrinsic as well as instrumental or extrinsic value.*'

Carl Mitcham

Philosopher of technology and professor
of Liberal Arts and International Studies
at the University of Colorado.

The exponential development of science, technology and engineering is changing the world we live in at an unprecedented rate. In addition to the evident progress, these changes are accompanied by uncertainties and a broad spectrum of so-called Grand Societal Challenges that are essentially global and for which no quick or easy solutions can be found, regardless of the effort that is invested and the commitment. In such an environment, Europe shapes its identity and strongly directs its development policies towards building a democratic, inclusive and prosperous society. This society bases its economic sustainability on two key components: (a) a knowledge-based economy, driven by a strong, digitalised and globally competitive manufacturing industry, and (b) vibrant innovation and entrepreneurial ecosystems that underpin successful socio-economic development and, in particular, the global competitiveness of European enterprises. In such an envisioned future, knowledge plays the role of a strategic intangible asset of the utmost importance.

2.a Context

To create a fertile environment for the production of knowledge and then its diversification, dissemination, networking, and in particular, its effective use and capitalisation through innovation processes and entrepreneurship, the European Union is building a wide corpus of linked policies, strategies, initiatives and instruments. At the highest policy level, these are strategic multi-year programs such as: Innovation Union, Framework Programmes for Research and Technological Development (FPx), European Technology Platforms (ETP), or Smart Specialisation Platform (S3 Platform) and the related Regional Innovation Strategy (RIS). These programmes are pan-European in character, and immense funds are allocated for their implementation. For example, FPx is one of the largest scientific funding initiatives in the world.

Education policy in Europe is regulated predominantly in national frameworks - each European country is responsible for its own education and training systems[1]. EU policy in this field is designed to support actions at the national level to help address common challenges and to promote the free movement of knowledge throughout the Union. Collaborative activities at the policy level have a broad scope and can be clustered into three groups:

a) activities related to fundamental issues of the interaction of education and European society, for example 'Strengthening European Identity through Education and Culture', 'Supporting Growth and Jobs – An agenda for the modernisation of Europe’s higher education systems', or the Vilnius Declaration focused on the integration of Social Sciences and Humanities (SSH) into education and science, through fostering interdisciplinary training and research, recognising knowledge diversity, and collaborating effectively on these issues;

b) activities aimed at leveraging the implementation of current policies in a constantly changing reality, for example 'On a Renewed EU Agenda for Higher Education' (this clearly indicates a high degree of agility in monitoring the situation in the field and consequently, the importance of education in Europe’s political agenda), and

c) tailored initiatives or instruments focused on narrowly focused topics, such as 'On the Digital Education Action Plan', which brings into political focus some very specific issues of education digitalisation in Europe, such as

    i. new learning tools, materials and open educational resources,

    ii. opening classrooms and

    iii. real-life experiences, and empowering the educational process by online technologies and online collaboration.

   Collaborative activities at the policy level have been consistently carried out for many years in a row, with them being of a reform character, and the efforts exerted become more intensive over time.

In the context of the aforementioned initiatives, it is important to mention the initiative to establish European Universities[2] as a key player in the European Commission's ambitious plan for establishing a European Education

[1] The Treaty on the Functioning of the European Union, Article 165: 'The Union shall contribute to the development of quality education by encouraging cooperation between the Member States and, if necessary, by supporting and supplementing their action, while fully respecting the responsibility of the Member States for the content of teaching and the organisation of education systems and their cultural and linguistic diversity.'

[2] European Universities are transnational alliances that will become the universities of the future, promoting European values and identity, and revolutionising the quality and competitiveness of European higher education.

Area by 2025. This initiative has its roots in the conclusions of the Gothenburg Social Summit[3], in which European Union leaders expressed their political will for a much deeper level of cooperation between universities, with the aim of fostering excellence, innovation and inclusion in higher education across Europe, and thus accelerating the transformation of higher education institutions into the universities of the future with structural, systemic and sustainable impact. The transformative processes covered by this initiative are focused on three groups of highly relevant topics:

a) Flexible and personalised European curriculum with embedded mobility leading to a European degree,

b) Innovative pedagogies with a challenged-based transdisciplinary approach to foster entrepreneurial mindsets and civic engagement, and

c) Enhanced staff mobility between partner institutions to teach/do research/work and equip students with a broad range of forward-looking skills.

The importance of this and other pan-European cooperation related to human capital production (for example, the ERASMUS+ programme with a budget of €14.7 billion for 2014-2020) has been recognised by the new Commission as one of its explicit priorities, with a clear political determination to further strengthen the European space for knowledge creators to be ready to respond to Europe's societal challenges[4]. The initiative to set up European universities and establish a European Education Area is just one component of a wider pan-European programme, called the Bologna Process[5]. It is obvious that pan-European cooperation in the higher education area is dynamic, expansive and very complex in operational terms.

Activities at the policy level are accompanied by efforts to build an appropriate pan-European institutional framework for their effective implementation. For example, the European Institute of Innovation and Technology (EIT), was established by the European Commission in 2008 with the aim of increasing Europe's ability to innovate by nurturing entrepreneurial talent and supporting new ideas. The key mechanism for achieving this goal is the building of so-called Knowledge and Innovation Communities (EIT KICs). EIT KICs are basically pan-European cPPPs[6] of leading higher education institutions, research organisations, companies and other stakeholders from the European innovation ecosystem. These superstructures (system of systems) are thematically focused on some of the European policy priorities and/or societal challenges, such as digitalisation, energy, food, climate, urban mobility, or manufacturing, for example. They are designed to be operational in a decades-long time frame, with the aim of catalysing innovation in the so-called Knowledge Triangles, which consist of: Higher Education – Research and Technology Innovation – Business and Entrepreneurship. In a way, the EIT can be seen as a conceptual protomodel of the world-class universities of the modern world. The fact that all active KICs are focused on very practical

[3] European Commission, Social Summit for Fair Jobs and Growth - CONCLUSIONS, Gothenburg, Sweden, 17 November 2017; European Council, European Council meeting – Conclusions, EUCO 19/1/17 REV 1, CO EUR 24 CONCL, Brussels, 14 December 2017; European Commission, European Universities - A key pillar of the European Education Area, European Commission, 7 November 2019.

[4] Ursula von der Leyen, A Union that strives for more, Political guidelines for the next European Commission 2019-2024.

[5] The Bologna Process is a political mechanism for promoting intergovernmental cooperation between 48 European countries in the field of higher education. Under the Bologna Process, European governments engage in discussions regarding higher education policy reforms and strive to overcome obstacles to create a European Higher Education Area. It calls for: (a) an inclusive and innovative approach to learning and teaching, (b) integrated transnational cooperation in higher education, research and innovation, and (c) securing a sustainable future through higher education. As part of the European Higher Education Area, all participating countries agreed to: (a) introduce a three-cycle higher education system consisting of bachelor's, master's and doctoral studies, (b) ensure the mutual recognition of qualifications and learning periods abroad completed at other universities, and (c) implement a system of quality assurance, to strengthen the quality and relevance of learning and teaching. The Process officially started in 1999. http://www.ehea.info/index.php

[6] cPPPs stands for Contractual Public-Private Partnerships.

and societally important topics, and highly related to technology and engineering, makes these ideal entities for the implementation of innovation. Within this, the EIT model of integration of education into the knowledge triangle, as well as the concrete activities of its implementation in practice ensures that these are recognised as particularly relevant for the Euro-CASE Engineering Education Platform.

In order to fully understand the environment in which the processes related to the creation, production and dissemination of knowledge take place, it is necessary to include another very important system. This is the labour market - its current state, the dynamics of the processes that take place within it, and the relevant policies that govern this system. The labour market is always one of the main drivers of transformation processes in the education sector. Quantitative statistical analyses show that 'by 2025 almost half of all job openings in the EU will require higher qualifications, usually awarded through academic and professional programmes at tertiary level; skills developed through these programmes are generally considered to be drivers of productivity and innovation'[7].

Various types of imbalances between the supply of graduates and the knowledge and skills the economy needs, generate impulses to which the education sector must listen and react. Field analyses show that over two thirds of students and recent graduates perceive a mismatch between the supply of graduates and the types or forms of the knowledge and skills that the economy needs. Undoubtedly, these findings are very disturbing. This is a red alert for Europe's education sector! However, there is an additional problem. This is methodological: our technical ability to effectively monitor the situation in the field.

Skills and competencies *per se* are not measured by the regular statistical programmes of most countries[8,9]. Therefore, special attention, as an example of good practice and possible direction of further action, is gained by initiatives such as ETER-Project[10], whose primary goal is to build a reliable database on higher education systems in Europe, and lays the groundwork for evidence-based policies for the modernisation of European higher education based on new foundations. Another example is the EU-wide graduate tracking system which is implemented by the European Commission, in order to understand better the labour market situation, and to prepare a better European education for tomorrow's challenges. Another initiative was the European graduate pilot survey, which reached out to bachelor, master and tertiary short-cycle graduates one and five years after graduation in eight countries[11].

The knowledge creation sector and the labour market must be observed holistically, as a composite of two coevolutionary systems involved in a highly intertwined, deep and complex interaction, with a significant time lag in the causality of mutual actions and reactions. Prediction and management of the future, i.e. answers to the enigma we call the Future of Work, requires the

7 European Commission, A NEW SKILLS AGENDA FOR EUROPE - Working together to strengthen human capital, employability and competitiveness, COM(2016) 381 final, Brussels, 10.6.2016.

8 Skills mismatch in Europe: Statistics brief / International Labour Office, Department of Statistics. - Geneva: ILO, 2014, ISBN: 9789221290438.

9 OECD (2019), OECD Employment Outlook 2019: The Future of Work, OECD Publishing, Paris, ISBN:9789264497009.

10 ETER-Project - The European Tertiary Education Register, https://www.eter-project.com/#/home

11 Characteristically, this pilot study also touches on very particular topics for the educational process, such as increasing the level of problem-solving skills (a skill typical of engineering!). The concept of 'activating learning environment', where lectures are complemented with problem-based and work-based learning, provides better preparation for the labour market. The experiences show that study-related work experience as part of the curriculum reduces by nearly half the risk of being unemployed or in a lower-skilled job. More details can be found in: Meng, C. at al. (2020), EUROGRADUATE Pilot Survey - Design and implementation of a pilot European graduate survey, Directorate-General for Education, Youth, Sport and Culture, European Union, ISBN 978-92-76-17882-8, doi: 10.2766/629271; and Beadle, S. at al. (2020), Graduate tracking: a 'how to do it well' guide, ICF Consulting, EUROPEAN COMMISSION, Directorate-General for Education, Youth, Sport and Culture, ISBN 978-92-76-18132-3, doi:10.2766/263936.

application of modern analytical tools, including computer simulation of complex dynamic systems. Labour market research is a topic to which Euro-CASE attaches particular importance. It is entrusted to the Committee for Euro-CASE Future of Work Platform, which consists of a number of Engineering Academies, that are also members of Euro-CASE.

It is quite clear that the successful development of the European economy, especially its industry, whose growth and competitiveness are extremely sensitive to human capital, imposes the need for an explicit and more intensive focus of society on engineering knowledge and engineering skills. Engineering knowledge and skills are needed in European industry in all its sectors, from energy, mobility, communications, health, pharmaceuticals, and in turn to construction, and especially manufacturing, but also the creative industries, and the implementation in society of findings from the social sciences. In short, engineering knowledge and skills are necessary in all areas, because the analytical and synthetic mind, systems thinking and project management skills inherent in the engineering mind are universally applicable. These facts are clearly recognised within the engineering community and its circle of stakeholders. However, this is not the case with the wider community, including policy makers.

Engineering is simply not visible enough in the aforementioned corpus of tailored policies to create a fertile environment for knowledge production and its effective application and capitalisation through innovation processes and entrepreneurship. At present, this is embedded neither in an explicit form, nor to a sufficient extent in society's endeavours. Quite simply, the importance of engineering for the economic and social development of Europe is still out of focus – not well communicated to, and not well understood by, all stakeholders and other important social actors. Motivated by this situation, the Euro-CASE Committee for Engineering Education expresses its view that there is a need to establish a dialogue of this kind, in order to obtain satisfactory solutions to key issues of the present and future of engineering in Europe through a broader consensus of different stakeholders. In this regard, it is necessary to launch appropriate activities in the short to medium term that will have, as a basic outcome, visible progress on the creation of the desired multivalent fertile environment, and the production of associated concrete solutions, both at the policy level and at the level of their practical implementation. Europe needs a European Engineering Renaissance, and it needs a plan to stimulate it in the short term.

2.b General observations on engineering and engineering education

A relatively small fraction of the overall population undertakes the rigorous education and training required to become a professional engineer. This cohort often proceeds to carry a huge responsibility for the delivery to wider society of enormously complex working practical devices, systems and services.

The wider societal community of recipients and beneficiaries of this work often remains largely unaware of the extent to which their standard of living ultimately depends on the success of engineering endeavours. Complex products, services and working systems used daily by almost the entire population are made available at remarkably low cost and exceptional reliability to a public that often has little or no insight into the efforts and achievements behind the scenes that have conspired to create these aids to their wellbeing and quality of life. Making these achievements invisible to their beneficiaries is, paradoxically, one of the markers of 'good engineering'. Examples are the supply of electricity, fossil fuel supply to local filling stations, vehicles and land, sea and air-based transportation services, supply chain logistics, clean water supply and waste water treatment, computing, telecommunications and internet services, low-cost mass and customised manufacturing of goods and appliances used for labour saving and for leisure and entertainment.

This ignorance is, in a way, a sign of the success of engineering: it is so well embedded in society that people are quite unaware of the engineering activity that brings them the satisfaction of their needs. However, this imposes the need to find answers to a number of questions concerning the identity of engineering: what exactly is engineering, what is engineering thinking, what is engineering knowledge, what is the engineering method in creating engineering knowledge and its application through engineering practice? It is especially important to articulate answers to these philosophical and at the same time very practical questions, in a way that is comprehensible for a wider, non-engineering community.

It is also necessary to draw the attention of policymakers linked to the STEM (Science, Technology, Engineering, and Mathematics) sector to a specific and highly significant role of the E component in the STEM conglomerate. The need to profile today's prevailing amorphous view of STEM into something that we would formulate as stEmS (science, Technology, Engineering, mathematics, Society, capitalised to emphasise the priorities for engineering), as a new framework which would enable a more explicit recognition of the role and responsibilities of engineering in modern society. Engineering is the utilisation of ingenuity to make innovations happen. This applies across all sectors in society, and refers to strengthening competitiveness, maintaining the position of a global leader in innovation (especially in the manufacturing industry!) and Europe's engineering-dependent ability to respond effectively, and in a timely manner, to the great societal challenges it faces.

What is engineering then? Do engineers have an identity crisis? Are engineers thinkers or makers, or both? What defines engineering and what is the nature of engineering? After all, what do engineers do and how they contribute to society, explained in simple terms?

2.b.1 Basic determinants of engineering

Knowledge-based economy: As stated above, Engineering is the utilisation of ingenuity to make innovations happen. Modern engineering[12] is inseparable from the industrial economy, a new paradigm of making that has dominated the global economic space for more than the two centuries since the first Industrial Revolution, and on which the growth and economic sustainability of our civilization rests – both now and in the future. Without engineering, there can be no industrial economy.

The primary innovations of the industrial economy, such as the steam engine, the machine tool, (the mother of all machines!), or the factory, are basically engineering creations, regardless of the indisputable contribution of the wider context in which they were made. James Watt, Henry Maudslay and Matthew Boulton, were gifted engineers, ambitious entrepreneurs and visionaries. With their revolutionary ideas and synthetic spirit, they managed to find content in

[12] Modern engineering is associated with the industrial revolution and the birth of the industrial economy and as such separates itself from the ancient and wider historical period (pre-industrial) in which the characteristic form of material creation attributed to engineering today also existed, but it also evolved and existed in a fundamentally different social environment. The industrial economy is not only a consequence of the emergence of industry, but is the result of long-lasting and very profound social changes. This context is very important for a deeper understanding of engineering, which is not just an economic or technological phenomenon, but primarily a social one.

the then corpus of accumulated scientific knowledge and skills from which it was possible to create new values, relevant to business, the life of the common man and society as a whole. In this case, it was the new concepts and physical artefacts from which the global industrial system was built over time, an immense technological-organisational-social construct that 'bent the curve of human history – of population and social development – almost ninety degrees'[13]. Engineering leads to profound social changes and thus changes the world in which we live. Also, it is important to note that engineers were 'the first masters of modern enterprise'[14].

Even today we can see an equivalent contribution of engineering, albeit in a substantially altered and significantly more complex context of social and economic development that is dubbed by Erik Brynjolfsson and Andrew McAfee as 'The Second Machine Age'[15]. It is the age of digital machines, global communications, robots and artificial intelligence, modern drivers of prosperity, who, through enhancing the mental power of our brain, also enhance our ability for mastering our physical and intellectual environment. Access to practically infinite data, almost unlimited processing power and almost no latency in response has a disruptive impact on the economy and society as a whole. Primary innovations of the second machine age, such as the semiconductor transistor, digital computer, communication satellite, or mobile wireless communication, accompanied by an almost innumerable series of clusters of co-innovations, are basically the product of engineering creativity. Just as it was more than two centuries ago, at the dawn of the industrial manufacturing paradigm, engineering knowledge, skills and creativity are indispensable components of this transformation process.

The industrial economy of the modern *homo-economicus* and engineering are co-evolutionary systems. Engineering transforms the economy, and economy transforms engineering. From the perspective of economics, industrial economy defines the essence of the identity of modern engineering and all aspects of its extensive interaction with society.

The industrial economy today is the same as the knowledge-based economy. This statement has a multifold significance for engineering, and especially for the engineering education sector and the reform processes taking place at the university. In order to understand them more profoundly, it should be noted that these reform processes are not novel. They are rather a long-standing continuum. Today’s narrative essentially relies on the same concepts and phenomena, which were recognised many decades ago in a phase of modern social development, which the influential business thinker Peter Drucker characterises as 'The Age of Discontinuity'[16]. In his book first published in 1969, Drucker recognises tectonic processes in the global economic system that he argues 'while still below the visible horizon, (they) are already changing the structure and meaning of economy, polity, and society' and explores possible responses of society through, the then completely unknown, concept of Knowledge Economy. This was a new economy in which the availability of productive knowledge, not experience(!)[17], becomes a key factor in economic and overall social development: '... knowledge, during the last few decades, has become the central capital, the cost centre and the crucial resource of the

13 Morris, I. (2013). "The Measure of Civilization: How Social Development Decides the Fate of Nations," Economics Books, Princeton University Press, edition 1, number 9830.

14 Goldberg, D. E., (2005). 'The Entrepreneurial Engineer: Personal, Interpersonal, and Organizational Skills for Engineers in a World of Opportunity', John Wiley & Sons, Inc., ISBN:9780470007235, DOI:10.1002/0470038969.

15 Brynjolfsson, E. and McAfee, A. (2014). "The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies", New York: W. W. Norton & Company. ISBN: 0393241254.

16 In order to understand the term 'the Age of Discontinuity', the term 'the Age of Continuity' should be defined. For Drucker, the age of continuity is an age of slow evolutionary change, an age in which 'continuity' extends yesterday's trends into tomorrow.

17 The term experience here implies tacit knowledge and skills acquired through practice, outside of formal education, in the field of natural sciences.

economy ... this changes labour forces and work, teaching and learning, and the meaning of knowledge and its politics ... but it also raises the problem of the responsibilities of the new men of power, the men of knowledge.'[18]

The new 'man (or woman!) of power'[19] is the Knowledge Worker.

From the perspective of knowledge production, the knowledge worker is the basis of all reform processes that have taken place at technical and STEM universities in the last half-century. These are the processes of capacity building for the effective production of new intellectual capital for the modern industrial economy, or knowledge-based economy. This is also the essence of the transformation of a traditional university into a so-called research-intensive university. It is possible to show that in these transformation processes, engineering has a very important role, as well as the inherent potential for resolving many controversies that exist in this regard, both at the university and in the wider community. This primarily refers to the controversy of so-called 'useful knowledge'.

Engineering-Science relationship: The symbiotic relationship between engineering and the industrial economy is one of the basic building blocks of the identity (and essence) of modern engineering. This relationship obviously profiles engineering as a practice-oriented discipline, and the engineer as a person educated for practical action, implying both good practical skills and habits of mind, something that in the broadest sense could be described as a practical virtue. The engineer is therefore a *homo faber* – Man the Maker, or, more urgently, 'Man the Doer'.

But doing, implicitly means knowing. An engineer is also a thinker - *homo excogitatoris*.

This dualism directs us to explore the relationship between engineering and the world of science. It also reminds us of the necessity of erasing the long-standing division between 'hand' and 'mind' that has helped foster social stratification for millennia. This is encapsulated in the concept of 'ingenuity', and is the primary province of the engineer: *homo inegeniosus*.

The relationship between engineering and science is quite intricate.

We usually talk about how engineers use scientific knowledge and mathematics to solve engineering problems, primarily in engineering design. That is quite true. Reliance on the natural sciences and mathematics, to call it the process of scientisation of engineering, has separated traditional from modern engineering. The engineering that created the industrial economy was based primarily on experience, skills and intuition. It was not until the nineteenth century, when engineering found its place under the auspices of a traditional university, that the engineering method began to rely on science, the process of engineering creation, that is, engineering design, relied on findings in natural sciences and the exactness of engineering was based on a rigorous mathematical apparatus.

However, beneath the visible relationship between engineering and science, there is another layer of communication. Through the utilisation of scientific knowledge, engineering recognises those findings that can be immediately applied in practice[20] (immediately relevant knowledge) through the making of physical or abstract artefacts that meet the specific needs of society. In modern jargon, these are products and / or services that are placed on the market, thus

[18] Drucker, P. (1969), The Age of Discontinuity: Guidelines to our changing society, Butterworth-Heinemann, eBook ISBN: 9781483165424.

[19] The association with Bacon's '*ipsa scientia potestas est* – knowledge itself is power and its timeless, revolutionary contribution to directing human thought towards the practical, experiments, and natural sciences, which would later serve as the foundations for the liberal democracy and economics we know today; Francis Bacon, Novum Organum, sive Indicia Vera de Interpretatione Naturae, 1620.

[20] S. P. Nichols, W. F. Weldon, (1997), 'Professional Responsibility: The Role of the Engineering in Society', Science and Engineering Ethics, vol. 3, pp. 327-337.

reaching a specific user, regardless of who he/she is. Such products are, as a rule, innovations. If their source is scientific inventions, then these products are so-called disruptive innovations, economic singularities that dramatically change the state of affairs in the economic space, and then in the whole society (for example, the previously mentioned steam engine, computer, or mobile communications). This hidden communication channel between engineering and science is extremely important. It makes it possible for scientific knowledge to reach society quickly. It allows inventions to become innovations. It makes science innovative. This symbiotic relationship between engineering and science, which unfortunately and for unclear reasons, is usually societally invisible, or rather blurred for many, even policy-makers charged with responsibility for scientific, innovative and industrial development policy, is an essential generator of our civilization's progress. Thus, engineering is not just a consumer of scientific knowledge. Modern engineering is much more. It fulfils the societal role of a 'smart agent' who builds and maintains a functional bridge that productively connects the worlds of science and society, often via the arts, and, by so doing, connects scientific knowledge with the needs of society and the ordinary citizen with existentially important artefacts.

This explains a complex communication channel that functions in the direction from science to engineering, and further towards society. However, there is also a channel through which engineering and science communicate in the opposite direction. And that channel, like the one previously described, is not simple. It is also layered. First, engineering feeds science with physical artefacts that enable more efficient functioning of the world of science. To make science develop more easily and faster. To see nature deeper and clearer with its analytical eyes. For example, the Hubble Space Telescope, one of the key instruments of science for discovering the fundamental principles of the universe, is a marvel of engineering, a product of the finest engineering knowledge, skills, creativity and art of making. Engineering, therefore, can be viewed from the perspective of a key facilitator of the development of science, including both the natural and social sciences.

Second, engineering, through the consistent application of the engineering method, produces its own knowledge, knowledge that is different from that of the world of science. This is the knowledge we call the engineering sciences. The exceptional diversity of engineering has both good and bad sides. The diversity tends to create disciplinary siloes that sometimes create fissures in the smoothness of engineering knowledge and impede progress. However, in addition to its bad side[21], diversity also has its good sides. It encourages deeper investigation across a wide horizon of the details underpinning how to 'make innovations happen'. Resolving these two conflicting outcomes of diversity is crucially important in the education of engineers in the twenty first century. Engineering as a whole is synonymous with pluridisciplinarity. For example, what we usually call computer science today is nothing more than a very extensive aggregate of engineering knowledge, heavily based on natural sciences and mathematics, which together form a complete and stand-alone unit, an epistemological island in a very diversified corpus of engineering sciences.

The completeness here has the meaning of (self)sufficiency that such a conglomeration of knowledge produces a multitude of extremely diversified artefacts, physical and abstract, which not only satisfy the needs of society, but have the power to profoundly change it. The same is true of robotics[22], or

[21] Bad for engineering as, first of all, engineering is becoming more and more compartmentalised due to enormous and constantly growing diversification, and thus loses critical mass for shaping a unique and widely socially recognizable identity, and also a strong, united voice for its own social positioning.

[22] Robotics as a science is discussed by Prof. Maria Chiara Carrozza, former Italian Minister of Education and Science, in her book on robotics. Although robotics is an engineering discipline, it places it in the context of Robotic Science, emphasising the importance of knowledge which

genetic engineering, or aeronautical engineering, for example. There are almost countless examples like this! This new, or improved existing knowledge, multidisciplinary in nature, is added to the overall epistemological space of modern science, and almost as a rule, initiates new scientific research – in the world of natural and life sciences, but also in the world of social sciences and humanities and culture, and modern philosophies, too. Modern engineering, shaped in this way, and located somewhere between the world of science and everyday life of modern society, is building new epistemological scaffolding, which decisively directs scientific development towards the needs of society, needs that are not just a possibility for the future looming on the time horizon decades or centuries away from the present days, but on the time horizon that is placed in the reality of everyday life and the challenges it continuously imposes. These are the challenges that cannot wait, challenges that must be addressed immediately, without delay. From this perspective, engineering is a powerful, but paradoxically, not always sufficiently visible, instrument, which society inherently uses to bridge the gap between the world of science and the society in which that same science and engineering exist. The gap between the exponential multiplication of important knowledge about the world around us and the society that faces many challenges on a daily basis and which is forced to solve them immediately and effectively in order to develop further and thus move forward. Thus society is accompanied by science. But it is engineering that enables science to serve society's needs.

Another short addition to the previously described multidisciplinary aggregates of practically usable scientific knowledge, which is generated by engineering and which we rightly call engineering sciences. These structures should be viewed as dynamic. They are the product of the process of the continuous linking and re-linking, in specific clusters and configurations, of knowledge that is brought together on a temporary basis in specific contexts of application, which makes it strongly oriented to, and driven by, problem-solving[23]. This type of dynamics can be most simply explained with the example of a steam engine whose specific aggregate of scientific and engineering knowledge (and skills!), following the S-like shape of the accumulation time curve, was built in a long, centuries-long period. The steam engine rose to prominence in the nineteenth century because the price of grain rose exponentially as a result of the economic disasters across Europe during and following the Napoleonic wars of the late eighteenth and early nineteenth centuries. Science and engineering stepped up to the need to provide a cost-effective means of transport at a time when this was needed to drive the economics of the industrial revolution.

And then, with the arrival of a new technological wave, steam engine science literally became obsolete overnight. At the moment of its scientific and engineering culmination! Steam engines ended up in museums, and steam engine science ended up in the archives of technical libraries where it was soon covered with dust. The same happened with the engineering curricula of technical universities where mechanical engineering was taught. This situation, a kind of paradox, is inherent in science, but has been answered through Popper's instantiation of 'refutation' as a principle to underpin proof – nothing can be proved, only refuted, thus scientific knowledge is taken to stand temporarily and only until it has been refuted. Scientists are people of doubt, always testing the status of current knowledge. The dynamics of the

is necessary not only for the development of robotics, but its existence, too. In addition, starting from the position that solutions relevant to society are 'never confined to a single discipline' places robotics in a so-called anti-disciplinary context and sees it as 'a very courageous leap in quality, because it involves breaking the barriers and intersectoral differences' , which is part of a broader and perhaps much more important issue than a scientific, engineering or economic question 'of getting out of one's cultural domain and building a new, common one, developing new methods'. Carrozza, Maria. (2019). The Robot Inside Us: An 'Antidisciplinary' Perspective on the Scientific and Social Impacts of Robotics. 10.1007/978-3-319-97767-6_5.

23 de Figueiredo A.D., da Cunha P.R. (2007) Action Research and Design in Information Systems. In: Kock N. (eds) Information Systems Action Research. Integrated Series in Information Systems, Vol. 13. Springer, Boston, MA. https://doi.org/10.1007/978-0-387-36060-7_4

obsolescence of knowledge in the space of engineering knowledge, is different. Engineering knowledge is tested through application to achieve a desired outcome, and thus it becomes apparent (sometimes, immediately) if a particular idea or theory does not (or ceases to) work. The application cycle is then revisited so that improvements to try to make the required outcome are then tried and tested. In this way innovations happen. This is extremely important for the process of engineering education, especially when taking into account the fact that S-cycles of this type are getting shorter and shorter.

In addition to the above, it is especially important to emphasise another aspect of the return direction of communication in the very complex relationship between modern engineering and modern science. Recognising the scientific knowledge that is immediately relevant for practical use and enriching them with new insights gained through the experience of practical application, engineering comes to the position of a powerful instrument for effectively directing purely scientific research on topics and areas whose time horizon is close to capitalisation processes through the economic space of knowledge-based economy. In this way, engineering contributes in a very direct way to the strengthening of those scientific disciplines that are located within the framework of the so-called Pasteur's quadrant, i.e. 'basic science research that seeks to extend the frontiers of understanding but is also inspired by consideration of use'[24].

But how do things stand from an economic perspective? How does economy and the related logic of market and business understand a very complex and, for society quite potent, interaction between engineering and science?

First, what the world of science sees as knowledge, economy sees just as information, or even ordinary data. This view pertains as long as the information and data are in books, libraries, or on the Internet. The information becomes knowledge only when it is applied to do something because 'knowledge, like electricity or money, is a form of energy that exists only when doing work'[25]. This view of the space of scientific knowledge, certainly quite exclusive and categorical, stems from the understanding of knowledge as something that is a tool or instrument, which can be used to do something, or achieve a specific and purposeful goal. For economy and business, 'usable knowledge' is actually 'productive knowledge'. The dual nature of engineering, the engineer as a doer and thinker, in this context takes on a whole new meaning and further strengthens the position and role of engineering in its interaction with science. The engineering body of knowledge, in all its diversity, is inherently productive knowledge!

Second, for a knowledge-based economy, productive knowledge is really productive only when it is embedded in organisations and markets, and not when it exists only in the minds of individuals, no matter how smart they may be. Modern society is wiser (and richer) not because its citizens have become intellectually brilliant through a sophisticated education system, but because society possesses organisational mechanisms to accumulate, diversify and share productive knowledge, or know-how, and because it has the ability to

[24] The conventional one-dimensional conceptual space in which science is classified can be extended to a two-dimensional one. The vertical axis represents the degree to which a given body of research seeks to extend the frontiers of fundamental understanding – scientific rigor, while the horizontal axis represents the degree to which the research is guided by considerations of use – practical relevance. The two-dimensional conceptual space is further discretized into four quadrants. Pasteur's quadrant is determined by high scientific rigor and high practical relevance. It simultaneously fulfils two, seemingly incompatible tasks of modern science, thus creating a new conceptual subspace for building new policies for harnessing scientific development and scientific excellence, based on a dual dichotomy of epistemological basis, and not on the today's prevailing dichotomy. In this regard, the following reflections are possible on engineering and the issue of engineering science, and further on the so-called industrial research: '*The separation of 'pure' physical science from engineering has reinforced the impression of the inherent separateness of basic from applied science, and many of those who work on the physical science side of this divide see that split as validating the idea of an inherent separation of pure from applied. But a number of those who work on the engineering side of this divide see their fields, with some justice, as providing a home for research that is driven by the goals both of basic understanding and applied use.*'; Stokes, D. E. (1997). Pasteur's quadrant: Basic science and technological innovation, EDS Publications Ltd. ISBN 10: 0815781776.

[25] Drucker, P., 1969, The Age of Discontinuity: Guidelines to our changing society, Butterworth-Heinemann, eBook ISBN: 9781483165424.

recombine and integrate it into a larger variety of smarter and better products[26]. It is not an individual but a collective phenomenon. The knowledge worker is a concept that should be considered as a collective category. From an education perspective, this is a strong message for technical universities and curriculum creators.

The above points to a completely different attitude towards knowledge and the challenges associated with it. The long-standing controversy of useful knowledge, which has burdened the academic community[27], for decades, within itself and in relation to those who fund education and research, may be resolved through the economic perspective of understanding useful knowledge and thus lead to the necessary consensus to accelerate university reform. As a rule, universities regard themselves too narrowly, egocentrically, as exclusive carriers of knowledge, forgetting that the space in which that knowledge works and in which it gets its full meaning, real relevance for society, is not a university, but an economy. The knowledge-based economy is not a simple collection of smart individuals, graduates with impressive-sounding degrees under their belts. The knowledge-based economy is a system. Thus, an organised structure that possesses emergent properties and the ability to organise (and partly self-organise) potentially useful knowledge, which is imprinted in the brains of individuals through the process of education, in an effective way and thus make it productive for society. Only then does useful knowledge truly become useful. Part of that complex structure is the university. A part, not a universe unto itself. No matter how complex it is.

Philosophy of engineering: Contrary to the traditional, mutually constructed stereotype that engineering and philosophy have nothing in common, creativity as an essential determinant of engineering leads us to a diametrically different understanding of the possible relationship between these two seemingly separate worlds of knowledge. Philosophy is of critical and increasing significance to engineering.

There are many arguments for the previous, rather categorical assertion. First, there is no doubt that philosophy can be used as a means to greater engineering self-understanding. It is also quite obvious that modern engineering is forced to embrace some typically philosophical categories, because problems faced by engineers in practice cannot be solved simply with engineering methods alone. This primarily refers to ethics, aesthetics, epistemology, metaphysics, political philosophy, logic and related categories. These traditional categories are, to a greater or lesser extent, already present in engineering curricula through the framework of acquiring so-called soft-skills (extension of engineering to the domains of arts, humanities and social sciences). However, philosophy can offer to engineering entirely new fulcra for further increasing the engineering body of knowledge, as modern philosophy explores areas of central importance to engineers, such as: (a) conceptual analysis, (b) reflective examination of practice and thought, (c) thinking about aspects of experience, and (d) the practice of a distinctive way of life and thought. Philosophical knowledge in these areas can easily be related to the systemic approach in engineering, the complexity of engineering systems (system of systems) and especially significantly, with the wider practice of engineering design, which is increasingly placed in a much more complex

[26] Hausmann, R., et al., 2011. The Atlas of Economic Complexity: Mapping paths to Prosperity, Copy at http://www.tinyurl.com/lf8y4uw

[27] Flexner, A. (1939) The Usefulness of Useless Knowledge, Harpers, issue 179, June/November; also contemporary discussions, Collini, S., (2012), What Are Universities For?. Publisher Penguin Books, ISBN: 9781846144820 or Boulton, G., Lucas, C. (2008), 'What are Universities For?', Position paper, The League of European Research Universities (LERU), https://www.leru.org/files/What-are-Universities-for-Full-paper.pdf

context of the third culture[28, 29], alongside the arts, humanities and science.

Probably one of the strategic challenges for the future of engineering is how to bring engineering and philosophy closer, and then, how to integrate them into a new discipline - Philosophy of Engineering (following the example of philosophy of science, or philosophy of mathematics, for instance). Engineering is much more than the simple application of scientific knowledge and the instrument that society uses to meet its needs. Exploring the existential question of engineering, Carl Mitcham, a philosopher of technology, writes: 'Engineering is not only instrumental to other human ends, it is in itself an existentially meaningful activity,... engineering possesses inherent or intrinsic as well as instrumental or extrinsic value.'[30] We need an engineering philosophy not only to understand engineering through what engineers do, but also through a much deeper, ontological framework: what engineering is. The need, however, is mutual. Engineering at its core is about creating change in the world we live in, and therefore engineering is important for philosophical studies and philosophy in general.

Engineering method: Engineering activities are always motivated by the need of society, regardless of whether that need originated directly, from the society itself, or it was recognised by engineering and business as an opportunity[31] and then in some way imposed on the society. In the world of *homo-economicus*, the needs of society are articulated through the market. In this context, the customer exists as the end-user, or consumer, which brings modern engineering into the context of consumer society, and indirectly, with the not so new social and cultural phenomenon of consumerism, and further prosumerism[32]. However, in the modern world of *homo faber,* the question is one of doing things to enhance society, thus the prosumer is no longer an individual, but society as a whole. This the engineering method needs to take the wider view of 'usefulness' of society as a whole rather than merely the individual customer for their efforts.

In contrast to the engineering method, activities within the scientific method are most often motivated by curiosity, i.e. free choice of research subjects, starting from hypotheses that are confirmed or rejected by analytical and / or experimental means. Through the research process, science discovers new knowledge and a new understanding of the world around us, that is, things that exist ('know-what', 'know-why'). Engineering, through the process of design, creates what does not exist and thus changes the world in which we live. In this regard, it is worth recalling the famous quote of Theodore von Kármán, scientist and engineer: 'Scientists study the world as it is; engineers create the world that has never been.' The transformative nature (in relation to society!) of the engineering method is one of the most important determinants of engineering ('know-how').

A graphic of the ontological structure of the engineering method is given in Figure 2.01. It is possible to recognise Popper's three-stage iterative model of

28 The Royal Academy of Engineering, (2010). Philosophy of Engineering, Volume 1 of the proceedings of a series of seminars held at The Royal Academy of Engineering, Published by The Royal Academy of Engineering. ISBN 1-903496-38-1.
The Royal Academy of Engineering, (2011). Philosophy of Engineering, Volume 2 of the proceedings of a series of seminars held at The Royal Academy of Engineering, Published by The Royal Academy of Engineering. ISBN 1-903496-78-0.

29 Archer, B. (1979) 'Design as a Discipline- Whatever Became of Design Methodology?', Design Studies, Vol. 1, No 1

30 Mitcham, C. (1998). The importance of philosophy to engineering. Teorema: International Journal of Philosophy_ 17 (3):27-47.

31 In terms of the position advocated by Prof P. Dias: '... *the idea that engineering is an opportunistic discipline, which exploits a situation cleverly.*', Dias, P., 2019, Philosophy for Engineering: Practice, Context, Ethics, Models, Failure, Springer Briefs in Applied Sciences and Technology, Springer Singapore, https://doi.org/10.1007/978-981-15-1271-1, ISBN-10: 9811512701

32 In the conceptual space of consumerism appears a relatively new phenomenon of prosumerism, which is very intriguing for engineering and engineering method, because, with the development of technology, the industrial economics sees the emergence of conditions that enable the consumer to be transformed, in part, into a producer, i.e. a prosumer; Brown, D., Hall, S., and Davis, M. E., (2020), What is prosumerism for? Exploring the normative dimensions of decentralised energy transitions, Energy Research & Social Science, Volume 66, 101475, ISSN 2214-6296, https://doi.org/10.1016/j.erss.2020.101475.

problem-solving[33]: a) the problem - contained in a specific societal need, b) the attempted solutions - a response to a recognised problem that implies ambiguity, i.e. the production of many possible solutions for one and the same problem, and c) the elimination - an inherent feedback loop for rejecting insufficiently good solutions, i.e. minimising error, and on that basis, learning. Through the mechanism of perfecting and learning / generalisation, the engineering method contains an intrinsic mechanism for the production of knowledge. But that mechanism works differently from the one on which the scientific method rests.

When a specific need is recognised and singled out, it is translated into the language of technics and technology, and then the problem is identified, analysed and understood (not necessarily in full!), and based on that, functional requirements are formulated.

The engineering method is not as free in creation as the scientific one. It is burdened with a wide range of constraints, engineering and non-engineering in nature. For example, systemic constraints related to sustainability – economic, environmental and societal.

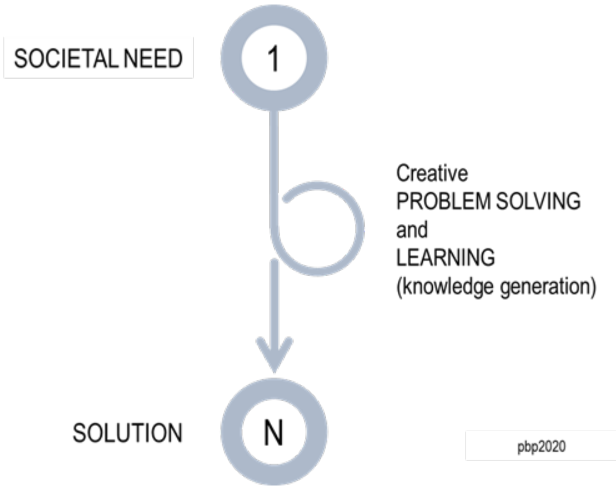

Figure 2.01 Engineering method as a creative problem-solving.

The centre of the engineering method is the design process. We understand design as mapping functional requirements into rational solutions that meet those requirements. As already indicated, this process is ambiguous – there is an infinite number of possible solutions that satisfy one and the same set of functional requirements! It is also nonlinear and hierarchically organised. It is extremely difficult to encode (we still don't know how to formalise the design process and then encode), and it is a process, not a solution – it is, like all creative processes, never finished. That is why the design process is complex. Extremely complex. It imperatively includes heuristics[34], intuition, and systems thinking – as a natural response to complexity. It is inherently creative - creative problem-solving. Creative problem-solving requires divergent and convergent thinking, analytical and synthetic talent, and it is ingenuity that brings all these together at the same time.

[33] K.R. Popper, (1999), All Life is Problem Solving, Routledge, London, ISBN-10: 0415249929

[34] *'The engineering method is the use of heuristics to cause the best change in a poorly understood situation within the available resources.' ... 'Surprisingly, this vague, non-analytic technique works. It has been used in computer codes that play championship checkers, identify hurricane cloud formations and control nuclear reactors. Like the computer, both the method for solving its problem (learning to play chess) and that of the engineer in solving his problems (building bridges and so forth) depend on the same strategy for causing change. This common strategy is the use of heuristics. In the case of the engineer, it is given the name engineering design.'* Citation from: Koen, B. V. (2003). Discussion of the method: Conducting the engineer's approach to problem solving. New York: Oxford University Press.

Deviation from the desired performance of the solution, scarcity of available resources and other types of constraints of technical and non-technical nature, impose the need to search for the optimal solution (more precisely, a good enough – 'satisfying' – compromise). Through the process of satisfying, the 'good enough' solution gradually evolves, improves and acquires harmonious functional and aesthetic features. Figure 2.02 shows a more detailed structure of the feedback loop that eliminates (to use Popper's term) insufficiently good solutions or concepts (actually testing).

This feedback can be decomposed into three components. The first, the most dynamic, is purely technical and includes the kernel of the design process: the identification and understanding of the problem to be solved. Sometimes a satisfactory compromise cannot be reached through the first feedback loop. Then the design process through the second feedback loop returns to the beginning. The initial setting is changed, i.e. the functional requirements are reformulated, the understanding of the problem is modified or completely changed, and enters a new iteration, going through all its phases from ideation to prototyping. Iterativeness and optimisation are inseparable from the design process!

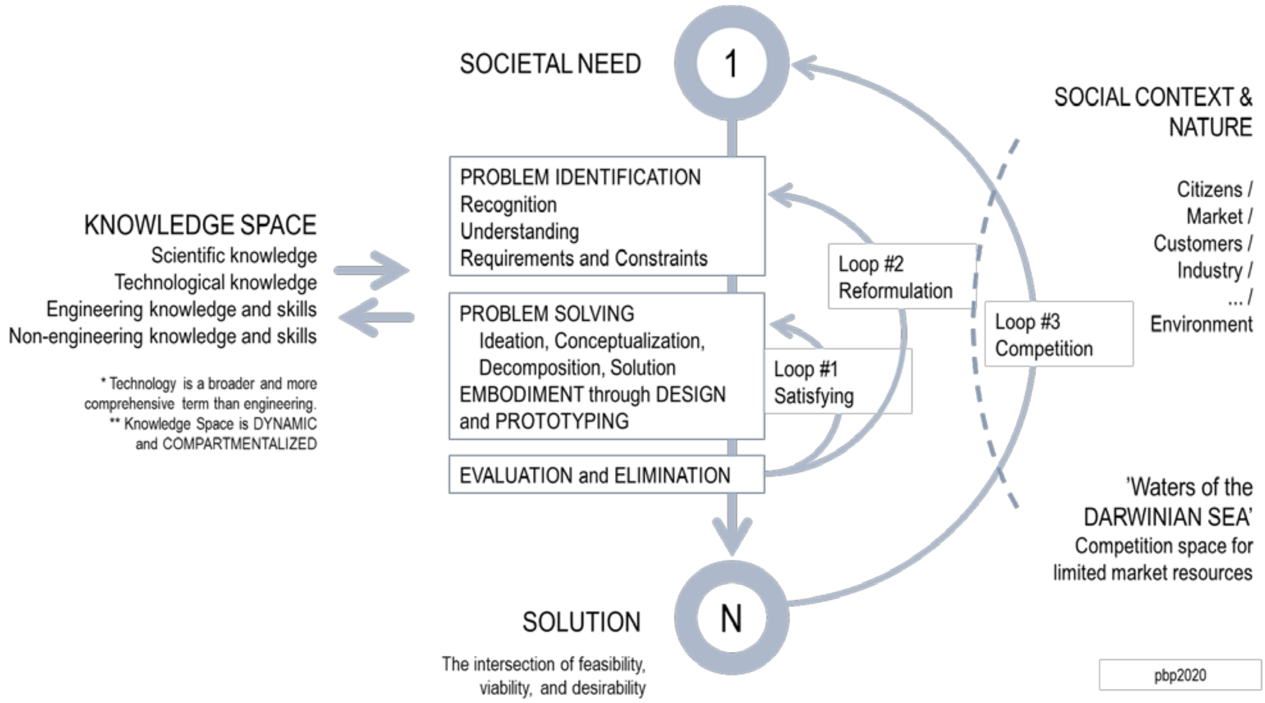

Figure 2.02: Flow diagram of the engineering method.

The third feedback loop is external. Seemingly outside the broader core of the design process, although in reality, it has a tremendous impact on all aspects of it. It is characterised by great complexity and its own dynamics. The third feedback goes through the market. The market is the space of the so-called 'Darwinian Sea', the space of competition for customer satisfaction and thus gaining their trust. Competing in this non-technical space requires additional knowledge and skills. First of all, this is knowledge in social sciences (especially economics), and then humanities and culture. In addition, the existence of a third feedback loop inherently expands the space of functional requirements and the space of constraints. And most importantly, it introduces a different way of reasoning (the concept of scarcity of resources and the concept of economic value). Natural sciences are completely deprived of this dimension.

The third feedback loop has the power to generate new needs for society.

In a broader context, the third feedback loop can also be understood as a mechanism of coevolution of engineering and society - engineering transforms society, and society transforms engineering. In this interaction, among other things, the question of the responsibility of engineering arises[35], which gives the engineering method an ethical dimension[36]. Also the imperative of a systems approach.

The engineering method, as shown in the flow diagram (Figure 2.02), is based on a layered and very heterogeneous base of knowledge and skills, which in addition to knowledge in the field of natural sciences comprises the corpus of engineering and non-engineering knowledge. Interaction with the knowledge base is two-way. In the return way, new knowledge, acquired through practical experiences, in a formalised or informal form, is directed towards the stratum of science. In addition to iterativeness, the process of learning and knowledge generation is inherent in the engineering method. This refers to the engineering knowledge from which engineering sciences are derived.

The engineering method also includes x-disciplinarity[37] and teamwork (involving participants from diverse disciplines working together to solve complex problems). Understanding this aspect of the engineering method is very important, especially in the era of globalisation. Teamwork requires special forms of social organisation and social intelligence, including communicativeness, collaboration, flexibility, multiculturalism, as well as the ability to work in complex and not well-structured / vague / uncertain / ambiguous environments.

The purpose of this brief reflection of the engineering method is to point out its uniqueness, complexity and the need to research this topic from the perspective of the future education of engineers. Engineers think and act in a special, distinctive way. If we understood this better, if we relied more on a deeper understanding of the engineering method, we could better design the kinds of teaching and learning experiences that would produce more effective engineers (and perhaps rare, great engineers) and in particular, develop engineer-learners. A better understanding of the engineering method is also essential for a better understanding of the identity of engineering, as the engineering method is one of its key determinants.

2.b.2 The possible future of engineering education – Drivers of change

We are entering the third decade of the 21st century. Just like the previous two, this decade is going to bring us surprises. Unexpectedly, the starting position will be determined by the challenges posed by the onset of the coronavirus pandemic. We are going to face a time of profound changes whose nature is largely unknown; a time in which we will have to find a way to establish new normality in the overall social life, its organisation and functioning. This, of course, applies to a large extent to both economy and education, and it will be the best of engineering thinking that will create the solutions that will enable both to survive well into the future.

In general, thinking about the future is a risky business. Especially the future of education. Speaking about the need of mankind to penetrate the events

[35] Regardless of the fact that engineering is synonymous with the progress and uplifting of humanity, the influence of engineering on society needs to be observed from a critical position, considering both its positive and negative contributions.

[36] Engineering ethics has its deep roots. It is linked to the Code of Hammurabi, a Babylonian law code dated from around 1750 BC. It consists of 282 laws dealing with all aspects of public life, citizen's rights and obligations and the Babylonian kingdom's justice system. Some laws in the Code of Hammurabi specify the professional responsibilities of builders / engineers.

[37] Activities that go beyond the boundaries of one discipline, x denotes one of the forms, as a cross-multi-inter-trans-anti, ... disciplinarity.

that are yet to happen, Peter Drucker once said that the trick to anticipating the future is not to determine what is likely to happen, but what has already happened that will create the future. Therefore, what are the phenomena and trends that are already present today in engineering education, and also in the wider social context, which have the power to significantly influence the transformation processes at technical and research-intensive universities, and which will most likely determine the course of reform processes and shape curricular strategies for engineering education and the identity of the engineering profession as a whole in the next 10, 20, or maybe 50 years?

In its research of extensive and burgeoning theoretical and policy literature, as well as statistical trends (not only for the field of engineering education, but also in the wider social context), the Euro-CASE Committee for Engineering Education has identified a number of factors that have the potential to significantly influence the future. Following the principle of parsimony, this myriad of factors is, according to the degree of similarity in their effects and transformative power, divided into seven clusters. These clusters are the drivers of change and will undoubtedly have a significant impact on all major processes taking place within the engineering education sector and on engineering as a whole. The key drivers of change are:

1. The ubiquity of knowledge and learning paradigm shift;
2. Grand societal and engineering challenges;
3. Market forces and integration with economy;
4. Inclusiveness and openness to access;
5. Contestability of markets and funding;
6. Globalisation of action radius;
7. Digital technologies and teaching innovation.

Before briefly explaining the key drivers of change, it would be useful to present three interesting observations, essential for the reform processes of the engineering education.

First, an understanding of contemporary engineering. Engineering as we know it today and what it really is today, cannot be separated from the university and the overall context of the wider academic community. Every change in the field of engineering is reflected in the university, and vice versa. These are two deeply coupled, coevolutionary systems. The same driving forces are changing both the university and engineering. Arguments supporting this view can be found in the historical facts relating to the process of integrating modern engineering into the academic community[38]. This process can be characterised as the scientisation of engineering. It lasted throughout the nineteenth and even for a good part of the twentieth century, profoundly affecting engineering as much as the university. The heterogeneous background of higher technical schools, i.e. the original model and the local environment from which they originated (not only in different national contexts, but also within the borders of individual nations), had a decisive influence on the trajectory and dynamics of their penetration into the academic space, as well as the organisational forms with which the process ended. This has produced a diversity in higher education that is still present in Europe, and which makes the overall image of the university, as an institution critical to prosperity, security and social well-being, quite fuzzy.

Second, the central requirement for universities as regards engineering education in the future is surprisingly simple to formulate. This requirement

[38] Rüegg, W., Editor, (2004) A History of the University in Europe: Volume 3, Universities in the Nineteenth and Early Twentieth Centuries (1800-1945), Anna Guagnini, Chapter 15 – Technology, Cambridge University Press, ISBN10: 0521361079.

is derived directly from the needs of society (again the need of society, which is associated with the engineering method!). It consists of three components: a) produce engineers of the best possible quality, b) make the production process as value-laden[39] as possible for society[40]; (engineering education is expensive; education of top or world-class engineers requires large investments!), and c) produce as many engineers as possible. Put simply: more and better engineers at the lowest possible cost.

Difficulties arise when we try to determine the attributes of this requirement, especially what the phrase 'better engineers' really means in the context of education (pedagogy), practice and the nature of engineering. Is ‘better engineer’ the same as ‘more responsible engineer’ in the 21st century and if so, what is the full meaning of the word ‘responsible’ in this context? Surprisingly, difficulties arise when we try to define the required number of engineers produced and their specialisation in a broader time frame (the dynamics of the education system and the dynamics of the labour market or economic system differ significantly and have inherent time asynchrony and also extreme complexity). Contrary to intuition, this requirement cannot be reduced to a classic supply and demand problem!

What if at least part of the reason that we don't have enough engineers is that we just don't know enough about how great engineers actually think, or at least, if we don't know this we don't make enough use of what we know?[41] A similar view is supported by UNESCO in its report[42] on engineering education, where it is explicitly stated that there is no simple answer to the question of how many engineers are required to drive economic growth and sustainable development objectives within a country, because 'it is not simply a numbers game'.

The need to go beyond economics in the search for answers to the elementary questions about the task of the education system in the production of engineers, indicates that things are much more complicated than we would like them to be and that the solution space is much wider than it may seem at first. A systemic and holistic approach appears here as a methodological imperative. The importance of this observation is universal and refers to the overall sector of engineering education.

The third observation relates to the broader social context of the public responsibility of higher education. In this regard, the Council of Europe in its recommendations[43] identified four major purposes of higher education:

- preparation for sustainable employment;
- preparation for life as active citizens in democratic societies;
- personal development;
- development and maintenance, through teaching, learning and research, of a broad and advanced knowledge base.

[39] Miles L.D. (1989) Techniques of Value Analysis and Engineering, Lawrence D Miles Foundation, USA; 'Competition, in other words, determines in what direction one must go in setting the value content in order for a product or a service to be competitive. This best value is determined by two considerations: performance and cost.'; 'Keeping appropriate performance while securing appropriate cost introduces the value concept.'

[40] Education of top or world-class engineers requires wide-ranging investments in people and facilities at universities, industry and governments to achieve the depth and breadth of capabilities that are needed to serve society well for the future. Appropriate engineering education may be expensive, yet the rewards for society from high quality engineering education are immense.

[41] This is precisely the approach the Centre for Real-World Learning (CRL) has chosen to adopt in its research for the Royal Academy of Engineering (RAEng) and set out in detail in the report: Thinking like an engineer, Implications for the education system, A report for the Royal Academy of Engineering Standing Committee for Education and Training, Full report, May 2014, ISBN: 978-1-909327-08-5.

[42] ENGINEERING: Issues Challenges and Opportunities for Development, Published in 2010 by the United Nations Educational, Scientific and Cultural Organization, UNESCO, 2010, ISBN 978-92-3-104156-3.

[43] Recommendation CM/Rec(2007)6 of the Committee of Ministers to member states on the public responsibility for higher education and research, Council of Europe, May 2007.

Personal development relates to individual growth at the psychological, cognitive, social and moral levels. Active citizenship encompasses the development of (inter)cultural skills, a sense of citizenship, and political literacy and participation (thoughtful participation in the democratic process has also become increasingly complicated as the locus of attention has shifted from local to national and global concerns). Although different formulations can be found, the fourfold role of higher education formulated in this way is generally accepted by a very wide range of stakeholders. From the perspective of engineering education, this framework of public responsibility is in all respects obligatory for engineering and it is in perfect harmony with the engineering method and engineering practice.

The ubiquity of the knowledge and learning paradigm shift: The primary responsibility of the university is the dissemination of the collected knowledge (even today there are opinions that it is the only one!). For centuries, the university has systematically collected knowledge and kept it in its libraries. Today, however, knowledge is ubiquitous. It is everywhere. In huge quantities. Since knowledge is available on any Internet-connected device, literally in a split second, what a student or graduate knows is becoming less valuable (for the employer) than what he/she can do with what he/she knows. The cognitive process is different from the acquisitive process! The learning paradigm is changing and this trend will continue in the future. Its focus shifts to knowledge and skills to combine and apply learned knowledge, critical and systems thinking, relational understanding, creative problem-solving skills, contextualisation of knowledge, and practical / digital experience – what we might frame as ‘wisdom’ – the wise use of knowledge. Also, non-technical skills, especially the ability of written and oral communication, collaboration, teamwork, and other social skills, become much more important than traditional academic knowledge. Tony Wagner, the Harvard education specialist, characterises this condition as learning to be 'ready to add value to whatever you do'.

The trend of accelerating the growth dynamics of the overall epistemological base has enormous implications for all aspects of engineering education, including the problem of knowledge obsolescence. Engineering knowledge is always multidisciplinary. It is an aggregate of immediately useful knowledge, sometimes clustered around a specific product or engineering sub discipline. Market dynamics affect the dynamics of the body of engineering knowledge, in terms of its continuous extension by adding new content and parallel contraction due to the obsolescence of existing ones. However, the net gradient of this process is always positive. The body of engineering knowledge is constantly growing and this is a trend that is a permanent determinant of engineering.

The constant search for a very sensitive balance between the 'relevant', which is exciting, and the 'fundamental', which will last a lifetime, both in the field of engineering knowledge and engineering skills, is one of the biggest challenges of any strategy for curriculum development. This balance is a measure of the quality of the curriculum, and its meaning is in response to the extreme dynamics of the epistemological base of engineering, natural sciences and technology, as well as the rapidly changing world in general. The challenge is to enable students to learn how, on a supremely rigorous basis, to determine that particular knowledge is relevant to the problem at hand – this question is perennial, whereas the knowledge itself may become outdated. Also, it is probably hiding many answers to the debate about the employability of knowledge and the surrounding controversy that has long been present in both academia and the wider community (perhaps more relevant today than ever!?).

Skills can be acquired only by doing. Practical experience can also be gained on simulated problems (digital experience and the like). LAB-FAB-APP context[44], followed by so-called Makerspaces, or various forms of direct cooperation with industry and learning in a factory environment (factory shop floor, product/process design offices, ...), are key methodological components of the curriculum for the productive acquisition of engineering skills. More recently, 'living labs' enable this practice to be extended to societal applications – even in some cases at quite large scale.

It is realistic to expect that in the near and distant future, the improvement of engineering curricula will be continuous (as a permanent task) and this development will take the following key directions:

a. **Method and practice of teaching** (including cognitive psychology, curriculum planning theory, and the like) - development and increasing application of new, hands-on / learning-by-doing learning methods, such as Design-based Learning, Problem, Project, and Challenge-based Learning, Experiential Learning (EXL), or Conceiving-Designing-Implementing-Operating Learning (CDIO)[45] and the like, aimed at active interaction with the learning environment, contextualisation of the acquired knowledge, systems thinking. These are characterised by a constant search for answers to questions of not only how students should learn, but also questions of what students should learn. The importance of this type of development is best illustrated by the fact that in 2007 the UNESCO Chair in Problem-Based Learning in Engineering Education was set up at Aalborg University (Aalborg, Denmark), or that the CDIO concept eventually grew into the CDIO global initiative, housed in the CDIO Organization with over 100 engineering schools.

   The development of new curricula in the future should, as much as possible, rely on the application of the so-called Bloom's Taxonomy of educational learning, as well as its recent revision[46], which introduces elements of cognitive psychology into the curricular methodology, i.e. a new understanding of the theory of human thought and its link with logical categories of knowledge.

   The complexity of the challenges of planning engineering curricula and the need to approach this task in the future through new methodological foundations and new understandings of cognitive psychology can be illustrated with a brief review of the issue of mathematics. Mathematics is inseparable from engineering. The modern computer tools that engineers use for everyday work, especially in the field of engineering design, are nothing else but mathematics – applied mathematics, translated into computer codes. However, in engineering education, this poses a paradox. Things just don't work in practice. Engineering, as an exact technical discipline and a discipline that bases its body of knowledge on the natural sciences, needs knowledge and skills in mathematics. However, the essence of the education challenge is how to achieve an effective confluence of mathematics and engineering methods. The solution lies in changing priorities[47]. Indeed, the goal is not to train engineers to be university mathematicians. Instead, mathematics should be imprinted in the context and specific profile of engineering habits of

[44] LAB–FAB–APP — Investing in the European future we want, European Commission, Directorate-General for Research and Innovation, Directorate A – Policy Development and Coordination, European Union, (2017), ISBN 978-92-79-70570-0, doi:10.2777/403189.

[45] Crawley, E. F., et al., 2014. Rethinking Engineering Education: The CDIO Approach. Springer International Publishing, Springer, ISBN-10: 1441942602.

[46] Marzano, R., and Kendall, S., (2007) The new taxonomy of educational objectives, Corwin Press, A Sage Publications Company, ISBN-10: 1412936292.

[47] Cuoco, A. at al. (1996), Habits of Mind: An Organizing Principle for Mathematics Curricula, Journal of Mathematical Behavior, v15, n4, p375-402.

mind. It is possible to design such a curriculum that transforms the methods normally used by mathematicians into the methods characteristically employed by engineers and researchers in the world of natural sciences. Engineering students will then gain a sense of emotional fulfilment and satisfaction as they work and learn in the context natural to them. They would no longer experience aversion, which is usually felt when learning mathematics in the engineering context is reduced to a purely mathematical methodological rigour.

It is not the intention of this short discourse to resolve the issue of mathematics and the challenges arising with it in engineering education. The meaning is in the message that the Euro-CASE Committee on Engineering Education wants to make clear to the professional public: A desirable engineering curriculum is any curriculum that is organised around engineering habits of mind and based on the principles of consistent application of the engineering method, regardless of the choice of content and location of their focus. Such a curriculum provides students with the opportunity to freely build their skills in creating (designing), inventing, conjecturing, and experimenting through the acquisition of new knowledge. They can also learn how to decompose complex problems into smaller ones, which are easier to manage, and then how to recompose them into the larger real world problem they are actually needing to solve. Finally, what is equally important for engineers and their future professional practice is to learn through mistakes, gain and strengthen the practical experience, and gradually build a scaffold of personal knowledge of each individual (each student is special!). From the aspect of cognition theory, this is related to the constructivist framework of understanding the learning process that says learners construct knowledge rather than just passively take in information; as students experience the world and reflect upon those experiences, they build their own representations and incorporate new information into their pre-existing knowledge (schemas).

b. Complementing the disciplinary body of engineering knowledge – academic rigour, deep disciplinary knowledge and the acquisition of solid background in maths, mechanics and engineering fundamentals, are the time-invariant characteristic of any engineering curriculum. Also, this includes corresponding engineering skills. The body of knowledge thus defined belongs to the STEM context. However, the growing complexity of technical and technological systems makes decision-making difficult and very complicated. Engineers are forced to decide not only on technical issues, but also those related to the broader context of social interactions. This refers to interpersonal relations and communication in heterogeneous teams, whose complexity is not only in the number of participants, but also in cultural diversity and other challenges that come from the globalisation of engineering practice. The second aspect relates to the broader societal implications of engineering work and related responsibilities. For example, the impact of engineering work on the environment. Therefore, within the circular economy (circular production), there is more and more talk about the ecodesign concept, i.e. a new form of engineering design. Third, and equally important, is the question of empathy. Empathy is of fundamental importance for engineering practice and education. Unfortunately, completely neglected, it appears as a hidden layer, deeply rooted in the engineering method. This is actually about the emotional level (the joy of being involved in cognitive processes and desire, and even passion for learning and at the same time building one's own identity) and about empathy, about the inner motivational engine that actually drives us and without which good engineers cannot be produced. An engineer is a state of consciousness.

An engineer is an emotional professional. Innovation is an emotional process. The emotional plane is so important to engineering that it is inseparable from it. By neglecting the empathic layer, one runs the risk of jeopardising the efficiency of the engineering method. That is why the concept of 'Empathic Engineer'[48] is a new research topic. The practice is more than evidently lagging behind the already available results. Of course, we are aware that attitudes of this kind can be interpreted as too sentimental, but we deeply believe that these skills are a crucial component of the formula for the production of well-educated engineers.

It is almost paradoxical that today's engineering curricula lack, or cover only in a very superficial way, the above-mentioned social aspects of engineering practice. Deep and urgent changes are needed on this issue and they must be an indispensable part of the reform process of engineering education. Efforts to build a new curriculum base at technical and research-intensive universities.

The key challenge for the future is how to incorporate the social component of knowledge and skills into the engineering curriculum, which is already inundated with the imperative of an ever-widening and ever-deeper intervention in the space of disciplinary knowledge and skills. It is a challenge to search for a functional balance between the so-called Hard and Soft Competences. On this issue, the Euro-CASE Committee for Engineering Education advocates the following two views. First, the acquisition of social skills and their understanding has extremely significant positive implications for engineering practice and engineering education. Social skills are a necessity in the epistemological engineering base and they must find their place. Second, the strengthening of the social component in the body of engineering knowledge and skills should not be realised as a simple linear superposition on the existing one, but that this type of confluence should be realised in the form of symbiosis, applying appropriate methodological approaches in curriculum composition.

As regards the aforementioned, it is important to note that in parallel with the STEM framework, a relatively new academic composite Science-Technology-Society (STS) is being developed at some universities, such as Stanford University, Technical University Munich (TUM), University College London (UCL), or the European Inter-University Association of Society, Science and Technology (ESST). STS is an academic programme aiming to train a new intellectual 'cadre' able to relate science, technology and society in novel (integrated) ways, with expertise to address the challenges that the global community faces, with an eye on the immediate future. Although it is noticeable that STS programmes are increasingly leaning towards engineering and innovation, perhaps the most rational solution is to bridge the existing gap between STEM and STS poles by extending STEM into a sTEmS composite, which would be shaped in that way to integrate an aggregate of social sciences, humanities and culture / arts into the existing STEM framework, or more precisely in the epistemological base of engineering knowledge, thus emphasizing the 'doer' component of graduates as the primary one, but on significantly different foundations. This would establish a new educational framework that would naturally strive for practice, closer to the factory, closer to the immediate needs of society, closer to industry, business and market, but would still be based on the harmony of three virtues: knowing-doing-being or Aristotle's concept of moral perfection:

48 Walther, J. at al. (2017), Model of Empathy in Engineering as a Core Skill, Practice Orientation, and Professional Way of Being, Journal of Engineering Education, Vol. 106, Issue 1, 123-148, doi:10.1002/jee.20159.

episteme-techne-phronesis, as a timeless guide to the good life of the citizen as a social being. The key principle of curriculum organisation on this issue is the integration of a heterogeneous / x-disciplinary corpus of knowledge of the sTEmS space, rather than a mechanical sum of five components stitched into one acronym.

The position advocated by the Euro-CASE Committee for Engineering Education on this issue is not the only one. Already today, there are ideas about the need to switch from STEM to STEAM (A stands for Arts). Even the European Commission shows bias towards such thinking and explicitly takes the position that science education should focus on competencies with an emphasis on learning through science and shifting from STEM to STEAM by linking science with other subjects and disciplines[49]. STEM subjects are important, but without the Arts, they are lacking a crucial component in any endeavour– the imagination.[50] University College London has a Bachelor of Arts and Science degree[51], in which students explicitly learn within both arts and sciences domains (including engineering), and this is proving to be a very interesting route into creative, functional and responsible graduates entering higher degrees in engineering.

c. Continuous personal knowledge innovation – lifetime learning and education, continuous upskilling and relearning. Again, again and again! Engineering is very sensitive to the obsolescence of knowledge. For some engineering disciplines, such as electrical engineering, or digital technologies in general, we like to say that they are the fastest aging disciplines. The life of the product and technology is getting shorter and shorter, and this trend will continue in the future. That is why the curriculum must teach students, future engineers, not only how to acquire new knowledge, but also how to continuously question it, and innovate it throughout their professional career. They have to learn how to learn, because learning is the only constant in a world that changes dramatically. This practice is not the case today, which is why significant changes will have to occur in the domain under the pressure of reality. Learning how to be a life-long learner must be part of the pedagogical tools of the curriculum. Two more aspects are connected with this. The first refers to digital technology, i.e. MOOC, and the second to the trend of extension of the educational process outside the borders of universities and classrooms. Industry in this context must partner with the university and take on a part of this very important responsibility, out of self-interest. Only engineers who are able to adopt and apply cutting-edge knowledge can be innovative and thus productive for the factory, company or organisation in which they pursue their professional careers.

d. Outward-facing curricula – adapting the curricula to new contents and methodological tools that will enable teaching to take place in the industrial environment. The main goal is to achieve the cognitive process, especially the unique acquisition of practical knowledge and skills in the real environment of future engineering practice so that students gain experience outside the classroom. This gradually moves the educational process towards the concept of academic dual education, which will bring various issues to the theory and practice of engineering education. These issues will have to be resolved in cooperation with industry through mutually acceptable and appropriate convergences and compromises,

49 Hazelkorn, E., (2015) SCIENCE EDUCATION for Responsible Citizenship, Report to the European Commission of the Expert group on science education, European Commission, DG Research and Innovation Science with and for Society, EUR 26893 EN

50 Kite-Powell, J., (2019) STEM And STEAM Education: Why We Need Them, Forbes; https://www.forbes.com/sites/jenniferhicks/2019/08/28/stem-and-steam-education-why-we-need-them/#161ea22176ae

51 https://www.ucl.ac.uk/basc/

which will lead to applicable and effective solutions. This composition of the curriculum should create favourable circumstances for teachers to systematically develop the entrepreneurial spirit and build entrepreneurial skills in students. Also, experiences of this kind have an enormous impact on building tacit knowledge in graduates. Tacit knowledge is of special importance for engineering as it is the main ingredient of practical skills.

e. Innovation-ready – Engineers are true masters of innovation. They turn ideas and scientific inventions into products and businesses. If we want innovative engineers we must educate them to be innovators, help them develop their talent, their creative abilities and their sense of entrepreneurship and business. These abilities and skills can be acquired and developed systematically. The existing curricula must be innovated with components such as x-disciplinary thinking, divergent / convergent thinking and also, practical skills related to entrepreneurship, business and marketing. However, one should be careful and honest here. Creativity, which is a metaphor for innovation, is a great mystery of cognitive psychology. 'Human creativity is something of a mystery, not to say a paradox', writes Margaret Boden, professor of Cognitive Science at Sussex University. Exploring the creativity hidden in the depths of the cognitive space of the human brain, she goes so far as to explore the possibility of transferring it to machines and turning the digital computer into a creative machine[52]. Therefore, when we think about curriculum development, we may need to be mindful of the possibility that in 10, 20 or 50 years, computer tools for engineering design will feature not only the speed and mathematical precision inherent in them today, but also a creative capacity. They will have built-in algorithms for an ultra-fast combination of concepts and facts, which will transform them from a blindly obedient machine into a creative partner, an active co-worker in the process of engineering design and creation.

Grand societal and engineering challenges: Unfortunately, the list is long and very diversified. With a population of eight billion people, and expecting that it will increase by a billion in about a decade, that list has a tendency to expand. No policy has the strength to oppose megatrends. Our only option is to adapt accordingly and find a way to turn serious challenges into an opportunity, a new chance for further development. However, the future is uncertain. Megatrends turn from challenges into a crisis by neglect, indecision or inadequate action.

Engineering, in this context, will not function in a vacuum separate from society. On the contrary, its natural role is that of a smart agent who constantly builds new bridges between the needs of society and the ever-increasing epistemological base of our civilization, and thus brings it to the central position. But, engineering in the 21st century has to be ready to take up these types of challenges. If we take ecology as an example, in order to make engineering ready to offer adequate responses to the challenges brought to society by changes to ecosystems, then we have to incorporate the logic of the circular economy/production into the engineering method as a new system constraint. This transforms traditional engineering design into ecodesign. Sounds simple, but that is only an illusion. Through ecodesign, the ecology and circular economy are put into a position of methodological (product, process or service) design invariant which changes the nature of overall logic of engineering design. The ecology and circular economy are becoming key components of the new mindset of engineering! To achieve this, we must teach students the new technical knowledge and skills, we must incorporate ecodesign into future curricula for the engineering education. At

52 Boden, M., (2003) The Creative Mind: Myths and Mechanisms, Routledge ISBN-10: 0415314534.

the same time, that technical knowledge and skills should be complemented with sensibility and understanding of the wide societal significance of ecology and related responsibility. This brief digression aims to illustrate the complexity of the requirements of this kind and the nature of their implications for engineering education and engineering in general.

Extensive research is needed in order to effectively incorporate the total context of grand societal challenges into future engineering curricula. The National Academy of Engineering (NAE) research, motivated by the need to identify the Grand Challenges for Engineering in the 21st century[53], can serve as a good starting point. 14 game-changing goals for improving life on the planet, announced in 2008, can be understood as an engineering complement to grand societal challenges. Among other things, NAE activities related to Grand Challenges for Engineering extend to the fields of education (e.g. NAE Grand Challenges Scholars Program[54]).

Market forces and integration with economy: The economy determines the future[55]. For engineering, this aspect is one of the key drivers of change. Europe's political platform for industrialisation of its economic system i.e. the 'European Industrial Renaissance initiative', cannot be effectively implemented in practice without strong and viable engineering. European Industrial Renaissance requires European Engineering Renaissance! That also applies to another political priority of Europe – innovation. The political platform 'Innovation Union' cannot be effectively implemented in practice without innovative industry (factories, especially the SME sector, must be more open to innovation!) and without strong and innovative engineering.

The prevailing concept of the Knowledge Economy and related concept of Knowledge Worker progressively evolve into a more complex and much more dynamic form – the Learning Economy and Learning Worker. In that regard, engineering education is faced with many challenges, and their scale is such that the solutions that we will have to find, and then implement, will make a revolution in the education process and university organization.

Contemporary society has the need to make the university closer to the market, to thoughtfully transform it into 'knowledge business' that can compete successfully in the global marketplace of the 21st century. In contrast, the university strives to maintain its traditional identity and show resistance to that process (is this nevertheless just an impression or the prevailing condition is truly that way?). It's worth recalling that, historically speaking, the university has always been adapting to current needs and the requirements of society[56] (but also, always jealously keeping its academic freedoms). In the 21st century, that adapting means a step towards the new concept – the concept of the entrepreneurial university. That is the concept which arises by merging teaching and research with the capitalization of knowledge. Some researchers, such as Henry Etzkowitz, consider this form of university to be the last stage of evolution of a medieval institution designed to fulfil the role of conservation of knowledge, then, of its production, and lastly, its capitalization i.e. conversion of knowledge into intellectual capital of the 21st century[57].

Although the idea of the entrepreneurial university sounds quite logical, for many people even appealing (particularly for those who fund the university and see in that a chance for achieving some type of economic self-sufficiency

53 National Academy of Engineering (NAE) (2008),NAE Grand Challenges for Engineering; http://www.engineeringchallenges.org/challenges.aspx.
54 http://www.engineeringchallenges.org/GrandChallengeScholarsProgram.aspx
55 van der Zwaan, B., (2017) Higher Education in 2040: A Global Approach, Amsterdam University Press, ISBN-10: 9462984506
56 The Magna Charta Universitatum; http://www.magna-charta.org/
57 Etzkowitz, H., (2007) MIT and the Rise of Entrepreneurial Science, Routledge, ISBN-13: 978-0415435055.

of the higher education and science sector), the solutions, which function in practice in a satisfactory way, are still being sought. Undoubtedly, such transformation processes are in fact very complex and slow, because they include different actors.

From the perspective of engineering education, disruptive changes should also be expected regarding this matter. Changes that will impact on the university to the extent that it was done by the breakthrough of engineering into the academic community in the 19th and 20th centuries. The 21st century will probably be marked by the final shaping of the third mission of the university and its transformation into an entrepreneurial university. That is the process in which the engineering education sector will undergo significant change and at the same time will be the bearer of those changes. The entrepreneurial nature of engineering is an integral part of the engineering method which is inherently focused on societal needs and the ever-present opportunistic component. Without engineering, the existence of the entrepreneurial university is not possible (nor is entrepreneurial science)!

The concept of the entrepreneurial university naturally leads to the extension of the education process outside the university framework, to some kind of integration into economic space, industry and factories. That's why new concepts such as Learning Factories and Teaching factories [58] exist and improve. They strive to integrate the factory environment into education process as a pedagogical complement to the revolution of production technologies and significant changes in the factory organization (Factories of the Future - FoF), as well as the overall chain of value creation. Such processes lead us to the need for designing and practical implementation of the dual engineering education model, which today represents an open question for all interested parties. Not on paper, but in practice.

Viewed from the perspective of the economy, it is useful to mention the gradual but stable approach to the age of the new division of labour. This time, it is between humans and smart machines. Adam Smith's revolutionary idea took on a new form that will, undoubtedly, produce significant changes, just as the first one did. Therefore, we need to start thinking about new approaches to engineering education, about 'Robot-Proof' education [59]. About artificial intelligence (AI) and smart manufacturing technologies, about concepts such as RoboFactory or RoboFacturing and the new role of engineers in that context.

Finally, it is important to mention that the impulses of changes in all the aforementioned matters, as a rule, do not come from the academic environment. They are imposed by the economic reality and policy-makers. This observation is very important because it also opens the question of natural inertia, as well as the resistance of academic community to these type of changes. That question has long been present in public discourse through search for compromises in the university dichotomy between 'humanism' and the 'market'.

Contestability of markets and funding: The funding of engineering education is a very delicate matter of reform. Above all, because the education of academics of such profile is expensive. The growing need for hands-on and learning-by-doing pedagogical approaches only makes things more challenging. But one thing is for sure: you cannot become a good engineer without an abundance of practical skills and experiences. The same is true for research, where the growth of a demand-driven funding model is

[58] Abele, E., Metternich, J., and Tisch, M., (2019) Learning Factories: Concepts, Guidelines, Best-Practice Examples, Springer International Publishing, ISBN: 978-3-319-92260-7;978-3-319-92261-4.

[59] Aoun, J., (2017) Robot-Proof: Higher Education in the Age of Artificial Intelligence, The MIT Press, ISBN: 978-0-262-03728-0; Professor Joseph Aoun is the president of Northeastern University in Boston, Massachusetts, USA.

evident. Contestability of funding for teaching and research will only increase in the future. Then, the academic community at universities and the engineering education sector should prepare 'for an environment where every dollar of government funding is contestable and any growth in funding comes from non-government sources — students, industry, philanthropists, and global collaborations — that are all fiercely competitive'.

The firm views that the academic community often – but not always – holds are close to the traditional understanding of the universities, (its role in society, organization model, autonomy and the way of producing knowledge), even when they are market-oriented, which is the case with technical universities and research-intensive universities. It seems that filiopietism stokes resistance to institutional reform.

However, the market resonates differently. The key word for the market is competition. The market understands knowledge as an intangible asset, a commodity that has its value for use, and the university as an enterprise that must be in accordance with the market laws and produce profit. Profit from knowledge is a magnet for interested parties and therefore, the market is one of key factors in democratization of knowledge. The university is at risk of losing its exclusivity, especially if it continues to rigidly persist in its traditional positions and does not adapt to current trends. The market is an arena where everyone participates, including those who don't want to! However, the market tends to look at the short term and there is a need for the market to realise that it needs to consider the medium and longer terms as well in engendering progress towards the future.

The third perspective is the perspective of the state and its regulatory and political framework. Universities funded by the state are facing the challenge of targeted i.e. contextual funding where in addition to the primary function of knowledge transfer, the university also has other secondary functions, which can cause a conflict with university freedoms in learning and research.

Globalisation of action radius: First, the globalisation of the world took over the economic space. Then the globalised knowledge-based economy accelerated the processes of internationalisation of universities (strongly supported by internet technology). It seems that prestige, above all other benefits, motivated universities to see greater benefits in the internationalisation of their activities[60].

Globalisation brought entrepreneurial risks, working with different cultures, new business dynamic and work models. The university sector has become a global business. As a result of those processes, local communities, the traditional islands of academic excellence with deep historical roots in higher education and research, no longer have a monopoly over knowledge. Knowledge has become a global phenomenon and global intangible asset.

In a 200-page report on global condition of the engineering education sector[61], Ruth Graham from MIT Department for Engineering, explicitly states: 'Evidence from the study pointed to a shift in the center of gravity of the world's leading engineering programs from north to south and from high-income countries to the emerging economic 'powerhouses' in Asia and South America'. Recognizing the significant role of public funds for the funding of dissemination and the production of knowledge, it is concluded that: 'many among this new generation of world leaders will be propelled by strategic government investment in engineering education as an incubator for the technology-based entrepreneurial talent that will drive national economic

[60] Gibbs, A., Haskins, G., Hannon, P., and Robertson, I. (2012). Leading the Entrepreneurial University: Meeting the Entrepreneurial Development Needs of Higher Education (2009, Updated 2012). NCEE.

[61] Graham, R. (2018) The Global State of the Art in Engineering Education, Massachusetts Institute of Technology (MIT), ISBN13: 9780692089200; https://jwel.mit.edu/news/mit-releases-global-engineering-education-report

growth'. From the aspect of globalisation, the engineering education sector enters the age of rapid and fundamental change, the time where the most advanced education programs will no longer be exclusivity of today's world leaders in the field of engineering and STEM education (and their 'small boutique programs' for experimenting with advanced concepts of engineering curricula), but that space will completely be open for the arrival of new players from all over the world, who will eventually establish new standards of excellence.

This development is also anticipated by Ernst&Young in their study of trends in engineering education[62], which characterises the present moment as the condition of punctual change - 'a thousand year old industry on the cusp of profound change'. It also foresees that future university business models will be more diverse that the present ones, while evolutionary processes will happen in three main directions: a) Streamlined Status Quo, b) Niche Dominators and c) Transformers. Within the third one, it is expected that the private providers and new entrants will create new market spaces which will merge traditional content of engineering education with the sectors such as media, technology, innovation, venture capital and such. Global partnerships, which will eventually be established between incumbent universities and new entry leaders, will produce new dynamic in the engineering education sector, with a greater potential for investing in their own development and strengthening of competitive performance. In the time ahead of us, universities will be exposed to increasing global competition for students, academics and funding. Only those who will understand and embrace the laws of globalised market (and not only the laws of traditional academic space), and succeed to effectively leverage their capabilities in the new digital age, will remain relevant and will benefit from internationalisation and global action radius.

Given these challenges for universities around the world, perhaps especially in engineering, there is an important need for universities and the engineering industries to work together to create a more integrated approach to engineering education. Rather than expect universities to provide a 'finished' engineer for industry to employ, industry needs to engage more with the universities in the educational process. Conversely, and in addition, the universities need to realise that much of engineering education can quite rightly and appropriately happen outside the university walls. Determining 'who does what' in engineering – between the various stakeholders: universities, engineering, society – is a necessary and urgent requirement if engineering is not to become disconnected from the future.

[62] Ernst & Young (2012) Report University of the future - A thousand year old industry on the cusp of profound change.

Part III

Challenges in engineering education

Key observations

- Industry 4.0 is not just digitalisation, no matter how much we talk about digitalisation and how, rightly, digitalisation of all production processes and value chains is a priority above all others, topic of the highest research, strategic, political importance.
- It is crucial that each engineering curriculum, regardless of disciplinary specialisation, contains at least 10% of the technical systems knowledge and skills in System of Systems stratum.
- Over the past few decades social skills have become essential tools for engineers in modern society. Industry, universities, as well as accreditation bodies now agree that technical competences only are not enough.
- We must prepare our students with appropriate experiences, such as undertaking complex design projects in pluridisciplinary teams. A critical element is that the study load in the first years of engineering is already typically quite heavy.

'*Today's problems come from yesterday's solutions.*'

Peter Senge

American systems scientist

MIT Sloan School of Management and New England Complex Systems Institute

3.a Engineering education for European Industrial Renaissance

As happened in 1929, when the so-called Great Depression swept the world like a tsunami and shook the foundations of the global economic system in unprecedented proportions, so did the financial collapse of the global market in 2008, introducing a new stage of social development for the global economy and even our civilization. This is, of course, a very broad topic. We will focus only on the economy and the dramatic changes that happened afterwards.

First of all, we realised that the leading economic theories suddenly became obsolete, that the world of the post-industrial economy is fiction, something that is yet to come in the future. Our reality is the industrial economy, and a radical shift in economic policies is needed in order to bring the global economic system back to normal, and provide welfare and prosperity to citizens on a sustainable basis. Once again we started to reinvent industry and its most important building block, probably one of the greatest innovation of the mankind ever — the factory. The world entered the wave of reindustrialisation.

Europe, the cradle of the manufacturing industry, the place where the first factory was born and then saw deep social transformations that today we call the first industrial revolution, heavily deindustrialised its economy during the nineties and in the first decade of the 21st century. The global financial crisis in 2008 hit the European Union hard. The European Commission reacted swiftly by adopting a strategic framework known as the European Economic Recovery Plan, strongly focusing its economic policy on manufacturing industry.

The essence of industrial policy for the reindustrialisation of Europe, or 'European Industrial Renaissance' relies on 4 pillars: a) investment in new technologies and innovation, b) access to markets, c) access to finance and capital markets (for financing innovation, research and knowledge production), and d) the crucial role of human capital. Full commitment to Europe's industrial future is indisputable today[1], especially to the role of the human factor and consequently, education.

The Next Generation Manufacturing: The role of the European science and research community is crucial, as is the role of European engineering, is placed in the broad context of scientific advice for policies closely related to technology, engineering, and innovation. The essential problem of the reindustrialisation of Europe is not in the political readiness and determination to face a huge challenge, but in the dramatically changed economic and social environment. The industry needs to return from low-wage to high-wage economic space and at the same time remain globally competitive. Also, there has been a manufacturing paradigm shift from mass production to mass customization. Then, the massive proliferation of digital and communication technologies and the complete cybernetisation of industry. There is also the pressure of sustainability (environmental, economic and social), as well as a long list of grand social challenges that considerably impact on industry and drive structural changes in nearly all manufacturing sectors. This does not exhaust the list of challenges!

In order to reindustrialise and return factories to their economic space, Europe needs Next Generation Manufacturing Technologies[2]. It also needs a consistent framework of pan-European research and innovation programmes, such as: European Technology Platforms (especially ETP ManuFUTURE[3]), Knowledge and Innovation Communities (for example EIT KIC Manufacturing[4]), as well as Private and Public Partnership programmes (such as Factories of the Future – PPP FoF[5], with its distinctive conceptual framework Digital Factory, Smart Factory and Virtual Factory, or Factory as a Good Neighbour for societally acceptable manufacturing in highly urbanized environments).

From the perspective of creating engineers' education policies and their implementation, such research programmes are extremely important,

1 European Commission (2020) A New Industrial Strategy for Europe, COM(2020) 102 final, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 10.3.2020.

2 Westkämper, E., (2014) Towards the Re-Industrialization of Europe - A Concept for Manufacturing for 2030, Springer-Verlag Berlin Heidelberg, ISBN 978-3-642-38501-8.

3 ManuFUTURE High-Level Group, (2019) ManuFUTURE—VISION 2030: Competitive, sustainable and resilient European manufacturing, Report from ManuFUTURE High-level Group, PUBLISHER: ManuFUTURE Implementation Support Group, ISBN: 978–989–95853–7–9.
ManuFUTURE High-Level Group, (2020) STRATEGIC RESEARCH AND INNOVATION AGENDA SRIA 2030 - For a competitive, sustainable and resilient European manufacturing, Report from ManuFUTURE High-level Group, PUBLISHER: ManuFUTURE Implementation Support Group, ISBN: 978-989-54695-0-5. http://www.manufuture.org/

4 https://eitmanufacturing.eu/

5 European Commission, (2013) FACTORIES OF THE FUTURE - Multi-annual roadmap for the contractual PPP under Horizon 2020, Luxembourg: Publications Office of the European Union, ISBN 978-92-79-31238-0, doi:10.2777/29815

because they outline the contents and composition of innovated curricula for teaching a new generation of engineers, knowledge workers for Industry 4.0 (I4.0)[6]. They effectively drive reform processes in engineering and STEM education. As an example of the complexity of the challenges in reindustrialisation that necessarily reflect on the space of education at technical and research-intensive universities, Figure 3.01 lists the research priorities for the Factories of the Future programme (a composite of the Factories FOR the Future and the Factories WITH the Future)[7], with a designated communication channel according to the domain of education.

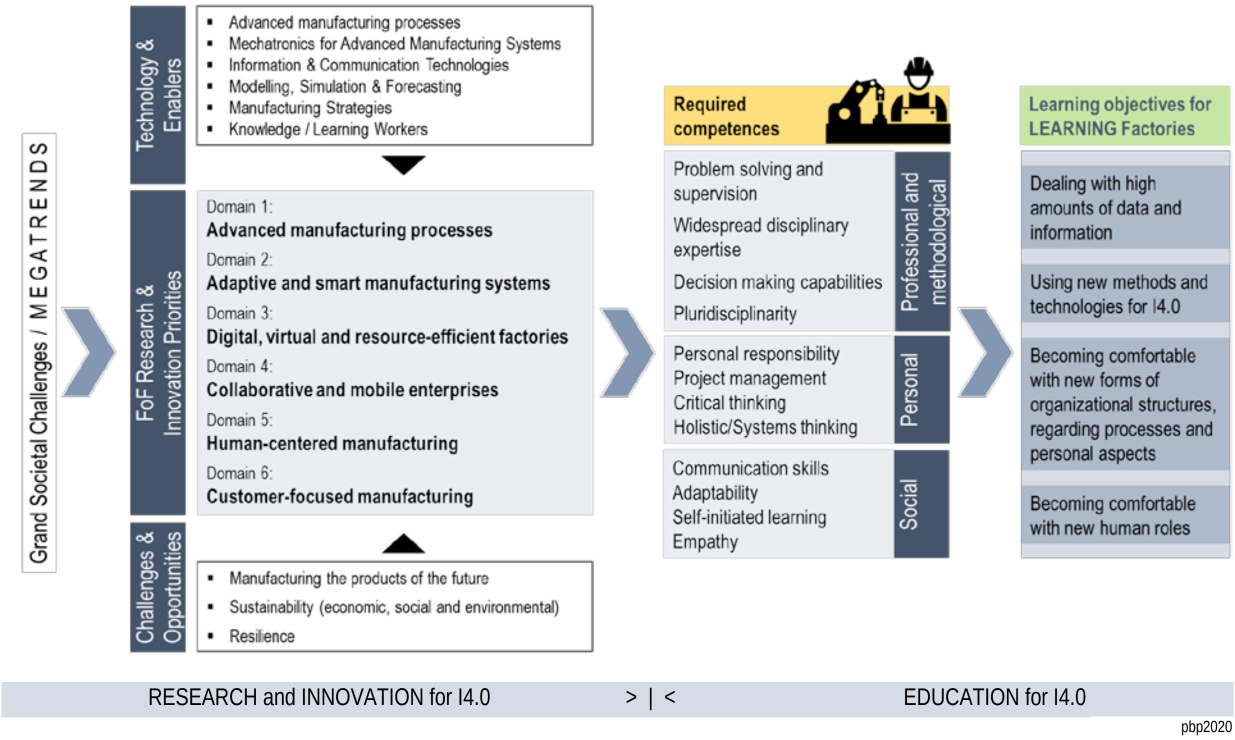

Figure 3.01 The research focused on the I4.0 domain generates a new epistemological basis for advancing the disciplinary knowledge of a new generation of engineers trained for manufacturing in Industry 4.0.

To the above we should add the national initiatives for the digitalisation of industry, whose collaborative activities at the EU level are coordinated by the European Commission. These are, for example: Industrie 4.0, Germany, Industrie du Futur, France, Piano Nazionale Industria 4.0, Italy, Smart Industry - Dutch Industry fit for the Future, Netherlands, Smart Industry, Sweden, Slovenian Digital Coalition – digitalna.si, Slovenia, or the nine Technology and Innovation Catapults in the United Kingdom[8]. As a rule, they function in the so-called Knowledge Triangle, i.e. close interaction of science, industry and education, through various collaborative models. For example, the so-called Digital Innovation Hubs (DIH) and Centres of Competence (CoC). These structures, as is the case in Italy, through the Knowledge Triangle, integrate three key national actors into a single system for manufacturing innovation,

6 acatech – National Academy of Science and Engineering, (2013) Securing the future of German manufacturing industry, Recommendations for implementing the strategic initiative INDUSTRIE 4.0, Final report of the Industrie 4.0 Working Group, Sponsored by German Federal Ministry of Education and Research.

7 Ursula von der Leyen (10 March 2020): 'Europe's industry is the motor of growth and prosperity in Europe. And it is at its best when it draws on what makes it strong: its people and their ideas, talents, diversity and entrepreneurial spirit. This is more important than ever as Europe embarks on its ambitious green and digital transitions in a more unsettled and unpredictable world. Europe's industry has everything it takes to lead the way and we will do everything we can to support it.'

8 https://catapult.org.uk/about-us/about-catapult/

in which the creation, diversification, networking and effective application of productive knowledge are of a nationwide scale. They deeply permeate the complete ecosystem for knowledge creation, innovation and material production of the national economy[9]. Coordination and other roles of government bodies in this context are of essential importance, which is why it is necessary to shift from the Knowledge Triangle to Prosperity Tetrahedron.

Knowledge for Industry 4.0: Industry 4.0 is not just digitalisation, no matter how much we talk about digitalisation and how, rightly, digitalisation of all production processes and value chains is a priority above all others, and is a topic of the highest research, strategic, marketing and even political importance. Before penetrating the field of manufacturing-specific digital knowledge, the disciplinary knowledge of engineers educated for the I4.0 context must encompass fundamental STEM knowledge and knowledge in the field of Manufacturing Technologies – hence the need to change the amorphous STEM into a manufacturing engineering profiled sTEmS framework. So, from the perspective of the disciplined episteme I4.0 of an educated engineer, digital technologies are just an epistemological island in the vast ocean of technological knowledge on which the manufacturing industry in the 21st century rests. However, digital technologies are characterised by their ubiquity. Within the I4.0 context, they appear as an agent of horizontal transformation, which has a disruptive effect on the overall space of manufacturing technologies. And that is the essence of the digital transformation of the manufacturing industry!

In the period preceding the appearance of I4.0, which dates back to the mid-fifties of the 20th century, the transformational effect of digital technologies led to new technological entities, mechatronic hybrids obtained through the convergence of classical mechanical engineering and digital technologies. This primarily refers to CNC machine tools and industrial robots. From the perspective of disciplinary knowledge, the essence of these technological hybrids is x-disciplinarity. For example, in order to design and use robots, engineers had to embrace that x-disciplinary space, but still without leaving the disciplinary framework of traditional manufacturing engineering. However, with the evolutionary processes that led to the emergence of the so-called Cyber-Physical Production Systems (CPPS), the traditional technological compactness of disciplinary knowledge of manufacturing technologies disappeared and two new epistemological aggregates emerged: a) manufacturing technologies symbiotically hybridised with digital technologies – Manufacturing Mechatronics, and b) an extensive aggregate of industrial digital technologies that includes communication technologies in their broadest sense.

Deep cybernetisation of the epistemological space of manufacturing technology is an example of a basic determinant of the I4.0 context. Further structuring of this space into subdomains is possible. For example, Sabina Jeschke divides the total epistemological space into five subspaces[10] (Figure 3.02). Traditional manufacturing is transformed into CyberManufacturing through such processes. From the perspective of education, this transformation has a disruptive character on the content, composition and methodology of the curriculum for modern education of manufacturing engineers. Therefore, by analogy, we like to dub this new construct Education 4.0, insofar as it actually represents a new educational paradigm in manufacturing, designed to effectively address the emerging challenges for

[9] There are eight Italian Competence Centers and since 2019 they constitute one of the central points of Italian Industry 4.0 national strategy. They are based in Bologna (BI-REX), Genoa (Start 4.0), Milan (Made 4.0), Naples (MediTech), Padua (SMACT), Pisa (ARTES 4.0), Rome (Cyber 4.0), and Turin (CIM 4.0)

[10] Jeschke, S., et al. (2017) Industrial Internet of Things and Cyber Manufacturing Systems pp:3-19 (Chapter 1), in Industrial Internet of Things - Cybermanufacturing Systems, Springer International Publishing Switzerland, ISBN 978-3-319-42558-0, doi 10.1007/978-3-319-42559-7.

manufacturing education and skills/capabilities delivery to the industry. 'Robot-Proof' education, as Joseph Aoun called it, in his research on the challenges of the new learning model in higher education in the age of artificial intelligence[11].

It is important to note here that knowledge for I4.0 necessarily includes knowledge and skills in the field of social sciences, humanities and arts, without which a modern engineer cannot function effectively in an I4.0 environment; hence the aforementioned initiative of the Euro-CASE Engineering Education Committee for the need to design a new sTEmS framework, as a complement to the existing STEM and STS frameworks for engineering education.

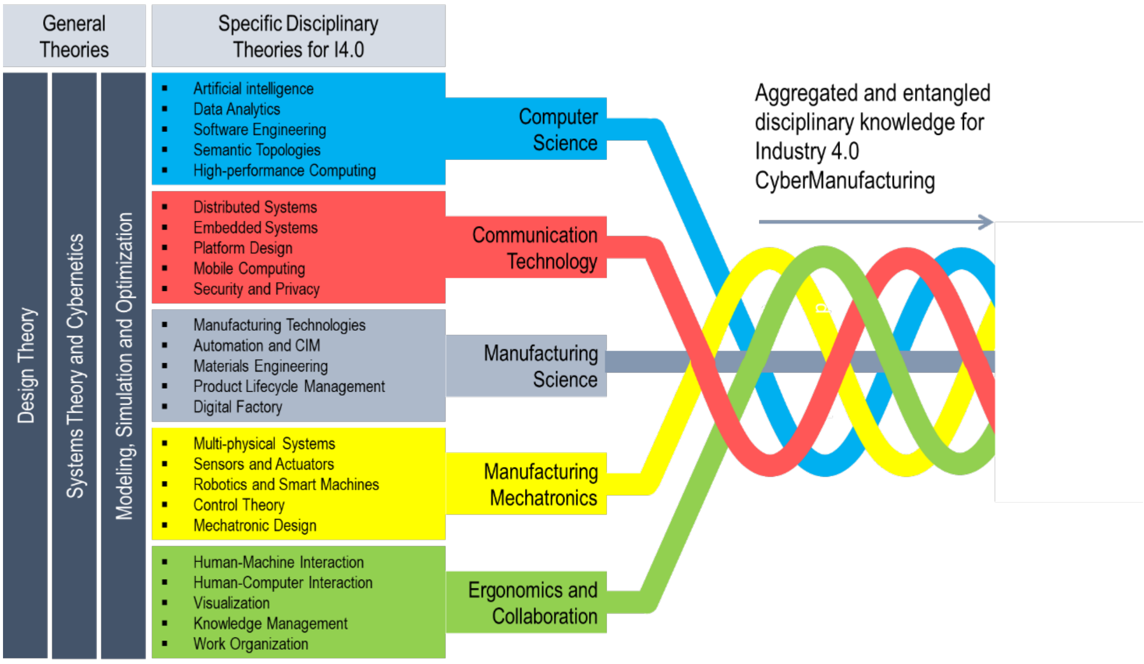

Figure 3.02 Composition of disciplinary aggregate of engineering knowledge for Industry 4.0, as applied to mechanical engineering.

Human role in Industry 4.0: When digital technologies began to penetrate the industry more massively during the 1980s, the concept of so-called Computer Integrated Manufacturing (CIM) was the holy grail of the digital transformation of the entire production and business system of a factory and the manufacturing sector as a whole. CIM was essentially the concept of workerless production, or so called 'lights-out manufacturing'. I4.0 is the opposite, a concept in which biological and engineered systems are seamlessly integrated. The human role in I4.0 is still relevant and essential for factory operation at all its levels. This concept implies the need for intensive interaction between people and machines, and also opens the question of labour division[12, 13]. The key trend is collaboration. Collaboration (or even teamwork!) of the human with the smart machine (robot, for example) in performing a common task in a shared fenceless workspace. Then came the collaboration between smart machines. And, the mixture of the previous two characteristic forms and the creation of a hybrid population of mutually

[11] Aoun, J., (2017) Robot-Proof: Higher Education in the Age of Artificial Intelligence, The MIT Press, ISBN: 978-0-262-03728-0; Professor Joseph Aoun is the president of Northeastern University in Boston, Massachusetts, USA.
[12] Levy, F., (2005) The New Division of Labor: How Computers Are Creating the Next Job Market, Princeton University Press, ISBN10: 0691124027
[13] Daugherty, P.R., (2018) Human + machine: Reimagining work in the age of AI, Publisher: Harvard Business Review Press, ISBN: 9781633693876

collaborative biological and engineered technological entities. In such a context, all technological entities are interconnected, and through two-way communication channels, Human-Machine Interfaces (HMI), the flow of information, knowledge and skills is achieved. Through such HMI channels machines learn from people by demonstration and from data, instead of from explicit programming. People learn too, from other people and from machines. CPPS is a dynamic learning system in which knowledge acquisition and continuous dispersion of acquired knowledge through the complete production system, horizontally and vertically, is one of its key technological determinants. This nature of CPPS transforms the concept of Knowledge Worker into Learning Worker and has dramatic consequences for the education of I4.0 engineers.

The challenge of tool complexity for engineering design: The above is just one of the completely new aspects of the role of people in the production environment I4.0. This primarily refers to the physical interaction between the biological and engineering systems within the production and other processes that make up the value chain of a factory. However, it is important to mention the importance of human-machine interaction in the engineering design process. Just a few decades ago, engineering tools were drawing tables and technical manuals. Today, the process of engineering design is fully digitalised, practically unthinkable without a computer. The complexity of many engineering tools for 3D modelling, simulation, and virtual reality, the so-called CAx tools, and the rate of change at which they evolve, give rise to a whole new set of challenges to engineering education curriculum. For example, Dassault Systèmes, through its 3DEXPERIENCE platform[14], offers a universe of 17 groups of digital tools of almost unimaginable performance and enormous technical complexity.

CAx tools move engineering design and engineering method to a whole new context. It is the context of mixed reality and consequently, mixed experience (physical and digital/virtual), which gives engineers the opportunity to see and feel what they create before their imagination and ideas become part of the physical reality. A significant part of the process of perfecting the solution takes place in the abstract space of the digital computer. This speeds up the design process. The number of iterations in the optimisation process can grow unhindered. The errors that naturally come with it are corrected before they affect the physical reality, with the inevitable financial and many other consequences. However, the use of CAx digital tools poses an immense challenge, as it requires enormous knowledge and practical skills that burden the cognitive system of engineers and, in addition, impose the need for continuous upskilling. Effective use of CAx technology should be given a special place in the formal education curriculum. Dassault Systèmes, for example, has an educational component in its business system, the 3DEXPERIENCE Edu learning portfolio. Dassault knows that CAx business and CAx education must go hand in hand.

Outline for Curriculum Reengineering for I4.0: A study on a broader range of issues related to the development of curriculum for the Advanced Manufacturing Technologies domain (AMT) [15] (subset I4.0) highlights several important observations related to labour market requirements for I4.0 sector. First of all, it is estimated that in 2025, about 75% of the workforce will be comprised of millennials, a generation that is particularly motivated by human contact, continuous feedback, training & development and flexibility. It is believed that their positive qualities are overshadowed by weaknesses in their

[14] https://www.3ds.com/products-services/

[15] European Commission, Executive Agency for Small and Medium-sized Enterprises (EASME), Skills for Industry Curriculum Guidelines 4.0: Future-proof education and training for manufacturing in Europe, Written by PwC, Publications Office of the European Union, 2020, ISBN: 978-92-9202-823-7.

critical thinking abilities. They are often referred to as 'overeducated, but underskilled' and also tend to demonstrate a lack of loyalty to their employers. Above all, they show a natural affinity and talent for the world of digital technologies (digital natives). In this context it is pointed out that students as well as broader public have a strong misconception about factories and the manufacturing sector, which they associate with poor working conditions and lack of prestige. However, the reality of the industrial environment in Europe is different. The reindustrialisation is transforming European factories into human-centred manufacturing, where the working environment has been significantly improved in relation to the negative stereotypes. Highskilled engineers are in strong demand. According to the WEF study about the future of jobs[16], employers want engineers who have the complex skills and abilities listed in the Table 3.01. However, these are the attributes of the qualification profile of engineers as seen by the world of economics and not the world of engineering! Two profiles are listed, one from 2015 and the other from 2020. The dynamics of changes in the labour market is greater than the dynamics that a university can keep up with! This is a very serious issue, a red alert, and concrete solutions must be provided.

	Skills required by the labour market for I4.0		
	in 2015		in 2020
1	Complex problem solving	1	Complex problem solving
2	Coordinating with others	4	Critical thinking
3	People management	10	Creativity
4	Critical thinking	3	People management
5	Negotiation	2	Coordinating with others
6	Quality control	new	Emotional intelligence
7	Service orientation	8	Judgment and decision making
8	Judgment and decision making	7	Service orientation
9	Active listening	5	Negotiation
10	Creativity	new	Cognitive flexibility

Obtained by analysing the answers to the questions asked to chief human resources and strategy officers from leading global employers across industries and geographies. Source WEF.

Table 3.01 The dynamics of changes in the labour market is greater than the dynamics that a university can keep up with! Two profile of skills required by the labour market for I4.0 according to WFO study.

From the aspect of pedagogy, the previously mentioned expectations of employers should be connected with the psychological profile of engineers, which is determined by 6 universal engineering habits of mind (systems thinking, adapting, problem-finding, creative problem-solving, visualising, improving) and, equally important, with the general outline of the engineering method.

If to the above we add the impact of the relevant labour market trends[17]:

a. the emergence of a wide variety of employment situations,

b. the rise of new forms of work outside the employment relationship,

16 The World Economic Forum (WEF), (2016) The Future of Jobs - Employment, Skills and Workforce Strategy for the Fourth Industrial Revolution, Global Challenge Insight Report.

17 European Commission, Executive Agency for Small and Medium-sized Enterprises (EASME), Skills for Industry Curriculum Guidelines 4.0: Future-proof education and training for manufacturing in Europe, Written by PwC, Publications Office of the European Union, 2020, ISBN: 978-92-9202-823-7.

c. growing individual expectations and diverse working conditions,
d. the transformation of workplaces, times and activities,
e. the emergence of multifaceted and discontinuous career paths,
f. increasing interconnections between work and private life,
g. the rise of agile and dynamic labour markets, and
h. fading boundaries between national labour markets,

then the puzzle thus obtained outlines a broader picture of the key imperatives of the Engineering Education 4.0 curriculum. It can be further stratified at three levels (qualification strata called 1st, 2nd and 3rd tier) [18], whose analysis and summary lead to technical and non-technical priorities of engineering skills and capabilities for I4.0 Factory of the Future shown in Table 3.02 (this table is predominantly focused on the today's dominant ICT layer; other engineering disciplines could construct their own versions of such a matrix).

	Must ...	Should ...	Could ...
	... be included in the skilled labour of the I4.0 Factory of the Future		
Technical Q & S	IT knowledge and abilities	Knowledge management	Computer programming/coding abilities
	Data and information processing and analytics	Interdisciplinary/generic knowledge about technologies and processes	Specialized knowledge about technologies
	Statistical knowledge	Specialized knowledge of manufacturing activities and processes	Awareness for ergonomics
	Organizational and processual understanding	Awareness for IT security and data protection	Understanding of legal affairs
	Ability to interact with modern interfaces (human-machine / human-robot)		
	Ability to understand and work within the situational socio-political-economic context		
Personal Q & S	Self- and time management	Trust in new technologies	
	Adaptability and ability to change	Mind-set for continuous improvement and lifelong learning	
	Team working abilities		
	Social skills		
	Communication skills		

Table 3.02 Priority matrix of technical and personal qualifications and skills (Q & S) of engineers educated for I4.0 Factory of the Future.

It is obvious that the diversification of the I4.0 curriculum is an inevitable pedagogical reality. The question is how to practically achieve this diversification, how to find the necessary balance between the practice-based

18 Kamp, A., Klaassen, R., (2016) Impact of Global Forces and Empowering Situations on Engineering Education in 2030, Proceedings of the 12th International CDIO Conference, Turku University of Applied Sciences, Turku, Finland.

and the engineering science-based curriculum dichotomy? This is definitely not a new topic, because tension of this kind has existed for a long time and extends almost through the complete timeline of the evolution of modern engineering. To this should be added another educational dichotomy of engineering – specialist versus generalist[19].

One of the answers could be a mission-oriented approach. This is a top-down approach, because the mission here implies the professional role of the engineer in projects and different work environments, regardless of the narrow engineering discipline (meaning the I4.0 context of professional engagement). The trick, however, is to find some sort of synergy between the multitude of particular missions, to avoid a monocultural context that oversimplifies things, and, for example, not reduce the mission-driven approach to a market-driven approach and blindly follow the current needs of the labour market, no matter how significant they may be. To illustrate this idea we will present the way of thinking of Aldert Kamp, Director of Education for TU Delft, who in his research recognises four profiles of engineers while looking for answers to four clusters of heuristic questions [20]:

a. How can we advance and optimise technology for innovations and better performance using scientific and engineering knowledge?

   Answer: I4.0 Engineer SPECIALIST – R&D for innovation in industry and engineering science

b. How can we bring together disciplines, products or subsystems into a functioning whole that meets the needs of the customer?

   Answer: I4.0 Engineer SYSTEM INTEGRATOR – Connector

c. How can we advance and apply knowledge and use technology to develop new products for the benefit of people?

   Answer: I4.0 Engineer FRONT-END INNOVATOR

d. How can we exploit diversity-in-thought to advance and apply knowledge and use technology in different realms to develop products and processes for the benefit of people in different cultures and context?

   Answer: I4.0 Engineer CONTEXTUAL ENGINEER

Profiles defined in this way are further attributed in more detail through a four-dimensional metric space: roles in university, roles in the field of work, goals and beliefs, pain and frustration. This systematically forms a scaffold of knowledge and skills/capabilities, combining basic building blocks of knowledge for I4.0 and pedagogical methods.

Interplay between systemic and disciplinary knowledge: It is important that teaching curricula embrace and engage in the triad of research, innovation and teaching, because this is where fundamental interactions arise. This also leads to the demand for Research-oriented Teaching and Teaching-oriented Research. Therefore, a very important goal of engineering education is to introduce students to the fields of research and innovation design in a continuous, involved and appropriate manner. It is also important that changes in the curricula of sTEmS education reflect the fact that today's products are very complex (as a rule, mechatronic) and that different forms of interaction between different disciplines are necessary (x-disciplinary approach, in general). In addition to expertise in a specific field, for example

[19] Crawley, E. F., et al., 2014. Rethinking Engineering Education: The CDIO Approach. Springer International Publishing, Springer, ISBN-10: 1441942602.

[20] Gehrke, L., at al, (2015) A Discussion of Qualifications and Skills in the Factory of the Future: A German and American Perspective, White Paper, Association of German Engineers (VDI) and American Society of Mechanical Engineers (ASME), Conference Hannover Messe 2015.

design of thermodynamic processes in combustion engines, it is of decisive importance that every engineer be capable to combine their specific, specialist knowledge with the overall design aspects of engineering systems. For this purpose, a Basic Dynamic Model was developed by IPEK to profile the competencies of engineers through the interaction between these two strata of knowledge (Figure 3.03).

First, there is a systemic stratum or a system-of-systems knowledge stratum (SoS stratum), from which the general system theory / knowledge (not only technical!) is taught as the core knowledge and skills for structuring and decomposition of complex technical systems as an approach with the aim of effective complexity management. The second stratum is the basic disciplinary STEM knowledge, which leads to specialisation, resulting from the subject areas and subjects in the direction of deepened knowledge in the respective area of specialisation. Combining knowledge from both strata leads to engineering ‘expert knowledge’ for some I4.0 manufacturing sectors, or domains within them.

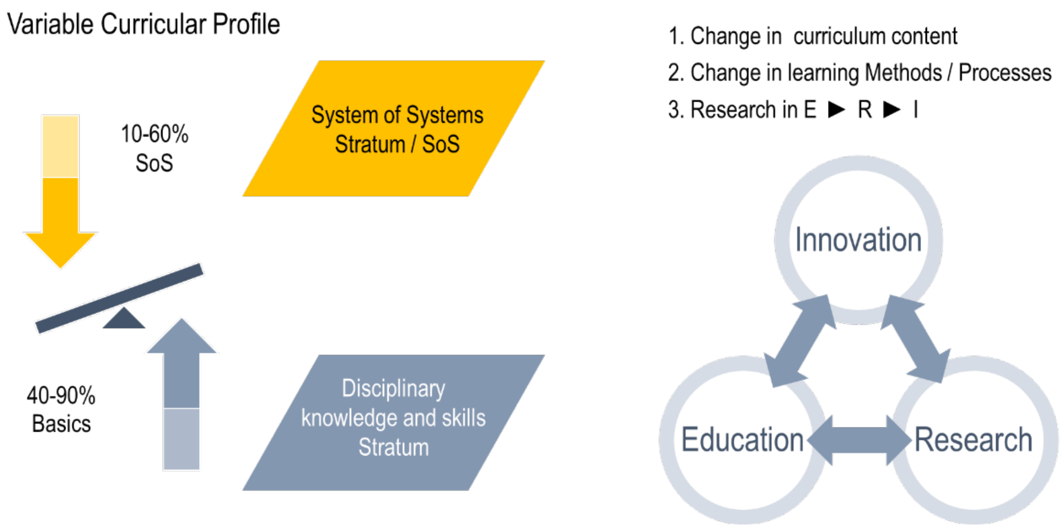

Figure 3.03 Basic Dynamic Model for the design of engineering science curricula.

However, it is crucial that each engineering curriculum, regardless of disciplinary specialisation, contains at least 10% of the technical systems knowledge and skills in SoS stratum and thus provide the necessary technical expertise that enable engineers to talk to each other as well as the ontology to help them connect with each other. This should be the essence of the Basic Dynamic Model for designing engineering curricula for I4.0.

Teaching and Learning Factory: First of all, the phrase Teaching and Learning Factory has nothing to do with criticism on the part of the academic community concerned about the growing commercialisation of the university and pointing out to the public that ‘the university is not a factory’. Here, however, the term 'factory' is placed in a new pedagogical concept designed to facilitate experiential learning, practical projects and collaborative problem-solving by bringing the educational process closer to the authentic environment of the factory.

Although the concept of Teaching and Learning Factory is not fundamentally new[21], it has only recently gained its full momentum in the pedagogical sense.

[21] Abele, E., Metternich, J., and Tisch, M., (2019) Learning Factories: Concepts, Guidelines, Best-Practice Examples, Springer International Publishing, ISBN: 978-3-319-92260-7; 978-3-319-92261-4.

In fact, it is probably a protomodel of the future learning paradigm, not only in engineering education or STEM at technical and research-intensive universities, but also a possible response to the challenges of university reform aimed at achieving its third mission. The concept of integration of the classroom and the future working environment in medicine has existed for a long time and today is an educational standard. Teaching factory is its equivalent, transferred to the domain of engineering and STEM [22]. This transfer to the domain of manufacturing engineering education has not been done without reason. The dynamics of change and the diversity of technologies in the manufacturing sector are of such proportions that engineering education for I4.0 requires close interaction between universities and industry in order to fully prepare the graduates for the I4.0 labour market. The previously mentioned Design-based Learning, Problem, Project, and Challenge-based Learning, Experiential Learning (EXL), or CDIO, as a kind of universe of various forms of hands-on / learning-by-doing methods, only within the concept of Teaching and Learning Factory reach their full pedagogical potential.

It is important to recognise that the interaction of universities and industry within the concept of Teaching and Learning Factories is motivated by mutual interests, which is why there are two communication channels.

The first is the Factory-to-Classroom knowledge and skills communication channel, which aims to make the authentic environment of the factory, its processes, equipment and overall culture (technical and non-technical) directly available to the university and 'transfer' it to the classroom in various ways. Here, the idea of the classroom should be understood as a metaphor for the learning environment, because, as a rule, it is about shared physical space. Through such a context, students can come into contact with expensive state-of-the-art industrial equipment (experience-based learning with hands-on on key building blocks of I4.0 concept is an extremely expensive pedagogical method, unattainable for the university in reality!), to see and feel the production processes, and equally important, to get acquainted with real shop floor problems and engage in problem-solving activities, side by side with factory engineers. In addition, this context also imparts learning of personal and interpersonal skills that are characteristic of the factory environment. The wealth of experience that can be gained in this way simply has no comparable alternative. Everything else is a pale pedagogical shadow – not only in the sense of acquiring disciplinary knowledge, but also stimulation, motivation and inspiration for the development of innovative and entrepreneurial spirit.

The second is the Lab-to-Factory knowledge communication channel. It is a channel of so-called vertical knowledge transfer, an academia-to-industry operational scheme through which the factory learns from the university. It should not be forgotten that laboratories at universities operate at different dynamics, unencumbered by market and business pressures, and that the processes of formal methodology in solving and dealing with problems differ significantly from those that can be used in the factory. In university laboratories, the real problems of factories are subjected to a rigorous scientific method with a strong emphasis on the practical applicability of research through the framework of engineering sciences. In this context, the term 'immediately useful knowledge' gets its true meaning and at the same time, a significant time dimension. Curiosity is intertwined with the sense (and responsibility) for practical application, and research challenges are graded into classes (e.g. three classes of knowledge and ideas: a) can it be improved,

[22] G. Chryssolouris, G., at al, (2016) The Teaching Factory: A Manufacturing Education Paradigm, 49th CIRP Conference on Manufacturing Systems (CIRP-CMS 2016), Procedia CIRP 57, pp44–48, Published by Elsevier B.V., doi: 10.1016/j.procir.2016.11.009.

time horizon of 0 to 3 years, b) is it feasible, time horizon of 3 to 10 years and c) is it possible, time horizon of over 10 years). It is quite obvious that innovation is emerging through this communication channel. Also, various forms of consultation open up almost endless possibilities for continuous knowledge updating of factory engineers (lifelong learning).

Today the concept of teaching and learning factories already covers a wide range of application scenarios [23]: a) industrial application scenario, b) academic application scenario, c) remote learning scenario, d) changeability research scenario, e) consultancy application scenario and f) demonstration scenario – with a reason. The diversity of embodiments is a consequence of a wide variety of learning, industrial and social environments. The flexibility and modularity of the concept is its inherent feature[24]. Nevertheless, this learning paradigm is still in the phase of development and searching for sustainable solutions. Issues such as morphology, operational model, financial sustainability, thematic sustainability, and the like, should be further looked into.

It is quite clear that the concept of Teaching and Learning Factories paradigm rests on the knowledge triangle. In order for it to develop further, it must be extended to the 'Prosperity Tetrahedron' context, in which policy planners appear, above all government bodies. They should devise new models and instruments to integrate this learning paradigm into the existing programmes, such as ERASMUS+, or the European Universities Initiative, or EIT KIC Manufacturing (the Field Study Pedagogy (FISP) project[25]), for example, all as a part of a general reform commitment to direct the university towards the effective implementation of its third mission.

It is also very important that this learning paradigm be integrated into research projects, for example in the calls of the forthcoming FP9 Horizon EUROPE, with the main goal of linking scientific results, especially those in the field of applied sciences, technology and engineering, with human resource development ready to immediately valorise the acquired experiences and competencies through the labour market. The essence is to shorten the time distance between the creation of knowledge and the transmission of the newly created knowledge into the space of formal education of engineers. Therefore, the Euro-CASE Committee for Engineering Education recommends that the concept of Learning and Teaching Factories become one of the missions of the FP9 Horizon EUROPE programme.

Key lines of action: Taking into account the above, as well as a detailed insight into the extensive literature which, in addition to general aspects of engineering education, explores the specifics of education for current industry needs through the I4.0 framework, the Euro-CASE Committee for Engineering Education has defined 5 key lines of action in an effort to modernise the engineering education curriculum and STEM human resources:

1. Shifting from Knowledge to Competences
    a. Provide strong Technical/Scientific Fundamentals and strong disciplinary Knowledge / Skills / Competences;
    b. Provide a strong social component of knowledge and skills and also preparation for life as active citizen (non-technical / personal

[23] Eberhard Abele, E., at al (2015), Learning Factories for research, education, and training, 5th Conference on Learning Factories (CLF 2015), Procedia CIRP 32, pp1–6, Published by Elsevier B.V., doi: 10.1016/j.procir.2015.02.187

[24] Prinz, C., at al., (2016), Learning Factory modules for smart factories in Industrie 4.0, 6th CIRP Conference on Learning Factories, Procedia CIRP 54, pp113–118, Published by Elsevier B.V., doi: 10.1016/j.procir.2016.05.105

[25] EIT Manufacturing Field Study Pedagogy (FISP) project aims at designing a Teaching Factory methodology to deploy the training of engineering students on implementing innovation in manufacturing systems, at bachelor and master levels. Teaching Factory consists in enabling a collaboration between factories and students with the double objective of solving industrial problems and increasing the competencies of the students. https://eitmanufacturing.eu/field-study-pedagogy/

competencies and understandings, attitude and empathy), shifting from STEM to sTEmS;

c. Provide strong personal learning capabilities and preparing students to be continuous learners (learn how to learn and become aware of the importance and need for continuous personal development) ;

d. Form a complete personality with a balanced relationship of three key virtues for a successful professional and private life – *episteme*, *techne* and *phronesis* (Knowing, Doing and Being).

2. **Forming a multidisciplinary spirit and systems thinking** (both technical and non-technical);

3. **Embedding new pedagogical approaches and new learning technologies**

   a. Develop problem-solving skills within the engineering method and engineering habits of mind (Problem, Project, Challenge-based learning, CDIO and the like);

   b. Stimulate hands-on experience (experiential learning, learning by doing, and the like) and interaction with I4.0 real-world environment (Teaching and Learning Factory);

   c. Enhance skills of critical thinking and decision making in uncertain and vague environments;

   d. Use CAx tools for engineering design, AR/VR technology, Digital Twin technology (digital experience) and MOOC technology;

   e. Develop skills and abilities for team work (collaborative learning), multiculturality and global communication skills;

   f. Develop an innovative spirit and ability (techniques of divergent and convergent multidisciplinary and systemic thinking) and entrepreneurial spirit, interaction with the innovation ecosystem;

4. **Embedding the ethical component and forming a sense of social responsibility** (especially economic, environmental and social sustainability). Engineers, as the creators of innovations for the future have a moral responsibility to ensure that these innovations are appropriate for society. That engineers should "do no harm" as a first principle, is a key component of the engineer's toolkit, and needs to be developed in both theory and practice during their engineering education.

   The engineer, as the holder of knowledge and the ingenuity to apply it for the benefit of society, also has a responsibility to ensure that the lines of communication between engineers and society are always open, that society can understand what is happening and why, and why a proposed implementation is going to benefit all of society. This requires use of essentially human skills – the ability to explain complexity simply, the ability to listen and the ability to understand another's point of view (allocentric thinking). As engineered solutions become ever more complex and thus potentially technologically distant from the person, the necessity increases for the solution to understand, and be understood by, the person. This becomes an ever more important part of an engineer's education: for example, "Intuitive" means that the mindset of each user of the technology should be understood and integrated into the technology, not just assumed to be the same as that of the designer.

5. **Updating the skills of teaching staff**.

   As regards the above, in order to establish the necessary methodological formalisms with ontological explanation and the appropriate consideration of exactness (or fuzziness), it is useful to consider the complete curricular strategy as an example of the conceptual framework of a cybernetic system. The curriculum, then, in a representative sense, becomes an abstract goal-seeking system that has the inherent feature of adapting to the environment, i.e. evolutionary processes, in the overall learning ecosystem. This system features:

a. inputs – students, labour market requirements, etc.,

b. outputs – graduates ready for the labour market, culture / capabilities to trigger innovation and entrepreneurship, capacities that affect the competitiveness of industry, and other benefits for the economy and society, and readiness within the labour market to be able to accept the graduates with their more comprehensive skillsets,

c. internal mechanisms of embedding knowledge, skills and capabilities into the cognitive system of students (learning experiences),

d. regulatory mechanisms that manage internal processes (in the classroom, at the university) and respond to various disturbances, or stimuli, which come from the outside world / environment, and finally,

e. The channel(s) of communication with the environment necessarily encompasses industry and the innovation ecosystem (startup community and the related cultural context).

It is quite clear that the cybernetic representation model of engineering education system for I4.0 is extremely complex, which is why such a methodological approach can come under criticism. However, it is essential to bring the necessary rigour of the systemic approach to problem-solving into this framework. The alternatives are intuition and informal verbal models.

In addition, it is useful to mention that the cybernetic approach leads to the conceptual framework of data-driven management of engineering education, which partly relies on big-data and reality mining technologies.

3.b Excellence through pluridisciplinarity

The present discussion relates to all types of engineering, including civil, bioengineering and industrial engineering as they are organized in the European countries. From a society point of view, engineering education needs to train the students to design products, processes, systems, and services aiming not only at a correct functionality and an economic and consumer value, but also with a positive societal impact. The global aspects, the consumer value and the societal impact are items that need to be integrated in the design, experimentation and test cycle. One can think here about the UN Sustainable Development Goals[26], and the Grand Challenges of Engineering of the National Academy of Engineering in the US[27]. Although these ambitions of setting up a separate course on the social aspects of technology might appear attractive, they are not the recommended approach, because the concepts involved need to be immersed in the engineering habits of mind and are thus core to being an engineer, and there is a risk for an unnatural or even hostile perception by some students and even the teachers. Whereas, when the societal issues are fully integrated within the science and technology courses, they are perceived as natural and hence maximally appreciated. There are arguments in favour of starting this approach already

[26] UN Sustainable Development Goals https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[27] National Academy of Engineering, (2005), NAE Grand Challenges for Engineering, http://www.engineeringchallenges.org

from the first year, since there is a wide perception mainly also among high school students and in particular among female high school students, that engineering is not dealing with society (see the motivation study of Sjoberg[28]).

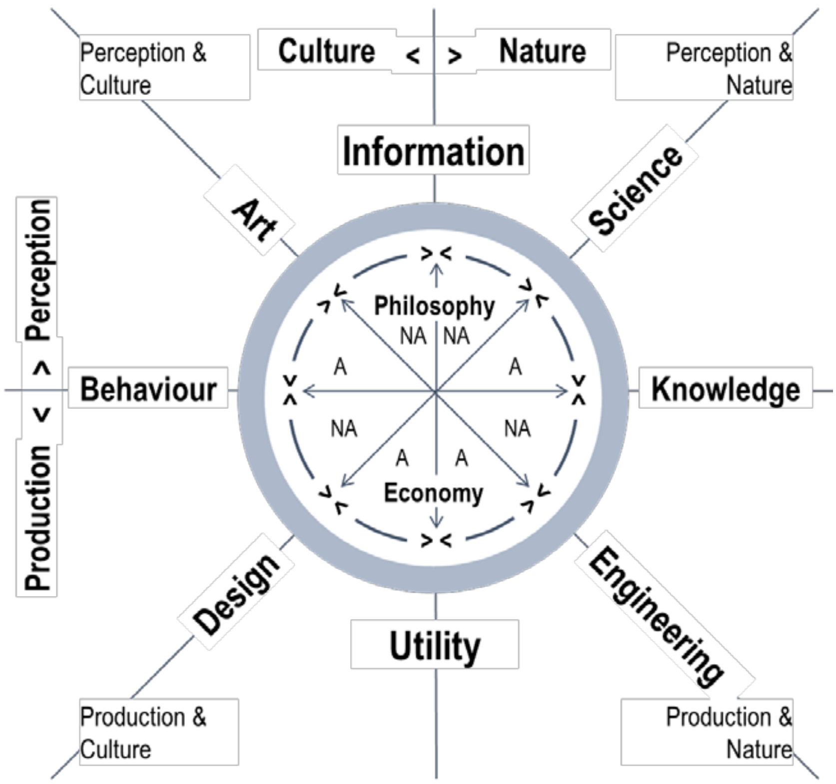

Figure 3.04 Krebs cycle of creativity.

Modern engineering challenges and the global issues that most enthuse our current cohort of students will not be solved by any one discipline, but instead by teams of engineers from across the disciplines and non-engineers, bringing together their skills and expertise to create innovative solutions[29, 30, 31, 32]. As a result, we must prepare our students with appropriate experiences, such as undertaking complex design projects in pluridisciplinary teams. Where this has been practised in university engineering programmes, it has been found that it proves both attractive to women students. In addition, they tend to encourage the male students, who are all too often more interested in the more technological issues, to adopt these methods and learn these approaches.

A critical element is that the study load in the first years of engineering is already typically quite heavy for the incoming students on the conceptual elements of mathematics, physics, chemistry and biology. So, there is some tension here. But the benefits are expected to outweigh the drawbacks. Universities can be creative in the ways their different engineering curricula make this combination. So, for example, bioengineering education can discuss the waste treatment in the food production, chemical engineering

28 Sjøberg, S., Schreiner, C, (2010) The rose project: An overview and key findings (Tech. Rep.), University of Oslo.

29 IET - The Institution of Engineering and Technology, (2017) New approaches to engineering higher education, Case studies of six UK universities leading the way for change in the sector.

30 CESAER, (2019) Discussion paper Science & Technology education for the 21st century, https://www.cesaer.org/content/5-operations/2019/20191218-discussion-paper-st-education.pdf

31 'Guest editorial ' (2019) Special issue on using enquiry and design-based learning to spur epistemological and identity development of engineering students, IEEE Trans Education pp.157-164.

32 Ito, I., (2016) Can design advance science, and can science advance design?, Journal of Design and Science, DOI: 10.21428/f4c68887

can address the plastic waste issues, electrical engineering can introduce the green energy production, electronics engineering can address the electronic waste issues, materials and mechanical engineering can address the recycling issues, computer and ICT engineering can address the privacy issues, civil engineering can consider the societal needs that generate the need for infrastructure. These are typically initiatives that the program director and the program committee for the bachelor education can establish. The impact of the pluridisciplinarity and design based learning on the identity development of students is evident[33].

In the broader perspective one can situate the various disciplines and creative actions and their relations to the individual human beings, society and nature in a diagram called the Krebs cycle of creativity[34].

In this discussion the word 'pluridisciplinarity' is used as a generic term for different forms of interaction between disciplines and for various scopes of it: wide and small. Pluridisciplinarity involves intense collaboration across the borders of the existing disciplines both inside and outside the academic world. The generic term includes more specific terms that are related to the degree or intensity of the interactions[35, 36, 37, 38]. Descriptors that differentiate between different types of pluridisciplinary activity are:

Multidisciplinarity (additive): Cooperation for the duration of one or more projects after which the unchanged partners each go their own way (example optomechatronics).

Interdisciplinarity (integrative): Cooperation in which progress has been made within each discipline because there is a cross-pollination on methodological and / or conceptual / theoretical level.

Transdisciplinarity (holistic):[39] The outcome from the melding of more than one discipline results also in the permanent change in formulations and approaches of one or more of the constituent disciplines (example, change in evaluation methodology across ophthalmology as a result of ophthalmologists and civil engineers working together on the theory and application of performance testing for a particular therapy)[40].

Antidisciplinarity:[41] research in spaces that does not fit into any existing academic discipline – a specific field of study with its own particular words, frameworks, and methods. A nice example of an antidisciplinary project is described in the work of Michael Vallance[42].

Pluridisciplinarity and antidisciplinarity have many benefits. First of all, the global view of the system. There one does not only consider the functionality of the design but the whole system, and the way it interacts with the user and society. So, an important topic of study is 'systems thinking and systems engineering' (see also Section 2b and Section 3). Many engineering societies are aware of it and stress it more and more. There are indeed several

33 N. Oxman, (2016) Age of Entanglement, Journal of Design and Science (JoDS), see also Krebs Cycle of Creativity, DOI: 10.21428/7e0583ad https://jods.mitpress.mit.edu/pub/designandscience/release/2

34 Van Noorden, R., (2015) Interdisciplinary research by the numbers, an analysis reveals the extent and impact of research that bridges disciplines, Nature, News feature, Vol. 525, pp. 306-307.

35 LERU Report, (2016) Interdisciplinarity and the 21st century research-intensive university

36 National Academies Press, (2015) Facilitating Interdisciplinary Research.

37 British Academy, (2016) Crossing Paths: Interdisciplinary institutions, careers, education and applications.

38 Van Noorden, R., (2015) Interdisciplinary research by the numbers, an analysis reveals the extent and impact of research that bridges disciplines, Nature, News feature, Vol. 525, pp. 306-307.

39 Miller, C.Z., (2016), Towards Transdisciplinarity: Liminality and the Transitions Inherent in Pluridisciplinary Collaborative Work, Journal of Business Anthropology, Special Issue 2: 35-57.

40 Bainbridge J, et al. (2008) Effect of gene therapy on visual function in Leber's congenital amaurosis, New England Journal of Medicine, 358(21) 2231-2239

41 Antidisciplinarity, https://joi.ito.com/weblog/2014/10/02/antidisciplinar.html

42 Vallance, M., at al, (2017) 'Development of a Synthetic Learning Environment in the Antidisciplinary Space, The 11th European Conference on Game-Based Learning ECGBL 2017.

transversal subjects within engineering education: system theory & control, optimization, data science, energy, mathematics, and ethics. A second benefit is the common language & understanding that is needed on the workfloor for engineers. And for industry pluridisciplinarity provides more flexibility, efficiency, and a global view.

However, a well-known hurdle against pluridisciplinarity is the typical department structure of the universities where departments keep their students inside the department[43], often emphasised and encouraged by university finance regimes that make it very difficult for departments to work together where there are financial implications of doing so. Also, assessment across disciplines can be problematic with regard to disciplines that use different means of evaluating knowledge. None of these hurdles is insuperable.

As incorporated in the engineering education, there exist several shapes of pluridisciplinarity:

- I-Shaped graduates are specialised deeply in one particular area.
- T-shaped = breadth and depth: in addition to the deep specialization, that industry expects, the graduates have wide set of skills (cope well with pressure, meet deadlines; prioritise work; committed; self-motivated) and a number of complementary skills across other disciplines and in short combine depth with breadth to understand the bigger picture.
- Pi-shaped = skills breadth is combined with not one but two separate domains of deep expertise, creating a shape similar to the symbol for Pi. Complementary sets of deep expertise can make people extraordinarily valuable, if combined with a breadth of perspective.
- Comb-shaped = many specific domains of expertise as well as breadth. It can certainly never match the knowledge of a deep specialist in any one area.

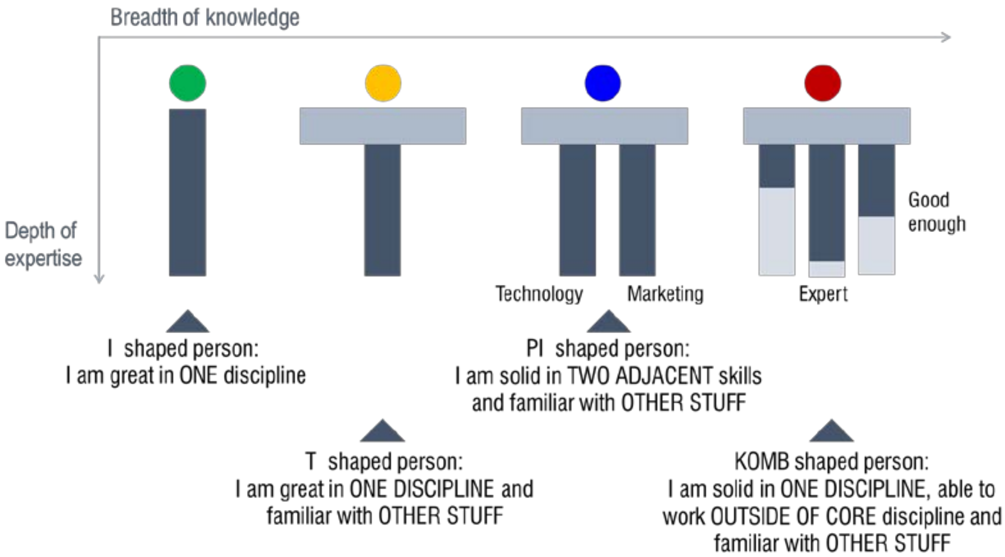

Figure 3.05 Shapes of pluridisciplinarity.

[43] Boulton, G., and Lucas, C., (2008) What are universities for?, LERU report, https://www.leru.org/files/What-are-Universities-for-Full-paper.pdf

An interesting trajectory for students combining depth and breadth is the following branching out implementation. After high school there is a common start phase for all engineering specialities during 3 semesters. Then there is a focus on two out of 6 specialities in the next 3 semesters of bachelor. In the 2 years of the masters programme students go into the depth of one master from a wide choice of deep specialities. Such a trajectory has the benefit that the students are in control of their avenue at two intermediate points of the trajectory by well informed choices based in their individual interests, and competences. A drawback of such a system is that there is no valuable exit to the workforce after the bachelor, but only a transfer to one of the masters.

Recommendations:

1. Academics should develop teaching experience in both core and interdisciplinary areas.
2. Institutions should show support for interdisciplinary, research–based teaching and recognise its value in evaluating academic careers.
3. Introduce basic concepts in critical thinking (for example, the difference between arguments, knowledge, and facts) and in the history and philosophy of science (epistemological positions)
4. Develop seminars with a problem-based approach to stimulate critical thinking and applications of knowledge

Two final remarks in this discussion on pluridisciplinarity are in order. First of all, it is crucial that every engineering education includes a strong and deep knowledge of at least one engineering discipline. Second the broader knowledge in other engineering and non-engineering disciplines should not be voluntary or inconsistent, but should be geared towards strengthening the global knowledge and towards linking it to societal issues.

How does business deal with interdisciplinarity:[44] For example, today Philips focuses on the big challenges worldwide: global warming, preventive health care, increase in chronic diseases, need for self-expression, healthcare for everyone, etc. Innovations are essential to meet such challenges. These innovations are very highly based on interdisciplinary cooperation.

It is necessary to combine innovations in the hardware or software of products and services with deep insights into biology, human physiology, human behaviour etc. The Philips' recent history shows many examples of this. Medical equipment cannot only be based on the integration of innovative technologies. A deep understanding of the syndromes and how they are dealt with in clinical practice is necessary, as is the understanding that the core and most important part of the system is the (human) patient. Handling chronic diseases in the home situation requires not only sensor technology, but also behavioural change on the part of all involved.

Even apparently simple devices such as Lumea or Airfloss are based on in-depth understanding of skin and mouth biology and physiology. Interdisciplinary research is therefore a priority within Philips Research. Cooperation between innovative talent of different scientific origins are stimulated in all sorts of ways. Interdisciplinary Research is also extremely stimulating: the cross-pollination of creative spirits from different backgrounds is extremely motivating and leads to completely new solutions.

[44] Paul Put 'Interdisciplinariteit' https://www.youtube.com/watch?v=rtsJ8vLiiPw&feature=emb_title

3.c Improving laboratory experience and skills

Agreement between the theoretically foreseen and experimentally obtained results has always been and will also remain the main motivation for science and engineering. The arrival of computers and their rapid development in the past decades have substantially enhanced the accuracy of the theoretical and experimental results followed by an extensive expansion of data that needed to be processed and evaluated. On the other hand, computers have also been introduced into the experimental work, thus introducing more complexity to the science and engineering teaching.

In the planning of engineering devices, computer modelling is introduced more and more. The comparison of the theoretical and experimental data has thus become even more time consuming.

Such an enormous change in technology can only be implemented by technically well-educated people. The engineering education programs should therefore be adjusted to the new demands. The number of experiments necessary for the understanding of the devices and processes is growing, thus bringing additional demands for study conditions and teaching quality.

The traditional engineering teaching laboratories do not fulfil the demands of the modern industry (I4.0) or offer the engineering graduates the appropriate qualifications.

Experiment-based learning in higher engineering education based on remote laboratories proves to be a significant improvement compared to the classical teaching approaches.

Remote laboratories: Traditional teaching laboratories require students to be physically present in order to interact with equipment. This limits the accessibility for students in time and space to the neighbourhood of the university. In addition, it is very difficult to cooperate the experimental work in sharing facilities from different laboratories, departments and universities[45].

The engineering educational process has been strongly influenced by the rapid development of the new information and communication technologies (ICT). The use of ICT has increased rapidly since the eighties with the dramatic increase in the capabilities of computer hardware and software. It has also changed the role of engineers as ICT has become indispensable in all aspects of their profession including experimental work in laboratories. Their knowledge must be constantly updated by accessing current information. For the development of the required professional capabilities the engineering graduates must have enough opportunity to develop an understanding of the use of some of the advanced engineering software tools during their educational program. They must, however, also be aware of what such technologies cannot do, and where people are actually superior to technology – for example, the human brain is quite a slow processor, but it can process multiple strands of discrete data very quickly and thus act on many multisensorial inputs far better than ICT has yet been able to manage. It is key for engineering students to understand where people or technology perform better and incorporate this in their solutions.

Combining the state of the art in ICT in the modern industry, one of the possibilities to improve engineering education is to develop and to implement the laboratories with remote access for the students. Using this concept of laboratories allows students to use the internet to remotely access the

[45] J. Grodotzki, T. R: Orteil, A.E. Tekkaya: Remote and Virtual Labs For Engineering Education 4.0, Procedia Manufacturing 26 (2018) 1349-1360.

laboratory in real-time. The interaction is supported by using sensors and cameras so that the students can monitor the laboratory equipment and actuators.

The immediate consequence of this concept enables cooperation of different teaching institutions all over the world using internet to enable the communication of the single student with the laboratory unit and groups of students in performing more sophisticated laboratory tasks.

The lab may be located within a teaching laboratories or it may be embedded *in situ* within industrial plants (e.g. CNC manufacturing units) in accordance with their interest[46].

The experiment may be interactive, where the user directly interacts with the equipment whilst the experiment is being carried out, or it may be a batch experiment where the user sets up the experimental parameters and submits these to the lab system to be carried out when the equipment is available.

The overall conclusion is that remote laboratories can provide significant benefits:

- Relax time constraints, adapting to pace of each student, if there is insufficient time in laboratory.
- Relax geographical constraints, disregarding the physical locality of the student.
- Economies of scale, improved quality of experiment, as it can be repeated to clarify doubtful measurements in lab.
- Improve effectiveness of student's time spent at a laboratory by rehearsal.
- Improved safety and security especially for the experiments in dangerous environments (e.g. radioactivity).
- Great increase in student accessibility to laboratories, especially laboratories with very expensive or rare facilities.
- Decrease of fixed and variable expenditures as sharing labs allows sharing of large fixed costs of traditional buildings.
- Improve learning objectives and outcomes to support better learning.
- Enhance sharing of knowledge, expertise and experience.

As an example of a remote laboratory several European universities built a remote laboratory for the curriculum in laser processing in the frame of Leonardo da Vinci Program. Each of ten participating universities provided at least one laboratory exercise and offered it via developed internet portals to the students of all other universities. Taking into account that laser laboratories usually require quite expensive equipment each of the participating students got the access to complete curriculum with minimal additional expenses.

Integrated work experience: In addition, the possibilities of incorporating work experience into an engineering degree program are widely accepted as a worthy direction. It gives the students an opportunity to get an insight into the engineer's work and improves their motivation. There are several versions of such practices. In order to attract students into engineering the employers offer them a one-year orientation work experience before entering their educational program guaranteeing them a challenging experience. Work

46 Lowe, D., (2013) Remote Laboratories: Enriched Experimentation and Shared Facilities, in Beanland, D. and Hadgraft, R.: Engineering education: Transformation and innovation, UNESCO Monograph, RMIT University Press, Melbourne (116-119).

experience can also be alternated with study periods. In such cases the employers can acquire new graduates dealing with their industrial problems in the form of possible diplomas, master theses and PhD theses. Vacation employment provides an attractive option for students seeking to gain experience with potential employers and providing earnings to support their studies. Visits to engineering companies and contacts with the practitioners about the joint projects might also be useful.

3.d New business thinking and soft skills (entrepreneurial skills)

Over the past few decades soft skills or personal skills have become essential tools for engineers in modern society. Industry, universities, as well as accreditation bodies now agree that technical competence is not enough for the work of an engineer which has become more team-based and interdisciplinary than in earlier times. Table 3.03 illustrates some of these changes, as became evident some 20 years ago[47].

	Old	New
The work	Done by individuals within a department	Done by teams across departments and functions
Education	Finite	Continuous learning
Job skills	Mostly static	Always changing
Career advancement	Career ladder	Multiple strategies
Worker expectation	Security	Personal growth
Career management	Company directed	Individually owned and shared

Table 3.03 Workplace Change.

Nowadays engineering must go beyond pure technology based on a solid scientific and technological knowledge. Society expects graduates from engineering schools to be highly competent in their analytical and scientific skills and in their capabilities to design and implement new solutions. As engineers progress on the career ladder they too need to employ a wider range of so-called soft skills such as communication, teamwork, leadership, presentation. Most job descriptions for open positions in industry will therefore require specific soft skills, directly or indirectly.

Hissey[48] explored two questions:

- What separates high-level engineers who rise rapidly within their organizations to positions of great prominence and leadership?

  And

- Why are some engineers capable of transforming their technical knowledge and experience into successful entrepreneurial ventures?

In conclusion the result shows that engineers and scientists should understand the career enhancing requirement for soft skills in order to progress into the global open market economy.

47 Wick, C., Perspectives, 1-98 Skills for Today's Engineer A customer focus Teaming skills A process orientation Technical skills Professional skills Competency in key technologies

48 Hissey, T. W. (2000) Education and careers 2000. Enhanced skills for engineers, in Proceedings of the IEEE, vol. 88, no. 8, pp. 1367-1370, Aug. 2000, doi: 10.1109/5.880089.

However, for many institutions the integration of soft skill courses into engineering programmes remains challenging.

There are several approaches to addressing this challenge, ranging between the extremes of setting up a new and restructured curriculum, and, as is still practiced at some engineering schools, offering a set of soft skill modules from which students may arbitrarily select some in order to achieve the requested number of ECTS points. Whichever way it is done, it is crucial that the soft skills are seen by all stakeholders – the students, academics, employers, engineering professional bodies – as vitally important in the curriculum, and not just some sort of nice-to-have add-on.

Furthermore, many engineering programmes still implement courses on non-technical or soft skills which are non-compulsory.

In the first case attention has to be paid to the ratio between technical courses and those containing soft skills. This has to be balanced according to which type of engineers is expected to graduate from the respective curriculum.

In the second case the student is more or less left alone unless given appropriate advice. Without this, many students may be inclined to opt for a path of least resistance, which may not serve them best in the longer term. Such modules should, ideally, be mandatory. The importance of soft skills has been emphasised throughout this report, so simply adding more mandatory courses, although it has the benefit of clarity, is likely to prove difficult to implement in practice.

There is of course a third way. And like many such alternatives, it is perhaps the most challenging to achieve, but could be the most effective in the long term. This is the incorporation of soft skills within the technical components of a degree programme. This requires thought in terms of looking within the curriculum for potential points of inflection where they can be incorporated. Where this is done, the soft skills become quite simply the way of expressing and performing the technical components of engineering. This approach means that the soft skills are embedded in the engineer – it becomes a central part of how an engineer works.

In general, however, it is often felt that many first year students are not interested in any soft skills because they are eager to study what they perceive to be the only important element of engineering, namely technical skills. For the reasons set out throughout this document, these students are incorrect, and it is essential that they learn the importance of the whole set of habits of mind that define engineering in all its ingenuity and responsibility to society. Therefore, it is recommended to start the degree programme with a course in which the students learn and embrace the core fact that the professionalism of an engineer is more than just to master a particular set of technical skills[49]. It is also observed that many students entering university are very sensitive to the wider skills and contextual aspects of engineering because of their experiences at high school, so this problem may be one of establishing for sure what the views of the incoming students on this topic actually are.

In any case whenever an engineering programme is established or changed in which soft skills are integrated it is quite appropriate to have engineers from industry, successful entrepreneurs and others from the worlds of policy making and implementation participating in the advisory team.

Even when students are not interested in soft skill courses they become much engaged as soon as they are working in groups on projects together with other colleagues. They mostly change their approach and become

[49] A. Berglund, F Heinz, Integrating Soft Skills into Engineering Education for Increased Student Throughput and more Professional Engineers, Pedagogiska Inspirationskonferenz, Dec 2014

enthusiastic to help solving the problem. This is, of course, an example of incorporating soft skills within the technical programme, although obviously it does not provide the complete set.

For example, as suggested by Berglund and Heinz[50], an introductory lecture could be delivered early in the programme, in which the students learn what professionalism for an engineer means, followed by soft skill courses in a block seminar structure. In these seminars the students get enough time to work in teams on small projects, learning a large part of the skills by doing under the guidance of an instructor or in cooperation students of a higher semester.

An important soft skill is the need for an evolutionary mindset - in which progression and change is central to progress – rather than a fixed mindset for engineering education and the professional career afterwards. With a fixed mindset the students are less creative and open to new ideas and even good students are limited in their mind by being fearful of making mistakes. In fact, the evolutionary mindset is needed over the entire education trajectory from kindergarten to master program. Jo Boaler[51] advocates with ample pedagogical research evidence the advantages of a teaching approach that stimulates such a mindset for mathematics[52]. Also, for engineering education there are clear advantages of an evolutionary mindset with more room for cooperation and the beneficial effects of learning from mistakes.

As engineers proceed on the career ladder, their need for more and more soft skills such as communication, teamwork, leadership etc. often becomes greater.[53] Therefore, all engineering schools and graduate employers, should strive to encourage and support engineers to continuously develop and improve their technical as well as their soft skills, by providing postgraduate courses, open for engineers working in industry or in enterprises.

In fact, soft skills should be so embedded in an engineer's toolkit that they are simply part of being a professional engineer without a further thought.

Human Literacy: Whilst engineers may be clear in their own minds that they are offering constructive solutions to the problems of mankind (e.g. by devising renewable power generation systems or major infrastructure projects), public debate is often dominated by articulate objectors who see every reason to 'do nothing' or 'move the problem to someone else'. Engineers currently seem to struggle in such public discussion fora. Whilst the 'Soft Skills' of Presentation and Communication (in person, in writing or through visual means) skills developed in existing engineering curricula appear to have improved substantially over recent decades, the broader challenge of effective communication with and convincing the wider, often very emotional, public leaves scope for further development.

The necessary 'Human Literacy' is about understanding people, empathy, communication and the ability to connect with people. It is also about being professionally competent in seeing what the negatives of an engineering project might be and being ethical and honest about these in considering the engineering solutions they intend to propose. Engineers should not be proposing schemes that cause harm. Often the determination of "harm" is not binary, and it requires sensitivity and intelligence to understand the issue as well as the good application of engineering ingenuity to resolve the matter satisfactorily. These skills may also help underpin an entrepreneurial mind-set.

50 ibid.
51 Jo Boaler, "Mathematical Mindsets : Unleashing Students' Potential through Creative Math, Inspiring Messages and Innovative Teaching", 2015 John Wiley & Sons Inc
52 https://www.youcubed.org
53 Martins, J., and Frias R. (2007) The Role of Hard and Soft Skills on Engineering Education, Int. Conf. on Engineering Education –ICEE 2007.

Dedicated 'Technical Communication' modules should help students to develop the capacities to:

- Understand the roots of the problem, including negatives as well as positives, as considered by people from different, especially non-engineering, perspectives.
- Perform an audience analysis to formulate useful and realistic aims for a communication, and structure a communication accordingly.
- Identify the relative benefits of written and oral communications and use this to decide what that communication usefully can and cannot do.
- Draft a practical presentation script (presentation only) separate to the set of visual aids.
- Understand the principles of cognitive psychology that relate to visual aids, such as visual perception, Gestalt grouping (to help understand how humans typically gain meaningful perceptions from chaotic stimuli around them), matching of intellectual and visual inferences.
- Appreciate the power of communication tools such as stories, analogies, examples, demonstrations, infographics, videos and audience interaction.
- Appreciate the benefits of creativity in generating multiple approaches before selecting the final communication plan.

Students should be given opportunities to practice their communication skills throughout their studies, particularly when inter-disciplinary topics are being addressed. Peer-review and discussion are important here.

This is an area where learning the skills inherent in the arts are important: contemplation of meaning (of texts, situations, appearances, thought), creation of understandable presentation of truth, consideration of the dissonances that both drive discomfort but also the search for solutions that create a more consonant accord, the ability to adopt an allocentric thinking approach, and the sense, creation and responsibility in performance.

3.e Digitalization, big data, AI and learning analytics

The enormous impact of digitalization in society, poses many challenges for the entire engineering education. The tremendous increase and spread of digital data, and of computing power is a transformation that is historically at least as disruptive as three previous inventions: replacing the spoken word by writing, the hand printing in the 15th century and the printing on an industrial scale using steam powered rotary presses in the 19th century.

This societal phenomenon is often called ‘big data’ because of the enormous increase in three aspects of data: the volume, variety, and velocity. The processes involve sensing and capturing of data, data storage, data analysis, search, transmission, sharing, visualization, querying, and updating. Many of these tasks have been designed at a much smaller scale by engineers over the past 50 years. Now the massive deployment in society is underway and creates enormous opportunities for many more services and products satisfying societal needs. It also, as has been seen around the world in recent years, places an enormous moral responsibility on the engineers who develop such systems, so that they do not infringe basic human rights, or abuse the processes involved in the democratic government of society. Engineering is crucial in each of these with new efficient and optimized algorithms and devices, but it is only appropriate if these are based on the application of morally responsible engineering. Professional engineers must not absolve their responsibilities in this area: Simply because 'it is possible' does not mean that 'it is right', and engineers are the gatekeepers of the application of engineering to such processes on behalf of society.

It is fair to say that the present transformation is challenging the current role, content, and methods of engineering education. So, an important role for many engineers should be the 'architect of the digitalization'. Also, the content of the engineering education should be focused on these designs, of course integrated in the various programs of specializations in engineering: computer science, electrical engineering, mechanical and production engineering, chemical engineering, civil engineering, and bioengineering. Because of their enormous impact on society, it is essential that engineering skills are built upon the human and ethical aspects of designs from the start. This requires the integration of human and ethical elements in the engineering education throughout the whole programme.

On a more general scale this digitalization brings about an important shift in the entire educational system with the introduction of digital literacy in primary and secondary education and digital humanities in the universities. This process of on-line teaching and learning has been implemented worldwide in the entire educational system due to the Covid-19 pandemic. The first-hand experience is now being evaluated (see experiences at IPEK). On top of that, several new methods of education are designed or in the process of being deployed. Massive Open Online Courses (MOOCs), blended learning, flipped classrooms and learning analytics are just a few examples and many more are expected to come. Learning Analytics (LA) aims for the collection and analysis of data from students and their contexts and for using these data to improve the learning processes. Many aspects of LA are affected by the local context, such as the available data (e.g. swipe cards and measurement of attendance), the educational context (e.g. free access to higher education or selection), the goals of LA (e.g. retention or rapid reorientation), national and institution-specific regulations and teaching and advising practices (e.g. whether or not each student has a personal and professional student advisor). The introduction of LA methods needs to balance the privacy of the students with the benefits of a better efficiency in the learning process[54].

The reader might be surprised why artificial intelligence (AI) has not yet been mentioned. AI builds methods and techniques for systems that are able to emulate functions normally performed by the human brain, such as sensory perception and pattern recognition, planning and control of complex systems, production and understanding of language, learning of regularities in order to make predictions, organization of knowledge, etc. However, AI does not try to literally simulate human intelligence, but to build systems that are capable of solving problems that require intelligence. There is already an impressive collection of methods in AI, that can be partitioned in two categories: knowledge-based methods and data driven methods[55]. The latter methods are covered by the learning algorithms and systems described in the previous paragraph, and encapsulated in the generic term 'Machine Learning'.

There is a lot of excitement that several recent designs have surpassed the human brain for specific tasks. From an engineering point of view, this is in line with the historical evolution, where computers have been taking over from humans for calculations, data access, and several other limited specific tasks. Science fiction makes then a big leap forward with futuristic

[54] De Laet, T., e.a. (2018) 'Learning Analytics in the Flemish higher education system', KVAB position paper. https://www.kvab.be/en/standpunten/"learning-analytics"-flemish-higher-education-system

[55] Steels, L., e.a., (2017) 'Artificial intelligence', KVAB Position Paper. https://www.kvab.be/en/standpunten/artificial-intelligence

phenomena such as superintelligence, singularity, and universal artificial brains surpassing human brains. These are however not considered realistic within the next 30 years, and hence are left out here. On the other hand, the combination of the human brain and human body enhanced with artificial brain and robot or body interfaces, can outperform the artificial alone or the natural alone. Here again there is a challenge for engineering education to incorporate systems where the natural and the artificial work together symbiotically, for example, like exoskeletons, teleoperated robots, human-machine interfaces, computer assisted surgery, assistance for disabled people and brain computer interfaces.

The change to digital teaching - Experiences at IPEK: Rapidly changing conditions, such as those we are all experiencing as a result of the Corona pandemic, require the ability to ask the right questions in order to solve unknown problems. After public institutions in Germany were closed down in mid-March, teaching without the physical presence of students faced previously unknown challenges. The organization of lectures, workshops or project work was no longer as convenient. A decisive factor in teaching was the changeover from classroom teaching to online lectures, workshops and project work.

'Education thrives on interaction'. This is especially important in face-to-face teaching at universities so that students can intensively deal with the subject matter. This is especially true in engineering education, for the reasons discussed throughout this report. The attention span of students from the Y and Z generation is reduced by the fact that they constantly use different information channels. In order to transfer digitization into teaching, the IPEK – Institute for Product Engineering established a course especially designed for collaboration in virtual space in 2016. This course focuses on distributed product development to be able to investigate methods and processes in this field.

In ProVIL – Product Development in a Virtual Idea Laboratory, 42 KIT master students work together in seven teams to develop products for a given problem. This year's task was to enable new digital concepts for the education and training of product developers. To master this problem, students go through all phases of the development process from market analysis to the development of first prototypes and present their results at four milestones. While kick-offs, milestones and workshops were held on site over the past four years, these also had to be adapted for distributed collaboration in addition to the virtual project work. This change was facilitated by the use of digital tools such as Zoom, Microsoft Teams and NextCloud, but required careful planning and development of the teaching formats. As, for example, students cannot raise their hands anymore to ask a question, it can be seen that teaching formats based on face-to-face meetings could not easily be applied to online teaching after the boundary conditions became totally different.

The distance between students and teachers, and between students and students, makes teaching and learning difficult. However, with the support of digital tools, interaction can be achieved through audio commentary, surveys and virtual hand signals. The ProVIL students gained knowledge during online workshops via Zoom and learned to apply methods and processes of distributed product development in their individual development project directly using NextCloud as a working environment. They were supported by innovation coaches from Karlsruhe University of Applied Sciences, which helped them to tackle their tasks.

Even though it was not possible for the students to meet each other face-to-face, they still learned how to communicate and work together in a virtual environment. They quickly recognized the advantages of working from home. The students mentioned that it is very comfortable to arrange appointments via Zoom since they do not have to meet in one place and are saving time by attending an online-meeting. Moreover, they underline, that working in a virtual environment makes it easier to quickly document and share information. The students have learned to overcome their inhibitions about digital collaboration and presented their results to 150 interested viewers via Zoom.

ProVIL is just one of the examples of how classic face-to-face courses can be carried out remotely using digital tools. The solutions and support services developed during the corona pandemic will be used in the long-term in the study practice. The aim is to combine the strengths of digital and analog content, so that education will add long-term value for students.

Part IV

Transformation pathways

Key observations

- Persuading more young people to consider engineering as an attractive career for them requires parents', teachers', engineering professionals' and policymakers' joint efforts throughout the whole education process.
- Increasing female representation in engineering studies is one of the most potent ways of responding to the shortage of engineering workforce in Europe.
- The university engineering curriculum does not exist in a vacuum: it lies in a multidimensional context based not only on the subject matter – what needs to be learnt – but also on when it is learnt – and how it fits into a programme of learning across the life span.
- The essence of a 'pathway' is that it leads from somewhere and enables movement to somewhere else. In the case of Engineering Education, it is essential to frame the discussion in the context of the whole pathway, not just the part that is specifically assigned to 'Engineering' – or even 'Education'.

'It is change, continuing change, inevitable change, that is the dominant factor in society today. No sensible decision can be made any longer without taking into account not only the world as it is, but the world as it will be ...'

Isaac Asimov

American writer and professor of biochemistry at Boston University

4.a Changing perception

It has been observed by educators that today's generation students at all levels of higher education lack some key skills and attitudes in relation to the information to which they have access. The questions are posed: whether inquisitiveness, perception, critical analysis and synthesis of information are forgotten skills for today's students? This becomes a particularly critical issue for future engineers.

According to Gene Bellinger[1], developing the context and understanding is the pathway to acquiring first the knowledge, and, afterwards, the wisdom. The author explains the basics of knowledge management, where data, information, knowledge and wisdom are subsequently following understanding and context independence on this pathway. It means that a collection of data is not information, a collection of information is not

[1] Bellinger, G., (2004) Knowledge Management - Emerging Perspectives; on-line: http://www.systems-thinking.org/kmgmt/kmgmt.htm

knowledge, and a collection of knowledge is not yet wisdom. There, the following associations are being made: Information relates to description, definition, or perspective (an answer to: what, who, when, where); Knowledge comprises strategy, practice, method, or approach (how); whereas Wisdom embodies principle, insight, moral, or archetype (why). Thus, developing the context and understanding of data, information, etc., within their context, paves the way to wisdom and possibly to its practical use to solve problems.

However, understanding requires proper prior selection of information, perception, analysis and synthesis of information. Here, some challenges arise in the modern, information-based society. First of all, the volume of information available (ubiquitously online from nearly every place on Earth) is enormous, impossible to perceive. We observe that schoolchildren and students are not able to select information *and* analyse it critically to produce useful knowledge. Therefore, necessary information processing is often narrowed to 'copy-and-paste' without understanding and without providing the used source of information, and this is often allowed by teachers. Engineering students undergo the same process before they face technical challenges in the laboratory or during on-site practical experience, e.g., when it comes to design, to prove, to measure something that requires context and understanding. The question then arises: What can we do in the (pre-)engineering education system?

Education in general, and engineering education in particular, starts long before university studies, even before secondary or primary school. Therefore measures have to be undertaken, special programmes developed already in early education for the school children to:

a. Properly search information using modern tools for data mining,

b. Learn to be selective and critical in information collection,

c. Understand the context,

d. Analyse and synthesize information properly,

e. Be aware of intellectual property, copyrights, plagiarism, etc.

Modern technologies can assist (pre-)engineering students in the information perception in a number of ways. For information search and selection, modern data mining engines should be used that consist of tools and software employed to gain insights and knowledge from data acquired from data sources. For information perception, user-friendly interfaces can be in use, e.g., augmented reality, intelligence augmentation tools. Finally, for understanding the information and developing the context, to get the knowledge (also practical knowledge) and acquire wisdom, practical training and hands-on courses should be in place from early-on education, e.g., interactive labs, remote access to labs, practical training programs, project-based learning.

Of similar importance, and a necessary addition, to the collection of information is the ability to judge what is 'good' and what is 'poor' information. The skills needed to make such judgements is crucial for the subsequent honest and appropriate use of information, including, but only, in the sphere of engineering. This can be learnt throughout schooling, with an increasing range of complexities incorporated as the students mature, and complements the parental and educational responsibilities of enabling children to learn about honesty, good, evil, safety and other basic tenets of societal living that are so essential for the progress of a thriving society.

4.b Attraction of young generations

Along with commonly encountered difficulties in information perception, due to its enormous quantity and ubiquitous availability, young generations, especially so called 'Generation Z', are also privileged in the modern technology-based environment. Generation Z is the demographic cohort after the Millennials, born between mid-1990s to the mid-2000s (and, importantly, includes the students now arriving at university from high school). This generation has been accustomed to the Internet, computers, mobile systems and software tools from a young age, and is comfortable with using technology. It is sometimes referred to as 'the first generation of true digital natives'. According to Tracy Francis[2] this generation searches for truth, values individual expression and avoids labels. They believe profoundly in the efficacy of dialogue to solve conflicts and improve the world. Finally, they make decisions and relate to institutions in a highly analytical and pragmatic way. Moreover, Generation Z college students like their learning to be practical and hands-on and want their professors to help them apply the content rather than share what they could otherwise find online. Entrepreneurship is also in their schools curriculums. This means that they might have particularly advantageous skills and attitude to study problems and engineer solutions using new, even constantly changing technologies.

Modern engineering education should be tailored to these challenges and opportunities of the young generations. On the other hand, no matter how higher education is being transformed, engineering is commonly regarded as difficult and demanding to study. It is also not commonly taught as a subject in schools. The combination of these two factors influence the reasons why it is not the most popular choice for young people, who have not yet established their priorities for their professional career. Contrast this with Medicine, which is also not taught as a subject in schools and is perceived to be difficult, yet is a very popular choice for higher education programmes. Why this difference? Basically, the difference is that many young people have experienced Medicine in some form or other, either personally (they were ill at some point in their life), or vicariously through knowledge of a relative or friend having been ill, and for many this gives them a personal insight into 'wanting to make people better' and thus choose Medicine as a subject to study at university. The irony is that most of these people will have experienced, either personally or vicariously, many engineering challenges – something not working, and something being made to work to help them do something – but they do not pick this up and carry it forward into a desire to study engineering. Even if their experience of medicine has involved massive engineering technology, many will still perceive this as Medicine rather than Engineering. This is something the engineering profession could and should address. The main reason for this difference is that the child will have encountered members of the medical profession in those incidents, but almost certainly will never have encountered the engineers who utilised their ingenuity to make it (or anything else) happen. The entire engineering profession can and should take this on board as an urgent priority.

Even if they do not realise it at a basic level, contemporary societies need engineers for their further growth and prosperity, and they need to make efforts to attract young generations to study engineering. An important obstacle to choosing engineering studies and an important reason for stopping engineering studies prematurely is the way in which mathematics is taught – especially in high school and first year of engineering. If it is taught

[2] Francis, T., Hoefel, F., (2018) True Gen: Generation Z and its implications for companies, McKinsey https://www.mckinsey.com/industries/consumer-packaged-goods/our-insights/true-gen-generation-z-and-its-implications-for-companies

in an unattractive way, and without reference to engineering problems sometimes good starting students lose interest and motivation in engineering studies. Yet many topics in engineering depend crucially on mathematical or science insights. Mahajan[3] gives good practical clues how to bring insight in science and engineering and thereby enthuse young people in the topics.

As mentioned, engineering education should start even before school, in pre-school, at home. As soon and a child can play, the parents and educators should make sure that it has no barriers to build interest in technics. It is our responsibility to present options for future interests and profession selection for both boys and girls. Children should be encouraged to play with technical toys, should get the attitude that technology is exciting and not too hard to figure out when one gets truly interested in it. However, this requires parents to be aware of this as a priority need, and this depends on how these parents were educated.

There are lots of stereotypes about engineers and their professional career path, such as difficult, time-engaging education, not spectacular career opportunities, not an interesting or creative job. These can and should all be disproved. The best way to do this is to engage engineers and practitioners in the education process, again from early on. As mentioned above, engineers should step out of the shadows and reveal what they have done, and the profession should step up to this challenge. It is also a reason for the incorporation of soft skills directly in the engineering learning process, as described in Part III of this report. Encounters and meetings with successful inventors and designers, workshops in engineering-oriented companies, manufacturers, industry should be as important for the children at all stages of education, in the same way as visits in museums, art galleries, etc. Even enabling a child to understand how their home is designed, constructed, energised, operated, would be a good start.

In many countries there are technology/technics courses in schools. There are some very good examples of how to build such programs, that involve pupils in 'Learning to be an Engineer' and teach 'Thinking like an Engineer', including Engineering habits of mind[4, 5]. Well-qualified educators for these kind of classes cannot be overestimated. There are reports on how to educate engineering educators in primary schools[6], which defines seven principles of primary engineering education:

a. Pupils are engaged in purposeful practical problem solving

b. Pupils take ownership of the design-and-make process

c. Pupils embrace and learn from failure

d. Pupils' curiosity and creativity is responded to

e. Pupils demonstrate mastery from other curriculum areas

f. Pupils draw on a range of thinking skills and personal capabilities

g. Pupils' learning experiences are guided by a whole-school approach

Summarizing the above thoughts, persuading more young people to consider engineering as an attractive career for them requires parents', teachers' and professionals' joint efforts throughout the whole education process starting

[3] Mahajan, S., (2014) The Art of Insight in Science and Engineering: Mastering Complexity, MIT Press. https://ocw.mit.edu/resources/res-6-011-the-art-of-insight-in-science-and-engineering-mastering-complexity-fall-2014/online-textbook/MITRES_6-011F14_art_insfin.pdf

[4] Thinking like and engineer, Royal Academy of Engineering and Centre for Real World Learning, 2014, www.raeng.org.uk/publications/reports/thinking-like-en-engineer-implications-full-report

[5] Learning to be an engineer, Royal Academy of Engineering, Centre for Real World Learning and the University of Manchester, 2017

[6] Learning to teach engineering in the primary and KS3 classroom, Royal Academy of Engineering and the University of Manchester, 2018

from a very young age. Some methods useful in these efforts are summarized in the literature below.

4.c Improving inclusion

Women have been and are still very much underrepresented in engineering and related applied sciences. Several types of actions have been launched by individual schools and countries to try to alter this gender imbalance but, so far, although there are often great improvements in female participation in engineering programmes that have resulted from particular initiatives, these improvements seem resistant to wider take-up and overall, the imbalance seems to be difficult to change.

Figure 4.01 First results of an image search with the Bing engine using the keywords 'Engineer Women'. This set of pictures is highly representative of the inaccurate image most people form of what engineering is today and how women fit in the engineering landscape.

How serious is the imbalance: The situation varies very much from country to country; most higher education establishments would nevertheless recognize their own situation in the description given in Engineering UK's 2018 State of Engineering Report[7]: In 2018 to 2019, women comprised just 21.0% of first degree entrants in engineering and technology (although this varied from 11%-29% between different engineering disciplines (ibid), whereas in 2018] only 12% of those working in engineering in the UK are women and only 5% of chartered engineers were women[8,9].

Why should this imbalance be corrected: This imbalance is not the result of a maladjustment of young women's skills with engineering curricula requirements. We believe that it is caused by a set of misrepresentations about engineering studies and employment opportunities that can be corrected. We also believe that increasing female representation in engineering studies is one of the most potent ways of responding to the shortage of engineering workforce in many countries and industrial fields. Finally, a better gender balance in engineering schools would be beneficial

7 Stephanie Neave et al., (2020) The state of engineering, Engineering UK
8 Women's Engineering Society 2018 https://www.wes.org.uk/content/wesstatistics
9 Engineering UK (2019) Gender disparity in Engineering https://www.engineeringuk.com/research/briefings/gender-disparity-in-engineering/

for all engineering students as it would lead to a more diverse approach to problem solving and collaboration strategies in project work.

What are the root causes of this imbalance and what actions can be taken:

a. **Insufficient skills:** There are no significant differences in the mathematical ability of young men and women at the end of high school but, paradoxically, the fact that young female students are, on average, better than their male counterparts in *literary* disciplines seems to be driving them away from science and technology curricula in higher education[10]. It is therefore not at all an often-cited hypothetical lack of mathematical skills that leads young women to preferentially choose non-scientific curricula but it is rather their broader skill set which gives them the opportunity to choose from a wider set of options.

   Actions: Guidance counsellors have a major responsibility in this respect and need to present all open options to the young students they advise, without any kind of prejudice. They need to be trained about engineering opportunities and they have to be given supporting tools to actively promote engineering studies to young women.

b. **An incorrect picture of engineering schools:** Engineering schools are no longer what they were some decades ago. Yet, the image of engineering studies in the general, and specifically the younger, public, remains that of grey-walled schools where classes of male-only students work in smoke-filled laboratories on noisy machines!

   Actions: The rather sombre image of some schools is not totally undeserved and those schools should reflect and act on their lack of attractiveness … but, overall, schools have changed and they should communicate, for instance by organizing open door days, on how they really are: open, creative, solution-oriented, environmentally-minded, socially aware.

c. **Gender imbalance causes … gender imbalance:** Young women do not embrace engineering because … there are too few women in engineering schools: the snake bites its own tail.

   Actions: Engineering schools are all too often a territory to be conquered, as the last frontier of gender equality and they must change to become one presented as being as up-to-date in terms of embracing gender equality as they would like to be in technological advances. Encouraging engineering schools to engage fully with other science and technology schools with a lower gender gap (agronomy, biomedical engineering, pure sciences –mathematics, physics, chemistry, psychology, architecture) might also counter this argument. Giving tenure to more female teachers and ensuring that promotion criteria do not discriminate against women would certainly help change the image of a male-only environment.

d. **A dated picture of engineering:** Engineering is no longer what it was a century or fifty years ago – or even 20 years ago. If there were perhaps then some valid reasons for the gender gap, these reasons have altogether vanished today. Engineering is no longer only about optimizing production and taming the workforce! Engineers are creative, work in environments that have improved a lot over the years and the old image of an engineer's unpleasant working condition is no longer true, collaborate within integrated teams, communicate with all other key corporate functions, need to harness soft as well as hard skills and face a

[10] Breda, T., and Napp, N., (2019) Girls' comparative advantage in reading can largely explain the gender gap in math-related fields, Proceedings of the National Academy of Sciences 116 (31) 15435-15440, doi: 10.1073/pnas.1905779116.

wide set of non-technical constraints (financial, social, commercial, environmental). Engineering work is diverse, constantly evolving, critical to the company's success. Engineering careers are multiple, varied, dynamic, rewarding.

Actions: Most people don't know what engineering is and what engineers do. Engineers and their representative bodies should work at conveying a more accurate, modern and positive image of engineering. It is very unfortunate that engineers are so badly pictured in movies and TV series as narrow, self-centred, unglamorous brats!

e. **Perception of Engineering as a 'closed' degree:** For some students, their perception of an engineering degree is that it is a subject that only relates directly to an engineering career ('you do a degree in engineering to become an engineer'), but at the relevant decision points during their high school education, they have not yet made up their minds about what career they might wish to follow. This seems to be more of an issue for women students than it is for men. The result is that their choices are driven more by what interests them, the quality and inspirational quality of teachers and mentors. In some cases, particularly where the school education system forces these decisions to be made early and irretrievably (e.g. in the UK) the university entry requirements specifically exclude women because they have made choices about their preferred study areas which turn out to render them ineligible for entry.

Actions: Universities can act to change this problem through better engagement with school students (and not just 'schools'), teachers, and parents[11] and in altering their entry requirements to address this (and then taking in-house the necessary mathematics and physics curricula for their courses[12].

Key conclusions:

a. There is a very common misrepresentation of engineering in society. Young men and women, their parents, their teachers, their guidance counsellors, all have an inaccurate picture of what engineering is today and how both women and men can pursue a happy, fruitful, successful career in engineering.

b. The Euro-CASE Committee on Engineering Education supports all actions taken in the various countries by higher education institutions, by professional institutions and by ad hoc associations to promote science and engineering careers to young women and change the currently prevailing inaccurate image of engineers and engineering.

4.d Curricula transformation

When rethinking the university curriculum for engineering in order to make it fit for purpose in the 21st century, it is necessary to think about the process that is required in order to make it happen. The process is important, not only because it is the means of putting into effect the thinking about engineering, but also because the thinking about 'how to do it' helps to refine what can be done. The recommendation is to consider curriculum development in four Steps.

Step 1: Understand the context

[11] Engineering UK (2019) Gender disparity in Engineering https://www.engineeringuk.com/research/briefings/gender-disparity-in-engineering/
[12] Stephanie Neave et al., (2020) The state of engineering, Engineering UK

The first point is to recognise that the university engineering curriculum does not exist in a vacuum: it lies in a multidimensional context based not only on the subject matter – what needs to be learnt – but also on when it is learnt – how it fits into a programme of learning across the life span. It is a good idea to consider this as a design process – how to design a curriculum first needs a comprehensive understanding of the contexts that pertain to its relationships – to society, industry, students, teaching staff, the university, professional institutions etc. – so that the curriculum can be centred appropriately for the future.

So a first consideration is to consider the demand from society for engineers: what needs to be learnt in order to become an engineer fit for society. This is, in the main, determined traditionally by industry – what skills ate needed by the engineering industry in order for them to function. However, the engineering industry is based in the past and, although as an industry it looks to the future, it can sometimes be very conservative in terms of who and what it wants to employ in order to reach that future. However, it is essential ,at a very early stage in the process, to engage with industry, the professional institutions and any relevant regulators in order to include their views about what changes might be made. This does not mean that changes that do not immediately meet with their approval should be abandoned, rather it suggests that the discussions about such issues needs to take place early enough that a sensible pathway to gaining agreement can be created in good time so that the process is not delayed.

Engineering, like any discipline, is a servant of society. Society needs engineering in order to progress, but responsible engineering needs to be seen in the context of society. As a result, engineers need to understand society and how it functions.

Therefore an important first stage is to discuss with society – the politicians, the officials who oversee standards, regulations and the law, the general population who will benefit from, but who will also suffer from, the engineering as it is applied to them as well as the current industrial practitioners – what the expectations and requirements are of future engineers. Today's students will be tomorrow's engineers and the future of human survival as a species is in their hands, not in the domain of the current engineering profession.

Just looking at 'what industry wants' is therefore insufficient. The curriculum to deliver this through university education is only a small fraction of the process – taking just a few years out of decades of life in and out of the profession. So the curriculum must pay attention to the inputs as well as the outputs. What is being delivered by the education curriculum before a student enters university, and how school students 'see' engineering as a societal purpose, as a career, and as a way to spend a future life.

The perspective of young people about the future of their – and the planet's – life is crucial. This is what will make them choose to do engineering and what will bring their vision and perspectives to the profession. This is how engineering will thrive. A student who wants to make the world a better place will come to the profession in a very different state than one who simply wants to apply mathematics and physics. Society – and the engineering profession – needs this far-sighted vision in order to survive. Therefore it is an important part of the process to enter into conversation with schools about what they deliver – and what they could deliver in the future – in terms of future professional members of society as well as the initiating skills for entering the engineering profession.

It is essential to enter into direct and meaningful conversation with school students, not just those about to enter university, but those much earlier in their school career. Students who have yet to be affected by the school curriculum have important perspectives about how the world should be and understanding that vision is a fundamental element of designing what the future engineering profession will be like. Starting these conversations with students of 11 or 12 years of age is eye-opening and revealing, and can be challenging. However, having conversations with school students who are even younger is also helpful. These conversations should not be about maths and physics, but about the future world. If engineers do not see how the future generations see their future world, they can hardly aim to make it a place for those generations to thrive. Of course this is not to say that the views of a 10-year old are the determinant of what an engineer needs to know! But knowing and understanding how to relate engineering to their perspectives is an essential ingredient of attracting the best people into the career.

This requires setting out a philosophy to underpin the engineer's education – What should be learnt and why – and this drives the formation of the curriculum. The learning starts by Realising the world as it is and extracting from that a comprehensive definition of the problem to be tackled. Too many design and engineering programmes fail to include this – often handing the students problems to tackle, rather than presenting them with a context and enabling them to develop the skills to find out what the problem actually is. In the context of accessible design, this is a crucial component of the learning process, because nobody will come to a problem with a complete and comprehensive a priori knowledge of its extent for all people's needs – so everyone will need to develop this from first principles for every problem they face.

The second stage is to Envision this realisation of the problem, so that it can then be tackled. A key component in this process is the study of Capabilities. When we talk about Capabilities – what you can do rather than what you cannot, we do so because it is important to support both how students and teaching staff tackle problems in the learning environment, and the requirements made of both groups by the learning environment in order to cope with it. This means that in creating the curriculum, we need to consider both students and staff and the learning environment in which they will learn. The outcome of this stage is a picture of what the curriculum will need to do.

Then, in stage three, the learning turns to Composition. We talk about composing rather than design, because this is about creating a new curriculum, rather like a work of art, such as a piece of music, where the need is to fuse art and science to engineer a feasible solution that responds to the differences between those required and provided capabilities. This is when it will become apparent if the proposed curriculum might or might not be achievable given the various resources available – financial, time, space, equipment etc. – and if it might be necessary to review Stages 1 and 2 in order to arrive at a potential curriculum that could work.

Next, in stage four, we have to learn how to Evaluate the composition. This means evaluating performance, not just benefits and costs, but the extent to which the curriculum will enable the students to be able to contribute to the societal good, through the full panoply of what they have learnt in their engineering programme, and what more needs to be done. It is often the case that in enhancing one element of knowledge another need is revealed, so it is important that the evaluation considers not only the curriculum itself but also its effects on the rest of the system.

Then, having adjusted the Composition, maybe also the Envisioned version of the problem, and even in some cases it might be necessary to question whether the Realisation obtained in Stage one is actually appropriate, the next stage is to Implement the composition.

Implementation is more than just 'installing' or 'constructing'. So the process has to consider all aspects of the implementation, including the needs of staff, students and the learning environment. It almost certainly will require some form of rehearsal of new components, but also the administrative requirements of the university and any professional institutions involved.

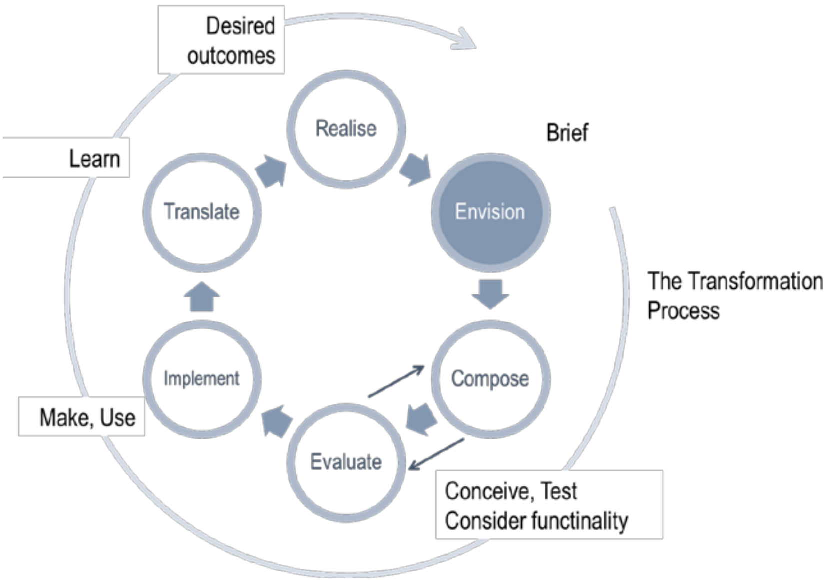

Figure 4.01 The Learning philosophy for an engineering education

Then Stage 5 is the evaluation of the implementation to ensure that the delivered outcome will be what was intended. As with the Composition process, this will involve some iterations to ensure that the programme is actually fit for purpose.

Stage 6 is the extension of the evaluation process that turns to the issue of 'what have we learnt from the implementation?'. This can be loosely thought of as 'How might this curriculum be adapted to go elsewhere?' – this is learning how to look at a solution in terms of its general principles – what makes it work, what compromises had to be made to do that, there, and thus what can be learnt about 'this example' that could be applied elsewhere: what are the absolute must-haves as they are, what are the 'could-be-adapted' and what are the must-nots to be taken into account for other implementations in response to this problem. In short, it is the check on the core quality of the curriculum.

Finally, it is important that the learning embraces the return to the Realise stage – how has this new curriculum changed the world, and thus how should we Realise the world anew? The whole process is about that transformation we are seeking towards a world in which the graduate students contribute meaningfully and comprehensively to the future society. By going through this process systematically, the curriculum can be created that can deliver all the hard and soft skills described in this report.

In this way, the context can be understood, not only as an external entity to which the curriculum needs to bow, but as an environment with which the curriculum creators should engage, in order to create the most appropriate curriculum for all – society, the students, the teaching staff, industry and the professional institutions. Designing a curriculum is just another engineering design exercise!

Step 2: understand the whole learning process for engineering

Secondly, University is in the centre of the early phase of an engineer's career, but it is not the beginning.

Figure 4.02 See the university curriculum in the wider lifelong learning environment

it is also important, therefore, before starting to consider what a university curriculum for engineering should include, to realise that the entire learning process of an engineer is not going to take place inside the few years they spend in a university. Therefore it is important to consider what should be learnt in university and what is going to be learnt in the course of a professional life. In short, what can be learnt most effectively in a university programme and what could be learnt much more effectively in industry, and when this should be done over the course of a career. Industry tends to want fully-formed engineers as new recruits, but this is a mirage. So the second element of the process has to be to determine not only what should be inside a university curriculum, but really what should be better learnt outside it. What does 'university' offer that makes it the best place to learn, and how does this translate into the curriculum for a lifetime's learning in the engineering profession.

There will be a whole set of learning experiences in an engineer's career and there needs to be understanding on all sides about what should be taught when and where. Current elements for learning include:

a. the undergraduate curriculum,
b. what is learnt in school,
c. what should be part of the postgraduate offer,
d. what should be learnt through graded professional experience,
e. what is a matter of new learning throughout a career,
f. upgrading of current knowledge
g. and so on.

What the university curriculum consists of is therefore the preparation for these other seeds of learning – some factual knowledge indeed, but much more about learning how to learn, so that the onward education pathway can be completed more effectively. It is crucial to realise that the university's task is not to create fully-fledged engineers with no need for further education or training for the rest of their lives. Indeed the task is not even to produce engineers *per se*.

The universities' task is to prepare people to be able to be engineers – to be able to use ingenuity to make innovations happen. The final step is undertaken by industry, where the engineer learns the final elements of the application of what they have learnt – whether this is in mathematics, physics, social sciences or philosophy. Engineers who are well-rounded in these matters will make better engineers for society, will be able to create, develop and implement innovations, and thus will have more enduring value.

Engineers need to learn how to be creative – creativity is a phenomenon that can be taught and developed and needs to be incorporated in the curriculum. However, learning 'how to be creative' without learning the attendant concept of 'Responsibility' – to create things that benefit rather than harm society, for example – is a crucial element of learning to become a responsible engineer.

It is pertinent to consider how engineering education should be financed. This will of course vary in different countries, with their different policies about the provision of and funding for education. However, at a broad-brush level, it is likely that Government would take a smaller proportion of the financial burden as the financial reward falls increasingly to industry: thus Government would support school and university education, with industry contributing a minor – but non-zero – amount towards these stages of the educational process. However, in terms of professional education needs, this should fall primarily on industry, with Government being responsible for only very particular elements of the process (e.g. the application and implementation of regulations or standards). The upgrading education should be an industrial investment, but it might be driven by the academic sector (e.g. the understanding and use of new materials, theories, principles which might be emerging from university (Government-funded) research.

Only once this educational context has been established, is it possible to start creating the curriculum. An important lesson learnt at UCL, when creating its 'new' degree programmes in Civil Engineering, was that this should not be left to specialists in the engineering subdisciplines. If it is, what happens is that each subdiscipline develops a very long list of what they consider to be essential inputs. It was far more successful to have cross-disciplinary groups discussing the learning requirements, both in terms of content (the 'what') and the timing ('when') [13]. This is crucial in understanding how to avoid repetition, but also in how to use repetition wisely in order to deepen the understanding of fundamental issues. It also creates the sense of the whole – how topics fit together – rather than just set up a series of stuff that has to be learnt, but in an unconnected way.

Although this can and should be done by people who will be responsible for delivering the university curriculum, there should also be involvement by the people either side of university – the schools who will be sending students into the university and their students, and the industry who will be taking on the people being delivered by the university, including both industry managers and leaders, but also recent and mature graduate engineers. These groups will not be able to contribute much to the detail of the curriculum but they can – and do – contribute wisely to the sense of importance of what the curriculum will hold and its context in the wider educational and industrial world.

[13] Graham R, (2012) Successful and Sustainable change in engineering education, Royal Academy of Engineering

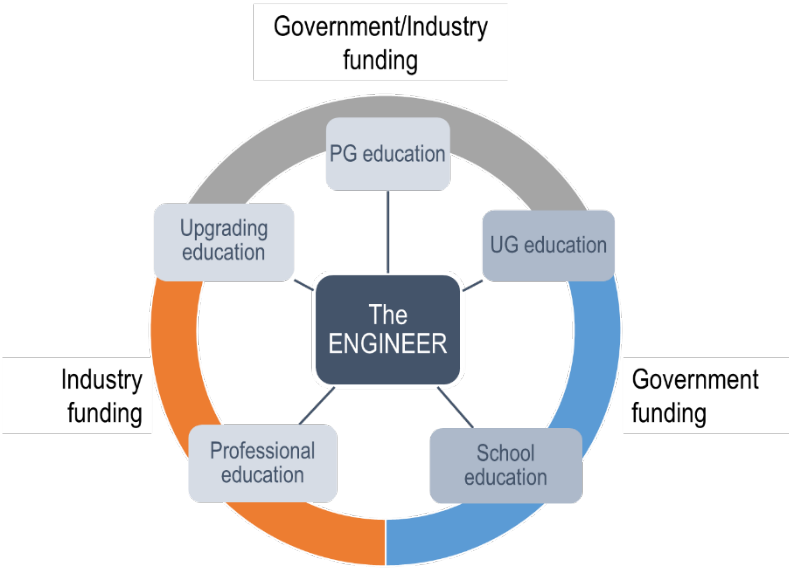

Figure 4.03 What is best learnt when and where?

Step 3: Create cross-disciplinary groups to devise the curriculum

The third step is therefore to constitute cross-disciplinary groups of engineering teachers to determine what should be learnt, and when, across the entire curriculum.

This forms the basis of engineering learning: as noted in Part III and illustrated in Figure 3.05, the relevance to society should be understood before learning how to figure out what a problem is, which in turn needs to be accomplished before learning the deep knowledge that will generate solutions to that problem. In brief, this is all about why an engineer should do what they do. Without understanding the 'why' it is negligent to start to develop the 'what' – and even more harmful to start 'doing' – before the understanding has been achieved. This is the educational basis for the development of the 'Prosperity Tetrahedron', described and discussed in Part III (Figure 3.01). Those interrelationships between the learning in education, the researching of new ideas in order to create that learning, the bringing into society in terms of defining what needs to be learnt and how this should be achieved, together with the interface with the means of putting this learning into practice, are all part of an interdependent quartet of processes. This quartet is held together by these links where all the nodes are constantly mutating.

This mutating and constantly moving world is what engineers need to learn to handle so that society can evolve: there are no fixed problems, and no fixed solutions, and this is why solutions are not the answer. Solutions always need to be seen in the widest possible context – across engineering as a whole – a bridge is not just about structure, but also about geotechnics, weather, physics, art, the societal reasoning for having the bridge in the first place, and the future evolution of society that makes the bridge contributory to improving sustainable health and wellbeing for future generations – and it needs to be designed so that it leaves options for future generations to decide how best to meet their future needs. A good engineer will be able to apply full understanding of all of these when creating their detailed and ever-evolving engineering design.

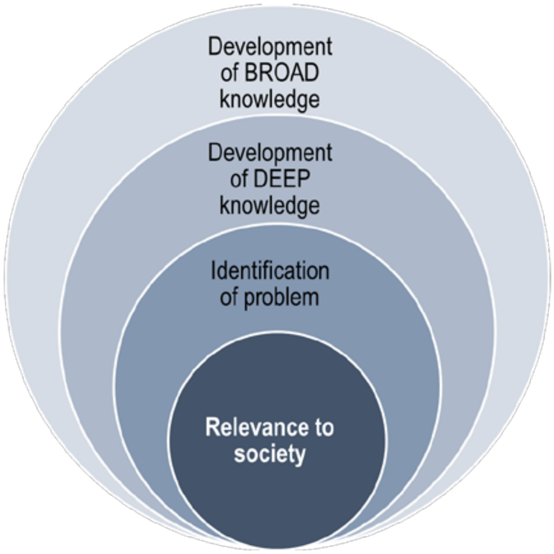

Figure 4.04 Learning engineering within its societal context is crucial to creating better engineers

Step 4: Put Steps 1, 2 and 3 together to create the curriculum

The fourth step in the process is to put all the previous three steps together. It is only in this step that actual courses, lectures, activities etc. are created. How the subdisciplinary sets are included in the curriculum, how each is best learnt, and how the crucial step of putting them together to create a solution is incorporated within each, but also jointly – how they are put together to form the best answer to the societal need and challenge. This will require innovation, without which nothing will advance successfully, and therefore learning how to innovate needs to be a core element of the curriculum. This is a separate skill from the core subdisciplinary knowledge and consists of the skills required to cluster all that knowledge in the most constructive – and creative – way. These then form the core basis for all engineering – the systems thinking that generates the systemic coherence which is necessary in any application of engineering, whether this is to produce the right kind of aircraft that does not destroy the planet but services people's needs for long distance travel, how a computer chip is designed to work effectively in delivering timely answers to political challenges, or the development of health-inducing environments in which people can thrive.

Ultimately what the curriculum has to deliver is not 'engineering' *per se*, but the learning of how an engineer should approach thinking about a challenge at hand. This is encapsulated by the Royal Academy of Engineering's 'Engineering Habits of Mind' (see Figure 4.06 and [14]), which it believes captures the fundamental requirements of an engineer, and that can be introduced to students long before they reach universities[15]. This captures the essence of engineering – visualising, improving, systems thinking etc. leading to 'making things work better' – and the essence of learning (curiosity, open-mindedness, ethics, reflection, collaboration etc.) to provide the framework for engineers in the 21st century. This is the key to a good curriculum.

14 RAEng (2014) Thinking like an engineer: Implications for the engineering system, Royal Academy of Engineering, London, UK, https://www.raeng.org.uk/thinking-like-an-engineer

15 RAEng (2017) Learning to be an engineer, Royal Academy of Engineering, London, UK https://www.raeng.org.uk/publications/reports/learning-to-be-an-engineer

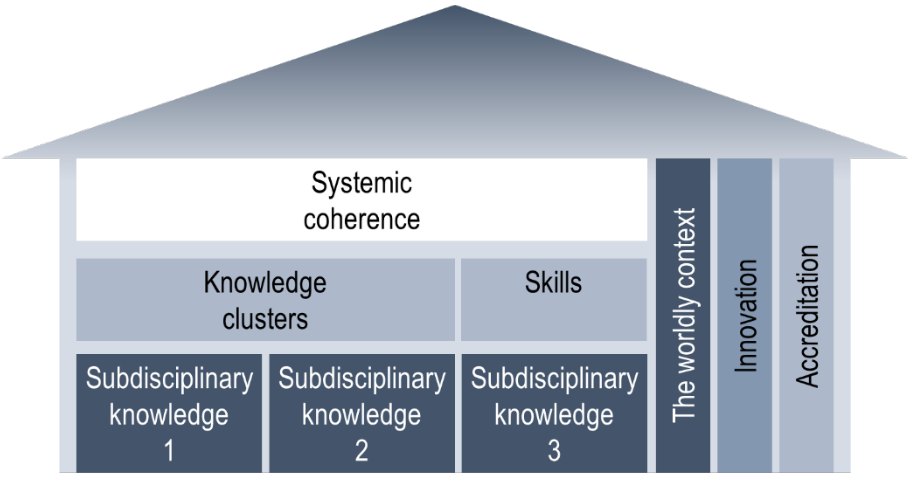

Figure 4.05 Create the engineering learning process as a whole, understand its role in society, drive innovation, and include all of this in the accreditation process

All the way through the development of the curriculum it is necessary to include discussions with two other entities: the worldly context and the accreditation process[16]. The worldly context is important because the systems coherence needs to be constantly checked against its place in the world. Otherwise great engineering can produce bad things. The accreditation process is how society checks that the engineers of the future are capable of delivering the quality of engineering that society will require. The worldly context challenges engineering, and the engineering learning needs to challenge the accreditation process. Both can only seriously be achieved if there is true engagement throughout the curriculum development process.

Note that 'the curriculum' does not just apply to what is learnt at undergraduate level in universities. It is also included in the postgraduate programmes, in the profession itself and in wider society, as well as in the basic education obtained in school.

The outcome: a continually evolving curriculum fit for purpose for future engineers

The whole has to be seen as a set that is alive and constantly updating., no engineer can be said to be complete, and every engineer should expect to undertake a constant learning process throughout their professional career – and to learn widely about how to learn and apply this skill in particular throughout their engineering career[17]. The principles contained in this document should apply to every stage of this education process, each being seen in the context of the others.

[16] RAEng (2012) Achieving Excellence in Engineering Education, Royal Academy of Engineering, London, UK https://www.raeng.org.uk/publications/reports/achieving-excellence-in-engineering-education

[17] Vaidya K (ed) (2016) Civil Engineering for the Curious: Why study Civil Engineering?, The Curious Academic Publishing: ISBN: 978-1-925128-47-5

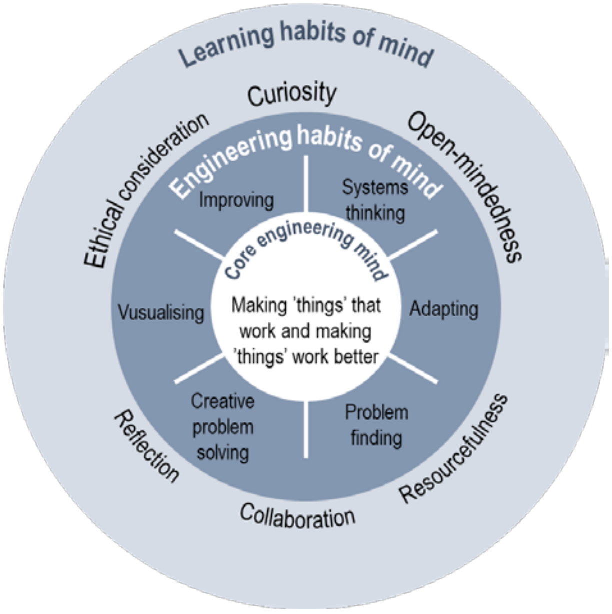

Figure 4.06 The Engineering Habits of Mind (Source: Royal Academy of Engineering, 2014)

4.e Sharing Responsibility

The essence of a 'pathway' is that it leads from somewhere and enables movement to somewhere else. In the case of Engineering Education, it is essential to frame the discussion in the context of the whole pathway, not just the part that is specifically assigned to 'Engineering' – or even 'Education'. 'Engineering', for this purpose, is the process of utilising ingenuity to make innovations happen in order to address a challenge at hand. This requires the engineer to understand the world as it is, and the transformations that could make it a better place, to realise the challenges involved in making those transformations, to envision these challenges in a tractable form, to compose the most appropriate solution, to implement and evaluate this solution, to learn how to translate the solution to other situations (including any necessary adaptations to enable it to generate the required outcomes), and thus to transform the world to a better condition than it was at the start of the process.

'Education' is the development of the mind to be able to achieve a sustainable prosperity for both future society and the planet. The concept is that a professional engineer is, first and foremost, a person who conveys a set of professional principles and exercises these in the form of solutions, processes and professional being, that achieve that sustainable prosperity for people and planet. The challenge for Engineering Education is how to inspire, encourage, create and develop people so that they can become and continue to be professional engineers in the full sense of the term. The pathway under discussion in this section is that of transforming engineering education from its present state to one that meets these challenges.

The processes discussed in this report are spread around the context of the process of creating the 21st century engineer and do not rest solely in one part, or at one point in time. Nor are they completed at a particular point: they are in continuous modification, according to changing needs, circumstances and opportunities. Engineering Education is therefore never finished, and part of the transformation required to meet future challenges must embrace this continuous deepening of knowledge – about techniques, materials, processes, but also needs to incorporate understanding of societal needs, moral prerequisites and implications.

It is questionable whether current engineering education really enables engineers to reach the professional heights that society demands, and this is a situation that needs to be addressed as a matter of urgency. No single body, or 'owner' of a single part of the process, is in a position to remedy the whole process, and neither should they be held responsible for its entirety. The transformation required is indeed a matter of a shared responsibility – but shared amongst whom?

Figure 4.07 illustrates the Transformation Pathway, showing the various entities involved in defining what should be involved in the concept of a 'New Engineer'.

Certification Bodies: The bodies who certify an engineer as a Professional Engineer have one part of the responsibility. They need to be ready to interpret societal needs in the context of the requirements that society can expect demand of an engineer. The first of these, and arguably the *'primum supra pares'*, is the requirement to 'do no harm'. Ingenuity is independent of moral responsibility and it can all too easily create solutions that can – unintentionally or intentionally – do harm, whether to people or the planet, or both, and the professional engineer should be required to ensure that they use their ingenuity to ensure that they harm neither people nor planet. Given that basic requirement, the Certification Bodies need to ensure that their process identifies appropriate knowledge, skills and techniques in their appointees – and that this includes the ability to understand their role in, and responsibilities to, society. To this end the Certification Bodies need to engage with other elements of the pathway to ensure that requirements are understood and promoted throughout the process.

The Engineering Profession: The Certification Bodies have a crucial role to play in the pathway, but it is the profession itself – the totality of all professional engineers – that does the engineering to support society and needs to ensure that this is done competently, responsibly and correctly. The Professional Institutions have a crucial role to play in encouraging their members to act professionally. This needs to go beyond exhortations and symbolism, and to project into the requirements for membership – both on admission and in continuation. In many ways the Professional Institutions are the outward-facing representation of Engineering to other parts of society – to governments, policy-making bodies, and they often are required to act on behalf of the Certification Bodies in providing the accreditation of university and training courses, and of overseeing the certification process in their particular domain. The Institutions therefore need to be in close communication with the Certification Bodies, the industry itself and the various university and other education and training providers. They also need to use their position as lobbyists to promote, not only their particular view of engineering, but also to encourage understanding of the need for high quality certification, accreditation, education and training of engineers.

Figure 4.07 The Transformation Pathway

The Engineering Industry: The need for engineers to act professionally places a responsibility on employers to ensure the continuing improvement of their employees in relation to their capabilities and responsiveness to changing circumstances. They need to be rigorous in the process of recruiting engineers so that they seek people who have the requisite capabilities. They also need to ensure that their employees upgrade their capabilities across the range of needs, including both technical upgrading and the wider responsibilities of a professional engineer. They also need to enact their responsibility in relation to clients, by ensuring that they do not succumb to pressure to perform in a less professional manner, whether this is in relation to commercial behaviour or to the technical options being considered as potential solutions to the client's problem. 'Do no harm' is as much a driver for decision-making in the industry as it is for the Certification Bodies. The Industry should therefore engage strongly with its Professional Bodies as well as the education and training providers in order to reinforce the requirement that graduating engineers have the right competences and attitudes of mind to be worthy of the title Professional Engineer, and to ensure that all potential engineers understand the importance of this need before embarking on their career. Engineering is not just a supremely exciting career to follow, it is a career embedded in a societal responsibility to ensure that society survives and prospers into the future.

Labour Markets: The need to energise the labour markets to demand and accept the new kind of engineer is crucially important. If the labour markets do not attract the right kind of engineer, the industry – and thence the profession itself – will remain in the same inertial state that it has arguably been in for the last 50 years. Therefore it is important that the engineering industry in particular strives to change the market for the engineers it needs, to seek creativity, innovation and entrepreneurial skills in the employees entering the profession, and to ensure that these skills are constantly updated, not only through ongoing education and training (important though these are), but also through the approach to the work that they do every day: the ultimate kind of 'learning on the job' approach that will keep the industry alive to the needs of society into the future. A major example where the industry could make a step change is in the encouragement and employment of women engineers: ensuring that the labour market is truly inclusive and open to all is a major marker for how healthy the profession actually is in reality.

Engineering Education: The most common route into Engineering is through university education, with some form of accreditation involved to ensure that the education process is appropriate for the needs of society – or perhaps more realistically, the engineering profession (the comments above suggest that these should be subsumed within each other). There is only so much that can be learnt in the course of a university degree. There needs to be a full and frank discussion between all the elements of the pathway to establish what should be learnt best where.

Some things are best learnt in a university, others in industry – still others in a more societal context. What is clear is that all needs to be learnt; the issue is where and when it is learnt. The truth is that without some sense of agreement on this issue it will be possible to have clear gaps in the learning, which will render the outcome less than 'professional', and the profession unable to meet the needs of the society it is supposed to serve. Essential in the learning process – and possibly something that could only really be learnt in a university situation – is the ability to learn. The material taught to engineering students in a university is likely to change significantly during the course of their career – as new materials, technologies, knowledge change of course, but also as social, environmental and economic requirements change. An engineer who cannot adjust their skills and competences to take account of such changes is hardly being professional. The basic tool they need to help them make such adjustments is that of the ability to learn. This ability can be taught in a number of ways and the 'other' material needed for engineering presents plenty of examples that can be used to enhance the ability to learn – the emphasis needs to be less on 'teaching what is' and more on 'learning what might be' – and the difference between 'what is' and 'what might be'.

Universities need to look hard at their curricula, many of which have changed only superficially and in a piecemeal way to 'keep up to date', or 'respond to industry's needs' in the last few decades. However, the higher needs of a higher Professional demand means that these curricula might now be quite insufficient in some regard. So content needs to be reviewed – this might require a line-by-line assessments of 'why is this here?' and 'why is it at this point in the programme?', together with a rigorous and robust assessment of how this stacks up against the professional requirements. Of course, the universities can only work with who enters their programmes. In many cases there might be pressures on universities to accept greater numbers, but in the case of Engineering, there is a societal responsibility to uphold: Engineers have the responsibility to 'utilise ingenuity to make innovations happen' for the challenge at hand, and in that context, they need to understand four basic principles. These are:

a. the challenge at hand,

b. the concept of 'at hand' and what that really means,

c. the knowledge that underpins ingenuity – and of course

d. Engineers should 'do no harm'.

Entering an Engineering degree programme at university means that the university believes that the student will be capable of achieving these high ideals. This means facing up to those pressures and engaging with the school system to ensure that there is a seamless path between school and university – even if this is sometimes not a contiguous succession.

Schools: Typically, schools play only a small part in the specific formation of an engineer, but actually a lot of what they do is fundamental to the professional engineer. Language, mathematical proficiency are obviously important attributes, but so is the ability to express oneself, act responsibly in society, understand the nature of higher orders, such as 'do no harm', 'be professional', and so on. The various elements of the pathway should engage with schools, not, as has been suggested in some quarters, to encourage/demand the introduction of 'engineering' into the school curriculum, but in learning the habits of mind that people like engineers need in order to make responsible decisions. This is a way of framing learning and doing for any subject, not just engineering – even if it was devised by engineers by invoking their ingenuity. So a stronger interaction between schools, universities, industry, the profession and the certification bodies is needed to ensure that the pathway is smooth, not least so that school students are in a position to make the right choices for them in terms of their next stage in life. This should enable those who are best suited to engineering as a line of study, and as a profession, want to choose to follow that pathway. Others may take advantage of that same skillset to realise that engineering is not for them, and that other disciplines would suit them better.

Government bodies: Society is in the end represented by its Government and it is important that Government bodies take their responsibility seriously in terms of engineering. The main way they do this is through the setting out of standards of course, to which engineers must comply, but actually this is not the most important contribution of Government. Many (although not all) engineering projects are based on Government policy – infrastructure of all types, priorities for investment, priorities for education, and so on. This means that Government is primarily influential, even where the markets are perceived to be highly influential. Many engineering projects are essentially Government-funded. However, even much of the highly market-based success of Silicon Valley is actually dependent on the huge Government investment in IT and associated research, development and education, and the marketization of the outcomes is only a minor element of its success – without that investment there would be no market and no people to enter it[18]. The challenge for Government is to act as an incentive: standards should not be aiming for the minimum, but incentivising the innovation to engineer something better – rather than encouraging ingenuity to avoid the bare minimum required by an existing standard. This is all about how Government understands its role in the process, and this is also about how engineering education is conducted – not only to engineers, but to everyone else[19].

The Pathway: In the preceding paragraphs, we have suggested possible perspectives and some actions that could be considered by different elements of the Pathway, and how these could transform the pathway to create an Engineering Profession that is more suited to the needs of the present and future centuries. However, it has also been made clear that there is a major importance in the junctions between these bodies. There is little point in making even the best and most appropriate changes to each body without thinking about the paths between them. In particular this applies to the links between school and university, and between university and industry.

In both school-university and university-industry links, it is important to understand the perspectives in each element, both from the institutional point of view ('what does a university want from school student applications?'; 'what does industry expect in a graduate?'), but also from the perspectives of their people – teachers, academics, industry managers. It is also crucial to have the views of the people who are really involved: the students at school, in university and those working in the industry as, or with,

[18] Mazzucato M., (2013) The Entrepreneurial State: Debunking the Public vs. Private Myth in Risk and Innovation: Anthem Press.
[19] Mazzucato M., (2014) A mission-oriented approach to building the entrepreneurial State, Innovate UK

graduates. Taking the university as an example, they can only be expected to work with the people and what they bring once they have arrived, to produce what those same people will take with them on departure. Identifying those two sets of capabilities would help to keep the review of curricula pertinent and realistic. However, they need to be set in the reality of what can be achieved in each case, which is why the path between them is so important.

A crucial aspect of all of this is the need for engineers to be able to communicate – the required harmonisation for prosperity as highlighted in Chapter 3 can only really happen if everyone understands what engineers actually bring to the table. This requires communication skills that engineers are often unwilling or unable to activate. Seeing engineers as 'ingenuity workers' rather than just 'makers/doers of things that other people want' – even more than the knowledge workers of the knowledge economy as described by Peter Drucker 50 years ago – is a vital component for society’s progress. Yet it seems to be so slow to deliver this in practice. Why?

One reason for this is that the engineering education system has failed to deliver the skills requisite to such an approach to professional life. There has not been enough about the skills of thinking, learning, communicating, or innovating and the tendency has been to rely instead on the proxies for these that are allegedly incorporated within (but only rarely actually seen) the 'hard' engineering skills of mathematics, physics, or geometry. Engineering is about how to use these skills, not simply learning them. Although it is necessary to understand the outputs of such subjects in the engineering context, the engineering curriculum needs to incorporate those higher-level (perhaps erroneously called 'soft') skills as well as the more traditional ones in order to contribute more comprehensively to society’s needs in the future. Without a high-quality performance in these 'soft' skills, the engineer will fail to be effective. The present imbalance needs to be corrected. This means thinking hard about what needs to be learnt when and where, and who incentivises – funds – the process.

Transformation: In order to transform the pathway, it is necessary to pull together all the previous elements and work together cohesively to establish a pathway that is comprehensive, complete, flexible and feasible. The discussions needed to undertake this mission are going to be complex, but are absolutely vital. Being able to have these discussions at a supranational level is an important way to bring in objectivity and flexibility: No country has only bad engineers at present, and no country has only good engineers. We can all learn from each other how to raise the engineering bar to a level where the expectation held by the people at large – and the engineers themselves – is of a profession that is highly competent, responsible, understanding of its place in and responsibility to society, and above all, one that 'does no harm'.

A good way to achieve these outcomes might be to constitute discussions involving panels with members from each element of the system. There should be a strong international focus to the discussions, although the education systems in different countries are very different, so it might be useful to have representation from more than one country representing each element. What we should not do is have committees representing only each element: this is a recipe for producing an idealistic set of needs for that element. Doing this in isolation of the others yields very conservative outcomes, with each one working hard to see the best for itself rather than for the system as a whole. Change will come as a result of a change in perspective, not as the outcome of looking in the same way at what currently exists.

Given the depth of the transformation, this is a process that is likely to take some time. It is essential that these committees are not seen as talking-shops, but that they should invoke action.

Although in many ways, this is a case where incremental change is unlikely to be possible, there are ways in which change can be made in small parts in order to benefit from previous discussions, and inform future ones. Such changes could be in the form of pilot studies so that learning can be achieved, measured and adapted as necessary, rather than wait until some definite change could be decreed.

The Chairs of these committees will need to be very carefully selected, as they will need to encourage and handle a very wide range of views experiences and opinions. Nevertheless, such people exist.

Part V

Concluding remarks and recommendations

We live in a time of progress driven by the unprecedented dynamics of technological development. But, equally burdened by the threats of grand societal challenges, which are constantly increasing. In such uncertain times, Europe envisioned its future as a democratic, inclusive, and knowledge-based society, which achieves economic sustainability through a globally competitive and reindustrialised knowledge-based economy. This is an economy where knowledge is the central capital and central resource for the sustainable growth.

But, the world of economy and business sees the knowledge differently in comparison to the world of the knowledge creators. From the perspective of economy and business, only the productive knowledge, networked and embedded in products, pushes the economy forward, creates new jobs and ensures society's wellbeing.

Academic knowledge is ubiquitous, easily accessible through any internet-connected device. That's why what our graduates know matters as much as what they can do with what they know. Transformation of academic knowledge into productive knowledge is the essence of reforming processes in higher education and related development policies that aim at a stronger and more decisive directing of universities towards the market and capitalisation of knowledge, i.e. achieving their third mission.

That is why the paradigm of engineering education is changing and why this tendency will continue in the future. Pedagogical focus of the curriculum shifts from the acquisition of knowledge towards knowledge, skills and evidenced judgement for the application and combination of learned knowledge, development of the capacity of critical systems thinking, relational understanding, creative problem solving, contextualisation of knowledge and extensive acquisition of practical/digital experience. Also, the acquisition of non-technical skills, especially the abilities of written and oral communication, cooperation, team work, empathy and other social skills and understandings, are becoming equally significant as the traditional academic / disciplinary knowledge. Engineers that we educate have to be ready to add value to whatever they do – to be ready to innovate.

Practical engineering skills can be acquired only by doing. That type of experience can also be gained on simulated problems (digital experience, Virtual Reality, Digital Twin Technology and the like). The LAB-FAB-APP context, together with so-called Makerspaces, or various forms of direct cooperation with the industry, and learning in a factory environment (factory shop floor, product/process design offices, ...), through a Learning/Teaching Factory learning paradigm, are key methodological components of the curriculum for the effective acquisition of engineering skills and readiness of graduates to respond effectively to the current needs of employers (concept of outward facing curricula). The development of curricular strategies in this direction is faced with many practical and systemic challenges. New solutions at the level of policy, broader partnerships of various stakeholders and adequate engagement of industrial enterprises are needed.

Fast-growing non-formal education markets, from work-based learning, MOOCs, to the emerging paradigm of continuous learning and personal development, are rapidly creating an alternative education sector which will have a dramatic influence on the organisation of the entire environment for engineering education.

The European economy has been suffering from an engineering skills shortage for years, and even more engineers will be needed in the future. However, these engineers need to be educated more completely - as indicated above - than has been the case in the past. For the engineering education sector, this simply means a requirement of the labour market for more and better engineers at the lowest possible cost (engineering education is expensive – education of world-class engineers requires large investments!). Contrary to intuition, this requirement cannot be reduced to a classic supply and demand problem. This view is also supported by UNESCO in its report on engineering education - 'it is not simply a numbers game!'. There are no quick or easy answers! The methodological imperative is for a combination of a systemic and holistic approach, active engagement of all key stakeholders, and long-term planning.

In addition, a solution to the mismatch of skills between what is provided and what is being demanded (which is a structural problem of the labour market that is induced by the enormous dynamics of the development of advanced manufacturing technologies) is required. Technological changes are so intensive and expansive that they introduce into the global economy an age of new division of labour. This time, it is between humans and smart machines. At the beginning of 21st century, Adam Smith's revolutionary idea took on a new meaning. We need to start thinking about completely new approaches to engineering education, for example, about 'Robot-Proof' education[1]. About Collaborative Robotics, artificial intelligence and Cyber-Physical Production Systems, where a human works in a team with smart machines in completing a common work task. About concepts like RoboFacturing or RoboFactory, but also about Human-Centered Manufacturing.

1 Aoun, J., (2017) Robot-Proof: Higher Education in the Age of Artificial Intelligence, The MIT Press, ISBN: 978-0-262-03728-0;

This report is the result of the on-going Euro-CASE research activities in the field of engineering education. It consists of five parts. Part I is introductory. Part II explores general aspects of the current state of modern engineering, primarily focusing on the European area, and identifies 7 key drivers of change that guide reform processes in the engineering education sector: 1) the ubiquity of knowledge and learning paradigm shift, 2) Grand Societal and Engineering Challenges, 3) market forces and integration with the economy and manufacturing industry, 4) inclusiveness and openness to access, 5) contestability of markets and funding, 6) globalisation of action radius and 7) digital technologies and teaching innovation. Part III addresses a selected set of the most significant challenges which the engineering education sector faces, focusing mostly on curricular strategies. Part IV deals with the analysis of the selected set of topics related to transformation processes in the engineering education sector.

In accordance with the above and with a number of observations that run throughout the report, the Euro-CASE Committee on Engineering Education puts forward the following set of general observations, positions and policy pointers.

To the European Commission and general stakeholders:

As the landscape of higher education in Europe is structured as a system of national education systems, with an integrative function that is enhanced over time through the intergovernmental cooperation between 48 European countries and various forms of strategic partnerships across the EU at the institutional level, general observations, positions and policy pointers presented in this report are formulated accordingly. In particular, the Euro-CASE Committee on Engineering Education wishes to draw the attention of stakeholders to three important issues that it considers to have a strategic impact on engineering and engineering education in Europe:

1. Change public perception of engineering and make engineering science more visible

This is a very complex, multifaceted issue. The topic of changing the public perception of engineering, primarily breaking down completely wrong stereotypes about engineering that dominate public discourse and burden Europe's ability to make full use of its engineering potential, deserves the greatest possible attention. The public's misperception of engineering is likely to have the greatest impact on the engineering education sector and the public policy sector related to economic development, technological research and innovation. Three key observations are important in this regard:

a) Engineering is critical to Europe's industrial future – Bringing manufacturing back to the European soil and the associated imperative of development and extensive use of the next generation of manufacturing technologies - digitalised and green, clean and lean as much as possible, largely depend on Engineering Sciences, as well as creative talent and practical skills of European engineers. European Industrial Renaissance needs the European Engineering Renaissance!

b) Engineering is key to Europe's ability to innovate – Due to its dichotomous nature (engineers are both thinkers and doers!), engineering is the key actor (but not yet visible enough) of Europe’s entrepreneurial and innovation ecosystem. Without strong and innovative engineering, whose position and role are explicitly and coherently recognised in relevant development policies, excellent European science will face insurmountable difficulties on its way to knowledge capitalisation, i.e. to effectively transform new scientific understandings, inventions, or innovative ideas into innovations and successful businesses.

c) **Engineering is gender-neutral** – There is no reason for women to be under-represented in engineering. If there were more women in classrooms, there would be more women in industry and research laboratories. European industry has been sounding the alarm for years over a growing shortage of skills, trying hard to find enough engineers daily, but have seemed to be resistant to employ women engineers, even when they have been available. This trend is self-harming: fewer women employed sends a signal that 'engineering is not for women', so fewer women enter engineering courses at university.

It is strategically important that future plans for the implementation of the Horizon Europe programme, in structuring its missions, especially for the two Pillars [Global Challenges and Industrial Competitiveness] and [Innovative Europe], explicitly recognise engineering sciences, and their possible contribution to more productive guidance of the European science towards tackling societal challenges of Europe, primarily bearing in mind the impact that engineering sciences have on society through the practical work of engineers (industry, innovation, entrepreneurship). The key challenge is to find a balance between basic research and applied research. Only then does science become truly productive for society. European science needs a new dynamism in Pasteur's quadrant! In this context, engineering sciences have an indispensable role to play. Second, the engineering sciences are naturally pluridisciplinary, and pluridisciplinarity is recognised as one of the key levers of the mission-oriented concept of Horizon Europe. Third, engineering creativity is naturally driven by the needs and requirements of society (engineering cannot exist outside that framework!). Therefore, the Euro-CASE Committee on Engineering Education strongly recommends to the European Commission to (where possible):

a) ensure that the social and political visibility of the engineering sciences in Europe's research and innovation system is significantly more present, as well as to ensure appropriate coherence with other relevant policies, in particular, industrial policy;

b) ensure that engineering sciences and engineering education are more explicitly visible and engaged in deepening the Knowledge Triangle integrative activities and its core mission of boosting sustainable economic growth and competitiveness (EIT KICs, also Horizon Europe, Erasmus and similar programmes);

c) ensure that the issue of addressing gender imbalances in engineering education and engineering, in general, is effectively considered and explicitly visible in relevant European policies, including Horizon Europe, and that activities of this kind extend to the level of European countries, ensuring coherence and complementarity.

2. Go digital in everything the university does

The most recent studies show that despite the increasing ubiquity of the term, and efforts made for decades at the university and policy-making levels, the concept of Digital University is still diffuse and indeterminate.

The idea that digital is all about technology is a common misconception. Additional efforts should be made, at the policy level too, so that universities:

a) create a new culture of trust in digital technologies (with caution regarding reliability and cyber security),

b) devise sustainable models of soft transition from the existing state to the extensive digitalisation of all teaching and organisational processes, and, what is especially important,

c) come to a deeper understanding of the power of social media and the need to effectively manage their potential.

MOOCs and other forms of internet-based online learning technologies are drastically changing the landscape in engineering education. The experience with COVID-19 pandemic showed both the advantages and disadvantages of digitalised education. New solutions, initiatives and legal regulation are needed in this field. The European Universities Initiative, in that sense, offers many opportunities which should be seized.

3. Improve students/graduates tracking and learning analytics

We need to understand the improvement made in learning and the pathways our students take both throughout their studies in higher education and later, throughout their career. Today we do not have reliable insight into the very important issues such as, for example, how many graduates from European engineering universities go to European factories and research laboratories, and how many of them go to the banking sector or marketing agencies, or other non-technical jobs?

Evidently, practice in Europe is lagging behind the latest theoretical breakthroughs, available knowledge and available technology. This is openly stated by the European Commission: '... however, since learning analytics is still in its infancy in Europe, we need more pilot schemes to research and experiment in this field', (COM(2018) 22, on the Digital Education Action Plan). The European Commission has recently initiated concrete activities in this direction (EUROGRADUATE Pilot Survey, 2020, or ETER project). Similar programmes can be recognised in some national frameworks. However, this is clearly not enough. It is necessary to intensify efforts in order to improve the existing situation, especially in terms of:

a) new policy initiatives,

b) appropriate legislation (issue of data privacy), and

c) extensive scientific policy advice.

Interaction with the European Universities Initiative, as well as with similar national initiatives can be fruitful. Therefore, the appropriate synergies have to be ensured, where possible. The Euro-CASE Committee on Engineering Education strongly supports the activities of the European Commission on this matter.

To the European Academies and relevant national stakeholders:

1. Put greater focus on engineering education

Engineering education is of such importance for society that dealing with the challenges in this sector cannot be left only to universities. National academies need to become aware of their responsibility and place engineering education high on the list of their work priorities. It is especially important to:

a) engage in a public dialogue with a wide range of stakeholders and thus make a concrete contribution to the reform process,

b) provide scientific advice to policymakers that is directly or indirectly related to engineering education, as well as setting them challenges related to how society attracts and nurtures engineering talent,

c) ensure regular and persistent presence in the media and similar forms of communication with the public,

d) use expert capacities of the Academy for research activities in the field of pedagogy, curricular strategies and new technologies for learning and teaching.

In order to build a broad scope of action, the exchange of information (especially practical experiences and examples of good practice), collaborative activities and creation of synergy between the Euro-CASE Member Academies is also desirable.

2. Modernise the curriculum due to an urgent need for 'Robot-Proof Engineers'

The Knowledge-Worker has to be transformed into the Learning-Worker to satisfy the demands of the rapidly changing world of work. National academies should contribute to the modernisation of curricular strategies for engineering education. The Euro-CASE Committee on Engineering Education believes that transformative processes should be based on four strategic guidelines:

a) Engineering Method and Engineering Habits of Mind should be a pedagogical backbone of modern curricular strategies, strengthened by diverse pedagogical approaches of the experiential learning paradigm (a constructivist method in engineering education), emphasising pluridisciplinarity, critical and systems thinking, and creative problem solving,

b) scientific fundamentals, mathematics and disciplinary engineering knowledge should be complemented with non-technical knowledge (social sciences, humanities, culture / arts and to this related skills) – a shift from STEM to sTEmS context (profiled engineering knowledge aggregate, composed of science – Technology – Engineering – mathematics – Society knowledge / skills layers), together with a strong emphasis on entrepreneurial and managerial skills, skills for managing complexity in a globalised world, as well as the cultivation of an innovation mindset (Entrepreneurial Engineer),

c) curricular strategies should enable and stimulate university-industry partnerships to enrich the learning and training process with student experiences gained in the real-world environment and through dealing with real-world engineering problems (Learning/Teaching Factory concept is of particular importance for manufacturing engineering), and

d) curricular strategies should enable and stimulate better use of new technologies for teaching and learning (MOOC, Remote/Open Laboratory, VR & Digital Twin technology, Learning Analytics, etc.).

not only to educate the student for specific tasks, but to educate the whole person. In that sense, it is important to follow the Council of Europe's recommendations on the wider, democratic mission of higher education institutions (while maintaining their academic freedom/autonomy). This will prepare students for:

a) sustainable employment,

b) role of an active citizen in democratic societies, and

c) personal development.

Personal (and professional) development should be placed in the context of continuous, lifelong learning across disciplines and cultures, and in that sense, the goals/competencies, organisation and teaching/learning technology of the curricula should be adjusted.

3. Improve national statistics of engineering

There is a vacuum in the national statistics when it comes to the explicit tracking of the educational and professional development pathways of engineers. There is an urgent need to improve data availability to help policymakers address challenges in engineering education and the related world of work. National academies should make the necessary efforts to initiate processes that will lead to visible and measurable progress. In this regard, Euro-CASE can contribute by harmonising actions and relying on its advisory role in the SAPEA project to communicate with the European Commission and draw its attention to the relevance of the topic and need for concrete actions and synergies at the European level.

4. Redress the gender imbalance in engineering

It's no secret that, even at the beginning of the 21st century, engineering is still hugely male-dominated and there are very few women in the industry. The situation varies from country to country. Unfortunately, there is no precise statistics on the number of women in engineering. But roughly, women account for 10 to 20% of the total engineering population.

Such a scale of imbalance has no reason to exist! There is no difference between women and men as engineers. Among others, this imbalance means that both industry and society are missing out on the contributions that women (can) bring to the discipline.

The Euro-CASE Committee on Engineering Education strongly recommends that European national academies take decisive actions to challenge this stereotyping and bias that still permeates our culture. A holistic, systemic and coherent approach is needed. This report has a special section dedicated to this challenge and offers key ideas on how to effectively address it – how to attract and retain women in engineering. To begin with, every effort should be made to double as a minimum – and to strive to increase this towards a 50% target - the current number of female students in engineering classrooms in the next 5 to 10 years.

5. Enhance the development of engineering identity

The question of the identity of engineering, primarily the public perception of what engineers do, how they contribute to society, and the like, is unfortunately still open in the 21st century. This question is as important for engineering as it is for society. Public misconceptions need to be rectified, or at least, be dealt with in a productive way. This issue is, of course, of the utmost importance for Euro-CASE and national academies. Therefore, national academies, members of Euro-CASE, need to face this challenge actively and persistently. It is recommended that the approach be achieved on a holistic basis, through systemic, long-term, and emphatic action in four main directions:

a) emphasising the role of engineers in industrial development, especially reindustrialisation,

b) emphasising the role of engineers in the innovation process – change the misconception that innovation is a matter of science, as opposed to the fact that engineers are true innovators, an indispensable actor in the innovation ecosystem,

c) emphasising the interaction between engineering and people – engineering as a servant of society that enables sustainable development to create new opportunities, as well as its role in the socialisation of technology,

d) emphasising the philosophy of engineering – the need for an ontological determination of engineering as well as the need to introduce philosophy into engineering education.

As in the case of engineering education, it is desirable to underpin the broad scope of action with the exchange of information, collaborative activities and creation of synergies between the Euro-CASE Member Academies.