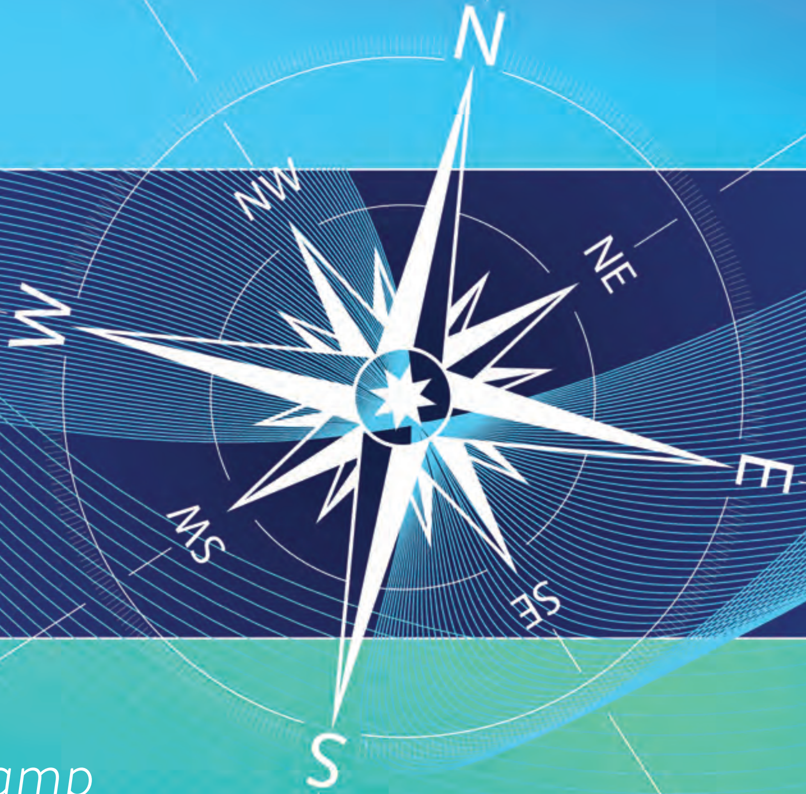
Navigating the Landscape of Higher Engineering Education

Coping with decades of accelerating change ahead



Aldert Kamp

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Colophon

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Some times call for a change, some require consolidation. The question is: in which time do you live? Staring into the future doesn't help, focusing too much on the past neither. It requires 'reading the past to predict the future'. For that an open mind is needed, a critical assessing of the current and the past. For more than a decade, Ir. Aldert Kamp has done so. While in charge of the educational programmes of TU Delft's Aerospace Engineers, he constantly scanned the world for clues on how to educate young engineers. Aldert consistently made a plea for outward looking: "open the windows and look around in the world; let the world flow in". And so he did, travelling around, visiting the leading conferences and being a well-respected key note speaker, recognized by the great institutions like MIT.

Aldert Kamp organised think tanks, free spirits to discuss the future of engineering education. He talked to the major industries trying to understand in what direction they were moving and what that meant for the education of the next generation (aeronautical) engineers. His ideas took shape more and more into the direction of real change. The current times are times of fast change, of greater uncertainty. Consolidation is no longer an option. Sure, engineers need engineering skills. But that will not suffice. Additional skills are needed and they cannot all be put in the heads and minds of each individual student. That made Aldert Kamp come up with various roles for different engineers. Roles that have one thing in common: they are connected to other roles and areas. Working in splendid isolation and then passing on the work to the next engineer is out. Team work, with multiple disciplines in each team, socially responsible engineering, entrepreneurial thinking, innovator roles, system thinkers and sustainability: those are the new ways of the world. In this book, Aldert has put together all the ideas, knowledge that he gained over the years. Read it! Even if you are not convinced that we are living in rapidly changing times.

The timing of the book, now that the world is in turmoil due the corona virus couldn't be better. Changing times, that's what we are facing. And we have to find answers to cope with this. In this book you will find food for thought and inspiration from one of the current thought leaders in engineering education.

Robert F. Mudde
Vice-President of Education
Delft University of Technology

Foreword

It is so Much Easier to Educate Students for Our Past than for Their Future

The Organisation for Economic Co-operation and Development, the World Economic Forum, the Global Engineering Deans Council and other thought-leaders in higher education are calling for a profound change in the engineering education sector[1]. Their call is for fast-pace initiatives to enhance curricula for key enabling technologies[2] and advanced manufacturing technologies[3]. They foresee a major shift in higher education's responsibility and purpose. They envisage a move towards socially-relevant and outward-facing engineering curricula[4] that offer students more choice, integrate engineering knowledge with humanities and social sciences, are all about interdisciplinary learning and education with societal impact, and offer more opportunities for self-development for those with unique learning demands.

Education is no longer complete when students have acquired a deep knowledge on abstract theories and concepts, but do not know how to act on that knowledge in the outside world or take multiple perspectives into account. Major challenges lie on the fringes of technological sophistication, societal acceptance and politics. Universities can only be a prime source of talent and technology when they bridge the existing gap between a university education and their graduates' contribution to and participation in society, both for the liberal arts as well as engineering. This can be achieved by an intensive collaboration between the world of education and parties in the field, including companies, governmental organisations and the wider public.

These collaborations are crucial in making engineering students familiar with the human aspects of and ethical issues in engineering, in other words, with being socially conscious. Over the course of their studies they need to become culturally agile citizens, with an international mindset and interdisciplinary and systems thinking skills, in order to get a holistic understanding of the role engineers play in industry and society. They need to develop entrepreneurial behaviour and be prepared to work in tandem with intelligent machines…., all this on top of the core value of fundamental rigour in science and technology.

Another important argument for a shift in the purpose of higher education lies in the race between education and technology. The digital transformation is boosting the race for world technological leadership. Artificial intelligence (AI), the Internet of Things, non-classical computing, and also bio-engineering are going to revolutionise the worlds of engineering, engineering business and society at large. Although we often seem to overestimate the effect of these new technologies in the short run, we underestimate the effect in the long run (Amara's Law). Many of these modern technologies are still prototypes and a long way from replacing human designers and engineers. They will not all at the same time reach operational level, but their arrival in the engineering profession is to be expected in the coming decades. We must assume that the adoption of these new technologies in the engineering profession will prompt a massive transformation of design, engineering, development and manufacturing processes, and will take tasks that can be automated out of the human. It will require major complimentary investments and a lot of experimentation to exploit their full potential. And although we all know that data are the new oil in the advancement and exploitation of these technologies, the bottlenecks will not be data centred, but related to the availability of the right skills and training of staff.

A third argument for a shift in the purpose of higher education lies in the fact that many jobs in the engineering profession centre on personal relationships and interpersonal communication. The most sophisticated computers have not yet been able to match the efficiency, creativity and speed of the human brain to address the randomness of human life or to transfer knowledge from one context to another. Although the first virtual assistants have arrived, human interaction and emotional intelligence are still far beyond the competence of any computer. Engineering education shall therefore emphasise the values and traits that cannot be imitated or copied by computers, like higher level thinking, emotions, community and virtue. Sustainable employment prospects for engineers will hinge upon what they are able to do better, or worse, than computers.

Thinking back to how I, of the Baby Boomer generation, was prepared for today's world of computers, internet, automation, and mobility, first when I was in secondary school in the late sixties, and then, in the seventies, as a student at the Delft University of Technology, I can be brief. I was not. We still worked with mathematical tables to look up logarithmic and geometrical values, with slide rulers, punch cards, typewriters, and a drawing board, and the library was our only source of information. I remember the shock in the classroom when, in 1974, a professor demonstrated his first legendary HP-35 scientific pocket calculator with trigonometric and exponential functions. At university, knowledge transfer and training focused on the fundamentals of construction, manufacturing and engineering practice. And in my first engineering job, I worked on remote terminals that were connected to mainframe computers. The computation of a comprehensive mathematical model for thermal predictions of a spacecraft lasted a full night.

Neither at school nor at university were we ever prepared for the mind-boggling developments that would change our life, our work and society. The credo of lifelong learning had not yet been invented. Still, most Baby Boomers managed, adapted and changed life for the better. With the missions to the moon, this generation made dreams come true, and the impossible possible.

In a similar vein, I cannot imagine that my parents, born in the first two decades of the 20th century, were ever prepared by their parents or schools to the use and impact of electricity, radio, telephone, TV, automobiles, airplanes, the mechanisation and intensification of agriculture, global trading, etcetera.

Why then do we worry so much about the need for change in higher education today? Simply put: how different is the present from the past? The older I get, the more references I have to put today's life in perspective. It leads me to think that the only constant in life is change. Never ending, all-encompassing and immersive change. Change seems the only constant and the new normal. But that would be a misconception!

We are living in an age where change in science, technology and society is not constant, but accelerating at a pace humankind has never seen before. An ever-growing part of the world's population is becoming digitally connected, has access to a wealth of accumulated knowledge and adds to it in a worldwide collaborative effort. Rapidly evolving markets, changing regulations, breakthroughs in technologies and political instabilities make it hard to look too far into the future[5]. My fascination with this day and age, and my preoccupation with the promises and risks of emerging technologies make me think that we are experiencing something entirely new.

Universities are institutions that look for innovation and advance knowledge, and in that respect they are at the forefront of society. At the same time, however, they are also filled with traditions and conservatism. Their leaders are supposed to be like antennae, looking out for signals of change that impact higher education. It is therefore worrisome when they decide not to think about the risk of higher education losing out in the race against technology. In my day to day advisory work in and outside of university I have noticed a scary widening gap between visionaries and thought leaders, and the majority of academic staff, including higher management.

In my previous report (2016) "Engineering Education in a Rapidly Changing World" I portrayed the VUCA world and my vision on its potential impact on higher engineering education. The report stirred up quite some debate and has been a source of inspiration for numerous institutions. This new report aims to complement this vision with new insights and offer a forward-thinking perspective on higher engineering education. It addresses the changing roles in the engineering profession, the shifts in mindset and various kinds of literacies in engineering curricula. It discusses the greater responsibility students have for their own education and learning process, the importance of professional skills, and the integration of digital

transformations and responsible engineering in curricula. And last but not least, it looks at the essence of impactful education, the need to upskill staff, and the impact of the vastly altered population of learners, mainly Generation-Z students.

My aim is to help bridge the gap between visionaries, thought leaders and those on the shop floor by describing frameworks, and by providing concrete examples and guidelines for a number of relevant subjects, such as challenge-based education, makerspaces and agile programmes. And when you are interested in long-term change and eager to learn how technical universities may have to transform the delivery of education in 2050 to meet societal expectations, the chapter about reframing engineering education will be of interest. The concluding chapter is a compass for educational leaders. It gives 24 recommendations in four compass points for the development of educational vision and strategy and their implementation in organisations and curricula.

This report is based on a broad spectrum of sources listed in the notes and bibliography: studies and experiments by the Dutch 4TU.Centre for Engineering Education, literature, personal notes, advice and consultancy to universities, workshops with university and engineering science academies staff, and workshops with industrial branch organisations and multinational players in engineering consultancy and business in the Netherlands, Scandinavia and the US. The ideas and examples in this report are multi-sourced and leveraged with my personal touch. The report has been written in a strictly individual capacity and does not necessarily reflect the opinion of any organisation I am affiliated with[6].

> "Faculty Boards, professors, teachers will tell you that the curriculum is over-crowded already; that there is an exponential growth of new knowledge as well as a bulge of students; and that there is no time to pack any more into the curriculum: A degree course in science and technology, they will tell you, simply has to concentrate itself on the expertise of physics and technology. Personally I challenge this attitude for a couple of reasons. The first is that the same Faculty Boards who pack the curriculum with specialist technological know-how, will tell you proudly that 60 percent of their graduates, by the time they are forty, are in leadership functions and not doing engineering anymore!
>
> The second reason is that intelligent machines will soon outperform engineers in non-routine cognitive work using the specialist knowledgebase. I guess we should not teach for automatable jobs because these will shift or simply go away by replacing technologies. Learning durable personal and professional capabilities has a higher value, because they last a lifetime. The third reason is that most of the technical expert knowledge taught in the curriculum has a short shelf-life and is obsolescent in less than ten years' time after graduation. And although there is an explosive increase in specialist knowledge, there is not, I believe, an explosive increase in principles, in seminal ideas." *(adapted from a speech by Sir Eric Ashby at the Faculty of Applied Science and Technology at Queen's University in 1956)*[7].

Contents

Rapid, Continuous Change as the New Normal

Under the influence of transformative technologies and economic and societal developments, European societies are experiencing a moment of great upheaval. The 5G network, developments in 3D-sensing and autonomous mobility, the Internet of Things, cloud computing, artificial intelligence and augmented human technologies are transforming industries at a tremendous pace, with a full transformation expected in less than a decade[8/9]. The digital transformation is changing every part of science and technology in a yet unknown and profound way. Every system, product or service, including higher education, will have aspects or parts that are dramatically enhanced or disrupted by digital technologies. Anything that can be automated, will be. Routine tasks are becoming increasingly automated, while newly created jobs require different competencies. High-tech skills are lacking[10].

Universities play an important role in this transformation. It is their task to provide their graduates with a skillset to best deal with and use artificial intelligence, working in tandem with intelligence machines instead of against them. They have to prepare students for a labour market that is being massively transformed by the Fourth Industrial Revolution and is undeniably moving towards the development and use of key enabling technologies. Engineering education must prepare students to thrive in this world of flux, to be ready, no matter what comes next. It must empower them to be leaders of innovation, to not only be able to adapt to a changing world, but also to change it. In the 21st century, 20th-century solutions and thinking will not get the job done. Yet many institutions are not keeping up with these rapid technological, societal and economic changes.

> *“The race between education and technology is a simple and robust empirical observation”*
> *(Quote of Carl Benedikt Frey in his book The Technology Trap)*

The identity of the modern university in its teaching and learning function mainly rests on the interplay between research-based professional training, disciplinary education, and academic values[11]. To be future-ready and remain relevant in the volatile, uncertain, complex and ambiguous VUCA world[12] (see its characteristics in Table 1[13]) higher engineering education requires a paradigm shift at an individual as well as an institutional level.

Volatility	high speed of change in industry, market and the world in general; fluctuations in demand, turbulence, short time to markets;
Uncertainty	different scenarios are possible, it is difficult to make predictions;
Complexity	the immense number of factors that need to be taken into account, with a high variety and complex relationships between them;
Ambiguity	a need to deal with incomplete, contradicting or too inaccurate information to draw conclusions.

Table 1 An attempt to define VUCA

Current higher education focuses on the exploitation of the existing codified and tacit knowledge base, on the "how we've always done it" [14]. Its key elements of rational problem solving, deep disciplinary knowledge, analysis, optimisation, understanding certainty, developing order and anticipation are compatible with a situation where the past can be extrapolated well into the future. The chaotic VUCA situation (Figure 1), however, is not a forecastable linear extension of the present. Long-term forecasts of discrete scenarios lead to billowing plumes of uncertainty. Which could, within the decade, already lead to an unimaginable future. Remember the superfast penetration rate (about 45% on a global scale within 13 years[15]) of new technologies like the smartphone, and its immense impact on every aspect of our life. To be prepared for such a future, engineering graduates will need a much more exploratory "what and why" mindset, with problem definition, holistic thinking, initiative taking, self-reliance, creativity, the handling of ambiguity and correlating chaos, lifelong learning and agility as key components.

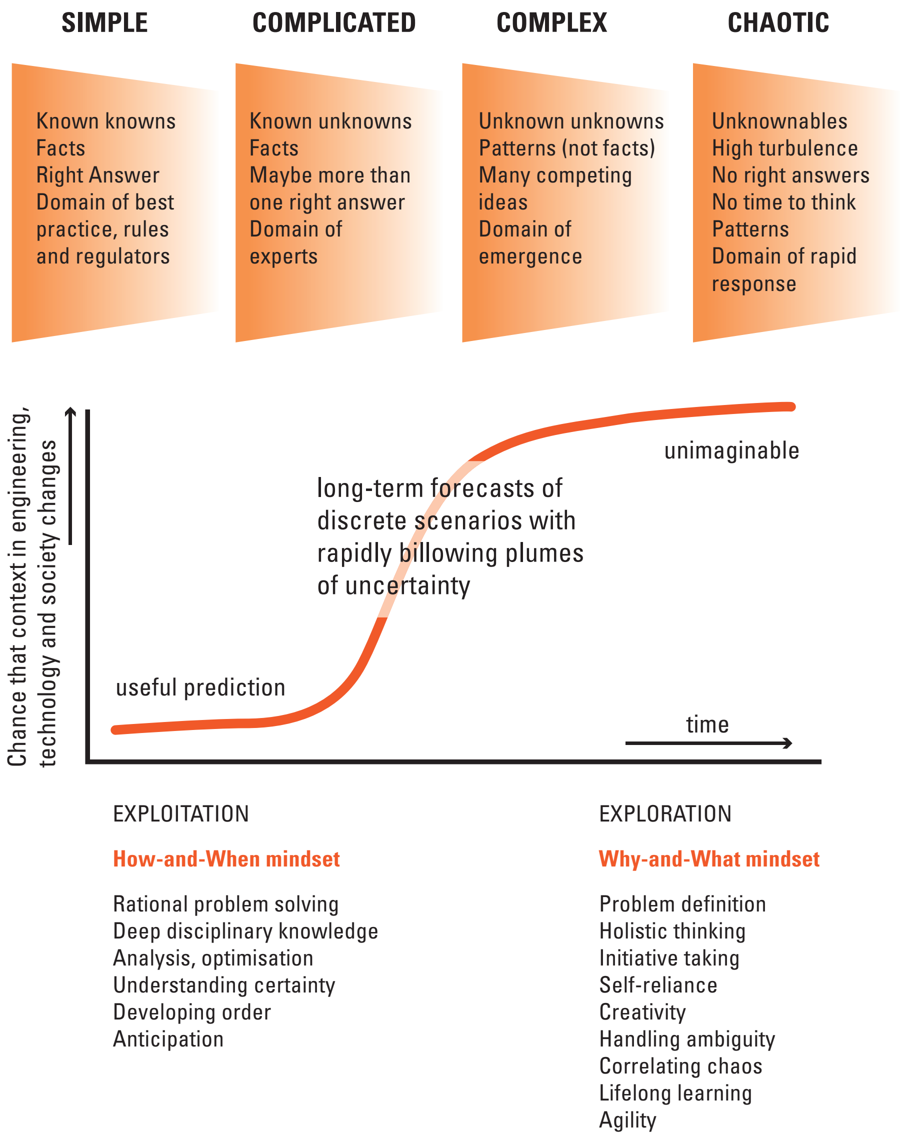

Figure 1 The shift from the "traditional and simple" situation of known knowns to the chaotic VUCA situation of unknown unknowns[16] and the changing needs for engineering graduates

The Knowledge Society is in a state of transition as well, with its shift to a Global Learning Society of continuous improvement and innovation. It is no longer the creation and dissemination of knowledge, but its acquisition, sharing and collaborative collection that are the key factors of success when it comes to science, technology and engineering. We are already observing a clear trend where learners are creating their own playlists of specific needs. Students attend universities to be collaborative, creative and flexible, and to apply their knowledge in diverse ways[17]. Teaching staff will have to rethink their role, that much is clear.

The Right Science & Technology Education for Society 5.0

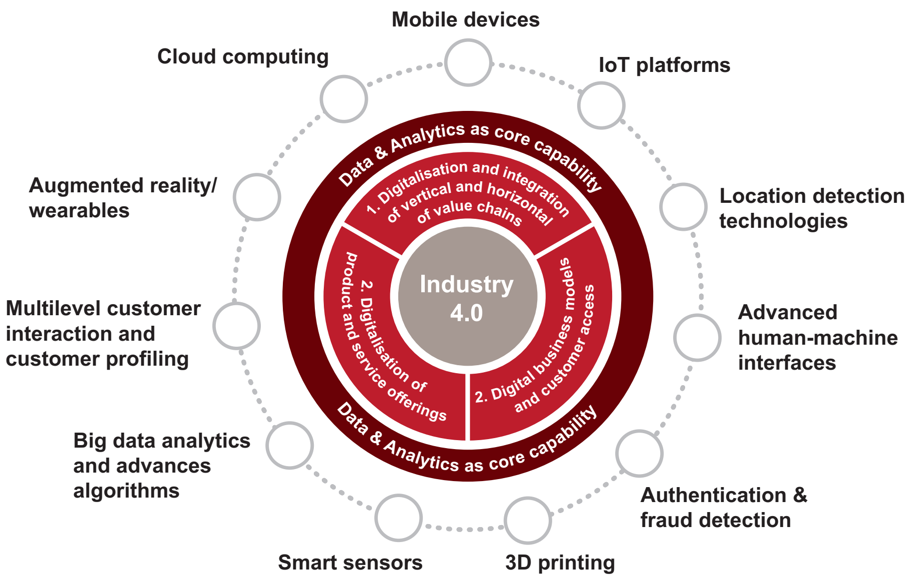

Figure 2 Industry 4.0 framework and contributing digital technologies (source: PwC[18])

"The future always comes too fast and in the wrong order" (Quote Alvin Toffler)

Complete mastery of technical engineering disciplines and logical thought has always been and will remain necessary for successfully analysing problems, designing solutions and advancing knowledge. To prepare students for a knowledge-based economy, our engineering education has to focus on the acquisition and development of core knowledge and capabilities in the domain of engineering sciences: to discover, analyse, conceptualise, design, develop, operate and innovate complex products, systems and processes. These attributes are hard won and only come with practice and experience.

Universities will obviously need to prepare their students for success in their first job, but also for success in learning, work and life later on. Their graduates will not only learn to cope with the changing world but know how to be change makers themselves. It is them who can make the difference by combining technical expertise with personal and professional attributes for effective leadership. They will be ready to advance and work with emerging enabling technologies, and be equipped in such a way that they cannot be easily replaced by technological progress. They will master the literacies, skills and mindsets needed to thrive in the world of Industry 4.0, which will evolve into Society 5.0.

The role of universities in today's VUCA society is changing. New actors and new educational approaches are emerging. No longer do universities have a monopoly on knowledge. External parties are likely to be more skilled and nimble in the areas of recruitment, digitised product delivery, as well as student support. Could it be that Google, Facebook or Microsoft become the Amazons of the academic education sector[19]? Will commercial MOOC platform providers become a kind of Facebook or Google+, trading learner statistics as a valuable product?

Historically, research-intensive universities in Europe haven't felt the need to make societal contributions, even though the combination of disciplines allowed them to play a key part in knowledge-based economic and societal developments. Academic staff scepticism of the private sector is one barrier, even though the private sector is getting more interested in what universities have on offer. And yet, old universities have not become old by simply sticking to the past. They have continuously reinvented themselves, identifying new challenges and adapting along the way. And as we shouldn't assume that the current course of change is inevitable (and therefore become complacent), universities have the task to help shape this new transformation and become the architects of the future. They need to become more socially engaged and culturally open in order to remain relevant and to be able to take the lead. No longer can they play the role of "knowledge factory" and produce knowledge for the world. Instead they need to be active in the world. "Impact-focused education" will become the leading motto.

The coming decades, with cutting-edge technologies at their core, will not see a linear extension of the current trend. The digital transformation will hit academic organisations hard and affect entire study programmes. A lack of agreement on what this digital transformation comprises, hinders many universities in formulating adequate policies for engineering programmes. They have not yet gotten to grips with the required strategic planning for educational change in this context.

There can be no doubt that every study programme in the engineering and technology domain needs to be permeated with data literacy skills. And although there is plenty of thinking on this front, there is still very little planning or action. For many research-intensive universities the disciplinary silos may be an obstruction. Without a shared understanding of the impact of the digital transformation and the key role it will play in research, engineering and design, the organisational structure in disciplinary silos easily contributes to inconsistent and unbalanced implementations of digital literacy skills in educational programmes. On top of that, students these days are far more versed in digital knowledge, social media skills and tools, mobile data analytics and cloud computing than staff.

"Engineering students have to learn that people policies, environmental aspects, politics, economics or cultural values often override disciplinary expertise"

Of course educational change will not be limited to digital engineering literacy and exponential advancements in technologies. It might even be more important to found educational change on the things technology cannot do, the things that are strictly human! The following chapters explore trends in engineering science and technology, education and society, and are a foray into how higher management at universities could take the lead in changing education at their institutions.

The Changing Landscape of Engineering in the Age of Acceleration

In his previous report[20], Kamp (2016) described the world as rapidly changing, increasingly complex, often chaotic, and fast-flowing (as already shown in Figure 1). We are on the brink of the Fourth Industrial Revolution, built on the revolution of globalisation, digitalisation and hyper-connectedness. It will lead to unprecedented paradigm shifts in engineering and technology, economy and business, on a societal as well as an individual level. The report mentions three converging driving forces behind this transformation:

1. Globalisation and Digitalisation that impact every job, problem, solution or innovation in all disciplines. Data, Algorithms, high-speed Networks, the Cloud, and the Exponential Moore's Law (DANCE[21]) is revolutionising the way we think, communicate, design, work, move, play and do business. The deep integration of (mobile) internet, big data, cloud computing, the Internet-of-Things and artificial intelligence with digital engineering, empowers a paradigm shift in engineering and design. A shift from the traditional 'design-build-test' to a 'model-analyse-build' methodology, using prototypes and experiments in a virtual environment that are based on enormous amounts of data. It will set and shape new standards around the world. Globalisation is no longer about trading goods across borders, but about trading ideas, know-how and services. Labour will cross these borders too, although it will no longer be the people, but the labour services.

2. The horizontalisation of the socio-economic world in which educational attainment is increasing and traditional hierarchies are being replaced. Horizontal communication through interdisciplinary networks and collaborative models removes the disciplinary compartmentalisation in engineering. Decision-making is becoming more decentralised, individualised and rapid. More power is transferred to consumers and

end-users, who demand that “products and services that are marketed on a global scale, feel local, personalised, and one-off”.

3. The blending of technical, economic, and societal cultures that leads to access to easy-to-use software, tools and equipment, along with free, perfect and instant access to an infinite amount of information goods. It revolutionises the way things are designed, manufactured, financed, advertised, sold and consumed, whereby the focus is no longer on making the cheapest, but the smartest and most personal products. And it fuses the public, private an people realms, where private companies have access to private data, and privacy is compromised.

To Change the World, Students Have to Be Taught Differently

Fastnet and Super Smart Society

Do today's universities prepare students sufficiently for the Fastnet[22] they live in and the enormous impact the monopoly power[23] of the big tech GAFA[24] companies have on society, engineering and technology? Do they educate their students to become "comprehensivists"? Do universities know how to engage research specialists with in-depth knowledge in a narrow field at a time that intelligent devices are developing into contemporary prosthetic appliances that will soon outperform humans? Have they thought of benefiting from students who are smarter and more mature in digitalisation than staff? Do they know how to respond to market trends that ask for engineers with a better and broader understanding of multiple fields, now that new systems are integrating computation, networking, and physical processes?

In this changing landscape, engineers will play a crucial role. More and more, they are competing in a labour market where intelligent machines that extract new knowledge from big data through advanced analytics and that assimilate lessons of the past worldwide, take decisions autonomously and work alongside engineering professionals. Universities have to prepare their graduates to cross the border of their specialism and communicate with people from other disciplines and with different economic or political backgrounds. Engineering students have to learn to respect the ideas and ways of working that are common in other disciplines. The days of the solo researcher and solo designer have come to an end.

The Super Smart Society, indicated by Japan as Society 5.0, in which the cyber space of data and information has fused with the physical space of the real world, presents opportunities and great challenges.

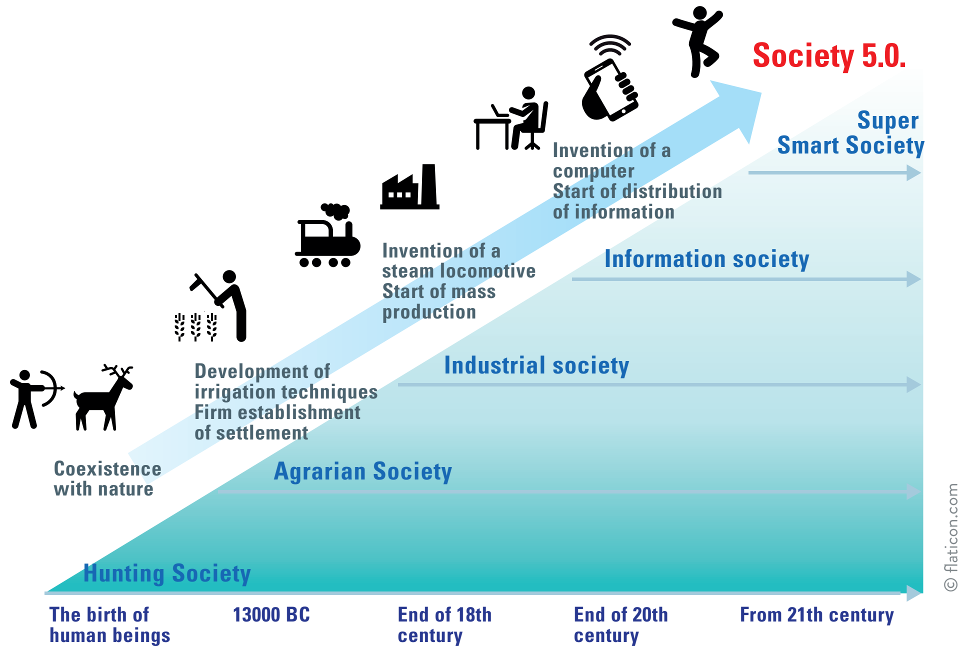

Figure 3 The evolutionary aspect of the Society 5.0 concept as introduced in the 5th Science and Technology Basic Plan of Japan (source: Keidanren paper[25])

The changing paradigms mean that engineering professionals need to be more agile and resilient, that they have to be thinkers who feel perfectly comfortable working outside of their comfort zones.

The impact of the Fourth Industrial Revolution on societal and individual transformations will be strong: new enabling technologies may be used in unforeseen ways or render current worker skills obsolete at an accelerating pace. The more the Fourth Industrial Revolution accelerates, the more the gap between what we currently do with new technologies and what we can do with them, widens.

In the past, we have seen many examples of job-replacing technologies bringing social unrest[26]. Unsurprisingly, these developments can provoke an emotional-ethical response of workers, users and consumers of new technologies. It is therefore important that our students know how to connect the rational and emotional counterparts of societal response to new technologies, so that they are prepared for debates on their impact. They have to be engaged in discussions about the values, ethics and morality that are needed to create a world that is more sustainable than the one currently on the cards. And therefore students will need to think holistically, be able to work in interdisciplinary global teams, and take ethical leadership. All skills that go well beyond "traditional" engineering skills.

We also see more and more collaboration across locations and disciplines. Engineers not only work together in teams to solve complex problems and manage people, they also work with robots more often. Communication and collaboration have always been widely regarded as key skills for engineers. Digitalisation makes working relationships more complex. Although teams and team members are more connected, the unrelenting emphasis on perfecting the speed of development and innovation processes is pulling away the human element from collaborative work. Consequently, social relationships are more fragmented and impersonal than 20-30 years ago.

Changing Roles, Skillsets and Mindsets

Engineering roles are breaking away from what they used to be, and it is no longer the role itself alone that you are prepared for or gain experience in. It is about the skills you have, perhaps as granular as the tasks you have successfully performed, and where these can bring you. Engineers are moving beyond the 20th century style of ”how-and-when-to-do it” engineering and need skills to work in a “what-to-do and why?” way. They are developing into cognitively augmented workers with “senses” that were not available to their predecessors.

“Training data engineering literacy and human literacy as well as mindsets has to become an integral part of the engineering fundamentals, just like the technological literacy of mathematics, physics and engineering sciences”.

Engineers collaborate and work together in flatter hierarchies in uncertain, sometimes chaotic environments. Increasingly, they need to “think statistically” rather than “deterministically”, and are supported by intelligent devices with algorithms and generative design software. These robots are a real design partner for the engineer, not only to represent or optimise , but also to make decisions for the designer, devoid of bias, intuition or emotions. They use data, digital representations of systems (“digital twins”), and digital artefacts to communicate between the partners and various stakeholders . In this “algocracy”[27], algorithms make real-world decisions more and more often: Anything that can be codified will be done better by computers, but the more tasks shift to real-world, ill-defined challenges, devoid of rigid rules or historical data, the more an engineer with range will need to add[28].

This change might shift the ethos of the entire engineering profession. What will be the implications for engineering education when algorithms are at the heart of the engineering profession and nudge the engineer in the right direction? When design and research work are no longer based solely on expert judgement and predictions, but also on collective intelligence applications, driven by sensor data and using algorithms that combine the collective knowledge and decisions of many thousands of engineering professionals and researchers? It could easily undermine the integrity and ethical behaviour of engineering.

When algorithms are replicating the process of creativity and are making the design or research choices, even if we don’t fully understand the methods that are used for making such choices or decisions, the free will of the engineer is surrendered. It would mean the eradication of human creativity in engineering education and kill the drive to translate information into knowledge and knowledge into know-how.

Technological, Data and Human Literacies

The purpose of higher engineering education has always been threefold: personal development (cognitive, psychological, social, moral), as preparation for sustainable employment, and to form a skilled and self-actualised citizen who is able to navigate a complex world (Council of Europe, 2007). Sustainable employability requires graduates to have a mindset of continuous upskilling and relearning. By accumulating experience, knowledge and skills, acquired in earlier phases of study and career, particularly from different domains, they create the opportunity to further develop and demonstrate their work potential, including their creative impact. This needs the coherent ensemble of deep working knowledge of engineering and technology, including digital engineering literacy skills, interlaced with a broad range of durable skills, and competencies that are related to innovation, marketing and services, with a strong sense of its actions and impacts.

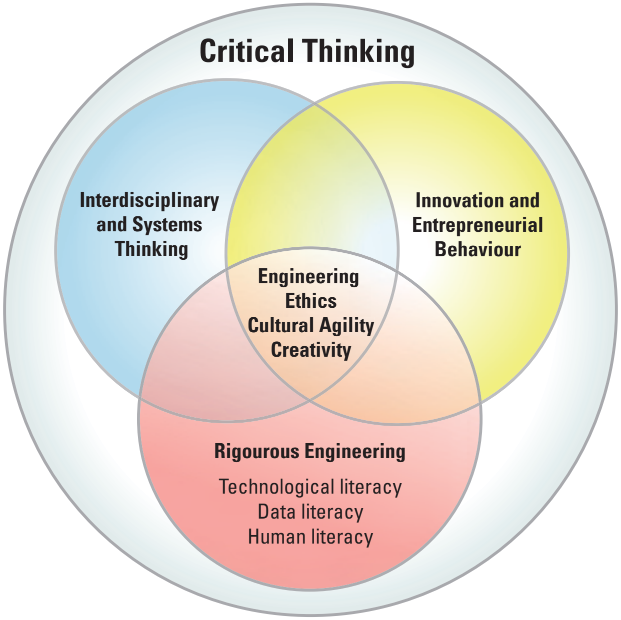

Figure 4 Key aspects of a 21st century engineering curriculum

Deep technical knowledge is more important than ever for higher-order thinking and creative problem solving. Solutions cannot emerge from a vacuum and require a solid, broad foundation of technical skills, a deep conceptual understanding and readily available amount of engineering knowledge. A major challenge in higher engineering education is to maintain breadth and a diversified experience, in an academic world that increasingly incentivises a path of unwavering specialisation.

Deep knowledge of engineering is also key in understanding the value of the exponentially growing amount of information in our world, and in assessing its reliability and usability. In a while, it will be the domain expert, complemented by augmented intelligence, who takes the final decisions. Until deep learning goes beyond pattern recognition and reaches a level of asking why things happen, intelligent machines may completely take over.

Besides the exponentially growing domain-specific body of knowledge, technological literacy is influenced by digital engineering literacy. Many universities are struggling with questions of how to cope with the digital transition and the kind of digital engineering literacy skills that need to be taught when and in how much detail. As always, context is king. For some disciplines, it might be sufficient to equip engineering students with easy-to-use advanced analytics tools. For data scientists and data engineering students it is important to learn to communicate effectively to stakeholders with no background in data science whatsoever. For many domains, sensor technology becomes a key subject. Sensors enable the connection of the Things with the Internet in the Internet of Things.

Per discipline and study level, a selection has to be made from a dizzying list of subjects: Programming, data structures and data analysis, data visualisation techniques, unsupervised machine learning, explainable and ethical AI, generative design with AI, smart manufacturing, 3D-printing, collaborative and intelligent robotics, automation, computer vision, Internet of Things, Virtual and Augmented Reality, cybersecurity, computing technology, machine learning, networked cyber-physical systems, etcetera. The integration of these skills in engineering courses will be one of the main driving forces for change.

To operate successfully in the increasingly "data-rich" engineering environment any engineer, well, any professional will have to become data literate during the Fourth Industrial Revolution that will lead to "Society 5.0". In this society, knowledge and other values are no longer created by humans alone, but increasingly by algorithms in intelligent machines that integrate the cyber and physical space (Cyber Physical Systems). Algorithms enable these systems to make decisions on their own and perform tasks as autonomously as possible. Data literacy will be relevant for every engineering programme. Every student on an engineering course must develop excellent skills in mathematics, computational thinking[29], programming, statistics, predictive analytics, etcetera.

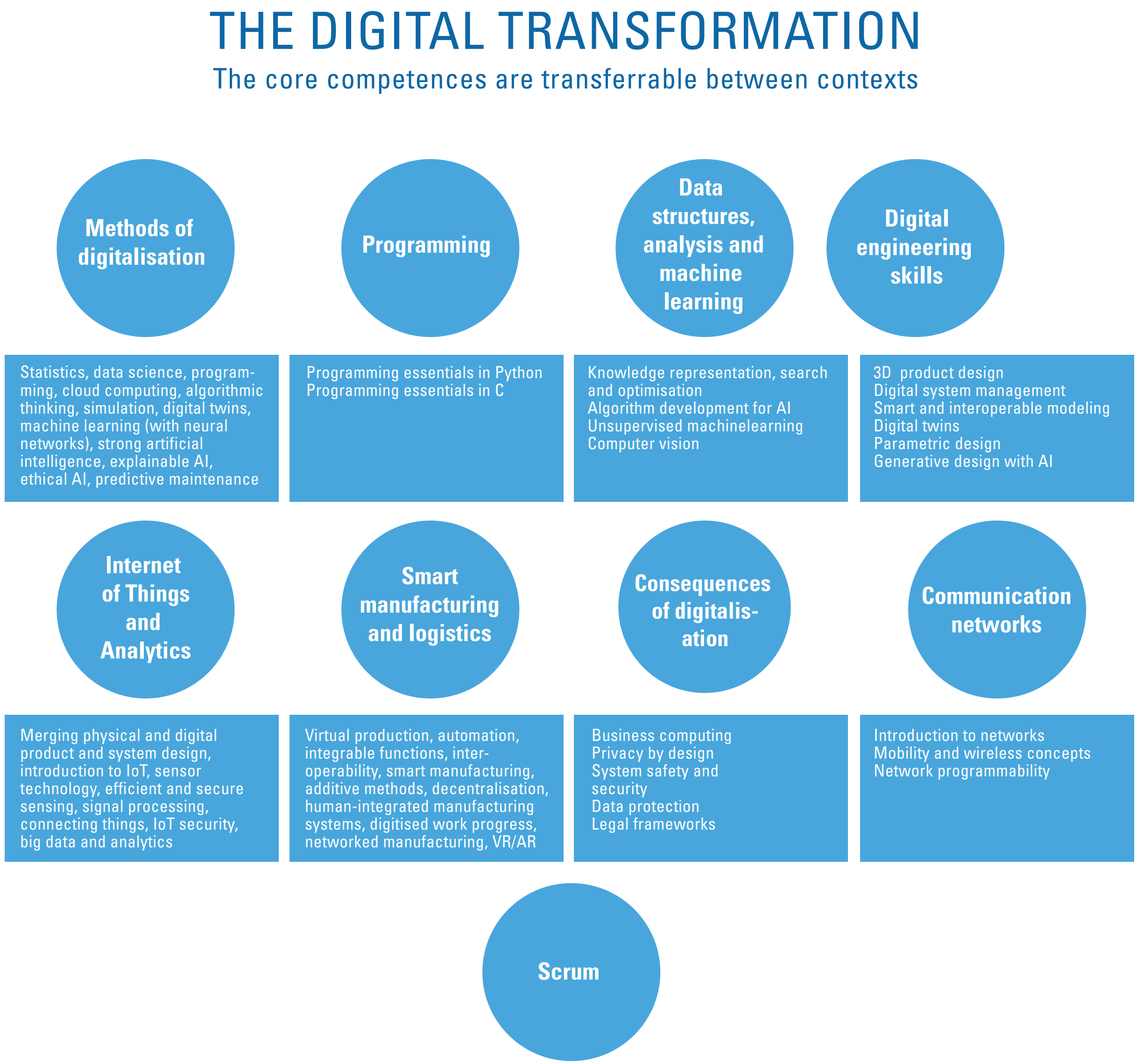

Figure 5 Kaleidoscopic picture of digital literacy elements for an engineering curriculum

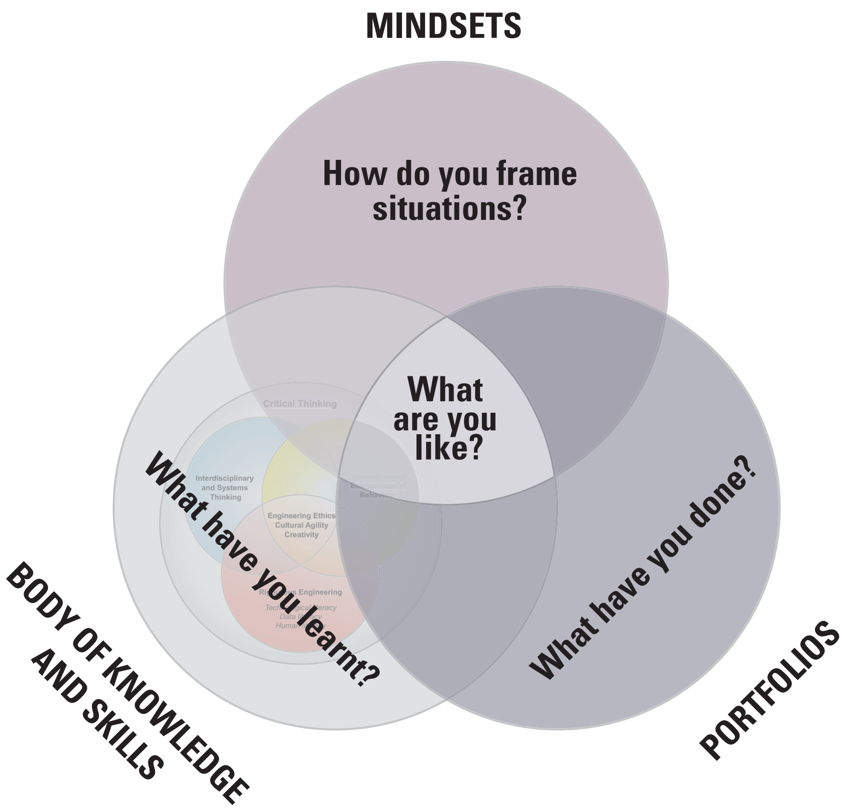

Figure 6 Engineering body of knowledge and skills, and mindsets in a curriculum make students what they are like

In our technologically connected society it is the people who matter the most. The literacy that is gaining prominence is human literacy. The more technological we get, the more we need people who have a broader framework. Developing algorithms for artificial intelligence may demand 20% effort by experts in terms of engineering, design and coding, but it takes 80% of non-engineering effort to get them implemented and accepted by society. Human literacy is about empathy, communication and the ability to connect people by putting relationships at the heart of the work, and about autonomy, agency, self-efficacy and emotional intelligence to function in the human milieu. These qualities are set to play an ever more critical role in the STEM field ("STEMpathy"). In an era where we seem to live in a "post-truth" world in which large engineering corporations are downsizing, the social contract is changing and the "gig economy" is expanding, the mastery of these skills help to instill the urgently needed entrepreneurial mindset.

Mindsets

Knowledge and skills alone are no longer enough for a successful career in engineering. This is particularly true once engineering professionals start to collaborate with intelligent machines that will do most of the heavy lifting in terms of data gathering, but at the same time will erode the free will, the spontaneity and creativity of the engineer. A successful career will depend on the mastery of the various literacies, and to an even larger extent on non-cognitive capacities such as consciousness, self-discipline, grit, the ability to face challenges and to overcome failure, and social skills. These are higher-order mental skills, personal mindsets and ways of thinking/beliefs about the world. They allow students to look beyond short-term concerns to longer-term or higher-order goals, and will help them to overcome challenges and setbacks in their pursuit of these goals[30]. All-round engineers with these capabilities are produced by educational programmes that are geared towards breadth on both a professional and a personal level[31].

Important mindsets in the domain of engineering are critical thinking, holistic and systems thinking, entrepreneurial thinking, interdisciplinary thinking, cultural agility, and value learning over knowing. These are non-cognitive thinking modes that cannot be imitated by (networks) of intelligent machines and that are unique to human beings. Other examples of mindsets to nurture in engineering courses are design thinking, the use of a data-driven approach, coalition building, taking the lead and playing to one's strengths, dissatisfaction with the status quo, a willingness to take risks and learn from failures, or simply a "getting things done" attitude.

The skillsets of technical literacy, data literacy and human literacy, and the mindsets demanded by the professional world are rapidly changing, faster than most universities can keep up with. With the emergence of deep learning and artificial intelligence in the engineering profession, robot-proof education has to teach people to think in ways that cannot be imitated or copied by networks of intelligent machines.

Changing Roles in the Engineering Profession in the Next Decade[32]

Predicting the future seems an impossible and futile activity. Well-intended predictions often become amusing quotes in presentations many years later[33]. And yet, by working together to envisage a course for a desirable "tomorrow", it is possible to formulate likely (but uncertain) answers to questions like "What should engineers learn in higher engineering education in 2030?", and "What professional roles will meet the specific demands in the job market in 2030 and beyond?"

These questions were the starting point for a Think Tank at TU Delft in 2015 that looked at societal and engineering trends, imagined possible scenarios of society and technology over a 15 to 20 year timeline, and explored the sort of knowledge and skills needed by academic engineers to survive and thrive in those situations.

Discussions about the profile of master graduates at research-intensive universities always demonstrate the tension between advancing knowledge, i.e. emphasising theory in a range of subjects (the research function) and developing highly qualified engineering professionals, i.e. preparing students for engineering practice (the teaching function). The dual nature of engineering education is about the delicate balance of analytical and professional competencies[34].

Logic and consistency in a ***research*** master would require students to learn to push the boundaries in engineering sciences. Graduates are prepared for research activities that emphasise the advancement of knowledge, or for the transformation of fundamental knowledge into applied knowledge for the subsequent use in engineering and the development of new technical products, systems and technologies. We can expect

Professional role	Main attributes	Pains and frustrations
Specialist 2.0	Deep expert knowledge Understanding impact of their specialism on the interfacing levels Innovating at the fringes of their specialism Collaborating with other specialists or in multidisciplinary teams	Respect for other disciplines; compromising; Language gap with non-experts.
Systems Engineer	Broad technical knowledge and business acumen Helicopter view; systems thinking Interdisciplinary teamwork (specialists, engineers, non-engineers) Human factor, agility and resilience	Deeper and narrower specialisations lead to a fragmentation of system knowledge and design work, which leads to more time and higher cost for system design and integration; Lack of systems thinking in specialists; Making of concessions.
Front-end Innovator	Broad knowledge in engineering and socio-economic factors Entrepreneurial attitude; disruptive thinking, scenario thinking, value creation Working in interdisciplinary teams of specialists, engineers, stakeholders Good social and empathetic listening skills	Intellectual property rights at higher TRL levels; Fast decision making due to short innovation cycles.
Contextual Engineer	Technically adept and understanding different realms Helicopter view, open mind Local and global thinking Good intercultural communication and collaboration skills Agility and perseverance	Moral dilemmas when maneuvering between personal and local cultural habits, norms, ethics and regulations

Table 2 Professional engineering roles with their main attributes, pains and frustrations

that these master courses prepare students for one of three research roles[35] (although in practice a clear-cut separation of the three roles rarely exists):

- Basic research specialist, who undertakes experimental or theoretical work, primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view;

- Applied research specialist, who undertakes original investigations to acquire new knowledge which is directed primarily towards a specific practical aim or objective;

- Experimental developer, who does systematic work that draws on knowledge, gained from research and practical experience, and produces additional knowledge, which is directed at producing new products or processes or at improving existing products or processes.

Although the goal of a research master is to prepare students for becoming research specialists with a fundamental knowledge of a single field of expertise, the programmes often ignore that 90% or more of their graduates will be involved in innovative engineering and design and entrepreneurial activities[36]. For which they need much broader professional competencies, such as interdisciplinary and systems thinking, and innovation and entrepreneurial thinking. Those are the qualities needed for the design and development of innovative products or advanced systems and technologies[37] in a company or in the gig economy. Many research masters offer only a minimal number of elective courses or extra-curricular activities to develop these competencies, and at best they include an obligatory internship at a workplace outside the academic learning environment.

The ideation of the TU Delft Think Tank yielded the insight that in future, academic masters will continue to promote specialisation in a single field of engineering expertise (Kamp, Klaassen, 2016). But on top of that, they will focus on a broader set of professional skills that are sought after in future engineering roles, which can be either academic or professional, research-oriented or aimed at innovative engineering or enterprise engineering. The Think Tank identified four specific roles that are likely to be in high demand in the next decade.

A description of these four roles by their main competencies, pains and frustrations can help to frame a master curriculum for future engineering students. It can also be used by students as a tool to navigate their individual study paths, and to make them think about prospective engineering professions at an early stage in their study. Finally, in interdisciplinary teamwork the roles can be used as a guiding principle for perspective taking, problem solving and mutual respect in teamwork: the Specialist 2.0, the Systems Integrator, the Front-end Innovator and the Contextual Engineer.

The personas description of each professional role starts with a different heuristic question:

- **Specialist 2.0:** "How can I advance engineering knowledge and optimise technology for innovation and better performance through research?"
- **Systems Integrator:** "How can I integrate disciplinary knowledge and subsystem expertise for a complete solution?"
- **Front-end Innovator:** "How can I apply knowledge and use technology to develop out-of-the-box solutions that cross disciplinary boundaries and create value for society?"
- **Contextual Engineer:** "How can I exploit diversity-in-thought in developing realistic and acceptable solutions that create value in different cultures and contexts?"

More specifically, the ***Specialist 2.0*** is able to use specific scientific knowledge to improve and develop complex technological systems and at the same time, works with non-specialists in order to integrate that knowledge into system and product development. They acquire expert knowledge and learn how to advance knowledge by research and experimentation, which is complemented by multidisciplinary project work. It enables them to see the big picture, to know which questions to ask, and which methods are relevant, and to coordinate cooperation between specialists in different fields of expertise. The broader view increases their flexibility and creativity.

The ***Systems Integrator*** is system-oriented and has a helicopter view of technological fields but can look beyond technology to understand the importance of a broad range of issues from restricted budgets and regulatory frameworks to public safety impact and the ethical aspects of engineering. As with the Specialist 2.0, the Systems Integrator is educated within a disciplinary department, while developing interdisciplinary and interpersonal skills in interdisciplinary projects that involve engineering companies.

The ***Front-end Innovator*** is an enterprising engineer with a broad knowledge of both engineering and socio-economic factors. They are able to design novelty products and understand the intrinsic interplay of business and commercial factors within the engineering and design process in a specific sector[38]. They have mastered future-oriented thinking and are able to work as an intrapreneur, an employee who works in the context of existing engineering businesses and industry sectors. They embody the entrepreneurial spirit of being innovative and constantly seek opportunities for improvement of things around them. They work in small intrapreneurial teams of specialists, systems integrators, design engineers, business managers, financiers, customers and end-users within a company. The Front-end Innovator has both a good understanding of

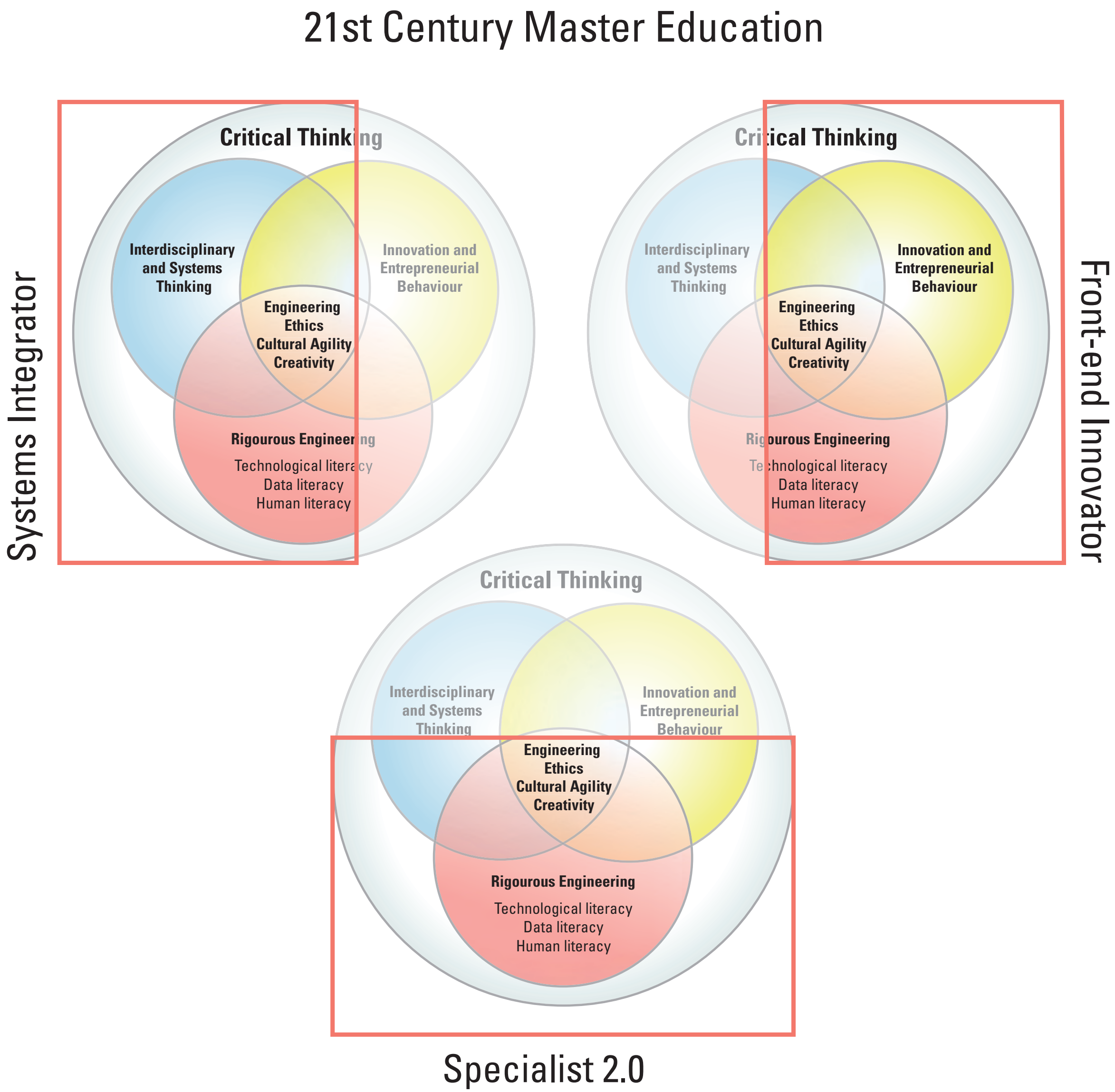

Figure 7 Three professional engineering roles projected on the key aspects of 21st century engineering curricula

the engineering context and thinks and acts in tune with the user and client. The disciplinary department provides the disciplinary education, while the innovation-business components are acquired during collaborations on interdisciplinary, entrepreneurial, and sometimes humanitarian design projects with actual clients and issues, and with students from other engineering disciplines and the humanities or social sciences sector.

The ***Contextual Engineer*** excels at understanding dynamic technological change within socio-cultural diverse contexts. Development teams within multinational companies make use of the diversity of cultures and socio-economic environments to benefit technological innovation, product design and engineering business. The Contextual Engineer needs strong intercultural communication and collaboration skills, along with an open-minded approach to operate in (very) different cultural, political, economic and societal contexts. Technically adept, the Contextual Engineer understands constraints and consequences from the ethical, judicial, disciplinary and policy perspective.

The four prototype professional roles have been enthusiastically tested in Western Europe amongst students, industrial and entrepreneurial stakeholders of multinationals in engineering business, small and medium-sized enterprises (SMEs), engineering and consultancy businesses and young entrepreneurs. The companies and entrepreneurs expressed a particular interest in (and had a high demand for) the Systems Integrator and Front-end Innovator roles. They appreciated and confirmed the shift in competencies needed for the Specialist in terms of sustainable employability, and warned that workers with highly specialised skills and knowledge usually face the most serious adjustment problems to change. They expressed doubts about the uniqueness of the role of the Contextual Engineer. Their competences would also apply, albeit to a lesser extent, to the other professional roles.

Shifting the Focus from Teaching to Learning

Learning to Know Who You Are

Kamp's 2016 report states[39] that the campus climate with its sense of community has become an important argument for students to join a specific university or programme. This sense of belonging is important for Generation-Z students and strongly influences their motivation performance in different learning environments. Gen-Zers want to be emotionally and behaviourally connected to a university or programme that has a transparent mission and a purpose. Engineering programmes need to help students cultivate this sense of belonging so they feel part of a committed academic community.

The Generation Z has grown up more slowly than previous generations and takes more time to adopt behaviours and environments that are associated with adulthood (see chapter Generation-Z students, a different breed). They also experience a great deal of pressure outside their studies and want to put energy into their social life and sports, earn money, and have a fear of missing out. Gen-Zers want to get to know themselves, to develop into citizens, define their personal professional profile, find a job, and be prepared to reinvent themselves during their careers. It helps when these students learn to identify where they would be in a world where humans come first, or in one ruled by innovation. What would happen if sustainability and social responsibility became the main drivers of society?

Campus universities need to shift their focus from student satisfaction to student well-being. A general sense of well-being, in combination with an open mind, enables students to unlock their full potential.

One of the solutions could be to allow students to delay early deep specialisation, and instead to expose them to self-directed problem solving and non-repetitive challenges in diversified student groups. These are great tools for them to develop a sense of the type of work that fits their abilities and inclination[40], and to find out who they are and where they fit.

Student wellbeing is an important factor in academic success because it stimulates the students to set (study-related) goals. Well-being triggers their intrinsic motivation by challenging them to think about who they want to be and what they want to achieve in their studies. In engineering programmes with jam-packed curricula and narrow trajectories, it is tricky to incorporate slow spaces that create a climate with time to reflect on and meet goals of developing self-esteem, social emotional skills, personal growth and well-being. It is particularly the social cohesion in the form of friendship groups or other forms of belonging that create a buffer against stress and loneliness. And although spending significant amounts of time with other students (in labwork for instance, or collaborative projects) is sometimes perceived as a drain on study time, it can actually be a remedy. Students on courses with many contact hours often have fewer problems than students in programmes that emphasise independent study.

Working hard is important, but not the only driver for success.

Learning by Creating Value

A major concern, it transpires from many sources, is that educational programmes in the domain of engineering sciences and technology do not align with the needs of today's professional arena, let alone the needs of tomorrow's uncertain world. It is valid to ask how interested students and employers will remain in higher education's traditional solutions. Generation-Z students, born between the mid-nineties and 2015, see themselves as a "customer" at university. They have been encouraged to act as consumers from an early age and have come to expect a high level of service in return for their engagement (read more in chapter Generation-Z students a different breed). They know they can't be passive and must take responsibility for their learning. It's therefore important that we encourage them to be conscious and teach themselves what they need to know in the face of ambiguously defined problems. Increasingly universities make students a change agent for innovations in engineering education or even strategic faculty development, see for instance the 24-hour DigiEduHack initiative[41], an EIT initiative under the European Commission's Digital Education Action Plan, to co-create the future of education.

Although Generation-Z students see themselves mainly as a customer, they also want to take part in the co-creation of educational services and are more open to emerging educational providers. A Master of Science degree may soon no longer be the only pre-requisite for the engineering professional world. What will happen when on-demand learning outperforms traditional universities in keeping their skillsets up to date? The job market has already started to assess the competency levels and personal traits of their future employees, based on portfolios of accomplishments at university level as well as in daily life. To be competitive in the job market students need to learn “job crafting” to market themselves (Can I do the job? Will I do the job? Will I fit in?). It is up to the student to show evidence of their individual learning.

The power of on-demand access to information is key to the next generation of learning. Generation-Z students have well-tuned strategies for where to go for what kind of information, They for instance go to YouTube to learn just about everything and prefer it to teachers, classrooms and textbooks. They listen to videotaped lectures twice the normal speed, and rewind when they don’t understand. They want control of their learning path, prefer unbundled courses to linear curricula in order to assemble them into individual pathways. They fuse the vast informational resources with their personal specific needs and desires. More and more people entering higher education have no desire to follow the beaten path. Perhaps universities have to anticipate future students spending less time in university classrooms, and coming back throughout their careers to update their skillsets with separate “knowledge packages”. This will require new forms of teaching, certification and administration. Courses may have to be broken down into snippets of less than ten minutes of concentrated content. Competencies have to be broken down to a granular level, so that staff are able to pinpoint very specific aspects of a competency in their teaching and assessment. Universities will have to assist their learners in finding and controlling their individual learning paths.

A major goal of higher education in the 21st century is to create a shift in learners’ minds - that learning is not just the acquisition of knowledge and skills, but a human quality and disposition to cope with an uncertain world, a complex life and a changing work environment. It requires pedagogies that focus on gaining skills to learn and relearn, and the agility to change perspectives. The current faculty-centred curricula, bound by existing physical spaces, staff resources, and time-restricted schedules, have to be transformed into (more) learner-centred purposeful curricula. Higher education institutions have to adapt to the changing customer needs of student experiences, the lived reality of the student and the challenges they face.

> *“In future, talent more than capital, will be the limiting factor in society”*
> *(Quote Prof. Flemming Besenbacher, Carlsberg Foundation)*

Impact-focused education accentuates experiential learning and is meaningful for students. It requires the accentuation of the relationship between engineering and society, where societal relevance is the centre of engineering. Curricula increasingly involve thematic studies across disciplines, human-centred and project-based learning with real-world connections, and integrate work-based learning. Learning in a scattered way outside the academic cloister is highly effective, but only when it is combined with student self-reflection.

In a 2018 MIT study[42] about the global state of the art in engineering education, Graham (2018) confirms that five themes that are well in line with impact-focused education are becoming increasingly prominent:

- Student choice and flexibility (educating students in the profile that is more oriented to their ambition, aspiration, future career);
- Multi- and interdisciplinary learning (in collaborative design or applied-research projects);
- The role, responsibilities and ethics of engineers in society (solving human challenges and problems facing society);
- Global outlook and experience (working across nationalities, cultures and disciplines);
- Breadth of student experience (more choice, learning beyond the engineering disciplines)

Impact-focused learning can be achieved by a connective spine of active, project-based learning about authentic subjects, possibly citizen-science projects. They require compelling design respectively research questions whose potential outcomes have relevance and meaningful impact. This spine of design projects is one of the effective practices proclaimed by the CDIO Initiative. This worldwide initiative (www.cdio.org) is a comprehensive framework for modern curricula that has been adopted by more than 160 universities all over the globe.

Master curricula prepare the students for innovative engineering activities. These activities often cross disciplinary boundaries. A reliance on linear monodisciplinary skillsets restricts graduates' ability to connect with colleagues in the workplace, as so many fields become augmented with technology and more interdisciplinary. Bachelor capstone projects and master theses shall therefore not only be academically interesting but also impactful. They shall not only involve feasibility (engineering, technology, creative problem solving), but also viability (business, economics), operability and desirability (psychology, arts, humanities). Innovation should run like a thread through the fabric of all modern master curricula. Learning how to advance Technical Readiness Levels (TRL) when innovating products, systems and processes is not enough. Students have to learn how to develop new engineering knowledge within the interdisciplinary context of stakeholders, companies and (changing) regulations, in an environment where socio-economic drivers act beyond today's business drivers. Ultimately, the things engineers design and produce are used by humans and need to be of service to society.

"We need to develop realistic teamwork, not heroic individuals"

Learning to Become a Socially Responsible Engineer

Universities have a moral and ethical responsibility to develop and facilitate the use of the new technologies that emerge from the Fourth Industrial Revolution, to empower society, particularly with regards to social change and social justice. The European Union calls for the integration of the social sciences and humanities with science, technology and engineering[43]. Today's engineers need the social awareness, necessary to satisfy disparate groups with different moral views and objectives[44]. Understanding the effects and impacts of science and technology on society and the environment is important, both as an engineer who is using science and technology, and as a citizen who is living in a society and who has profited from and been affected by science and technology. Students have to learn to comprehend the positive and negative influences that the outcome of their prospective profession can have on human society and the natural environment.

New systems and processes can have profound and unexpected impact on people, their behaviour, employment and environment. In the 18th and 19th century there were many examples where workers targeted new technologies and machines they considered to be the cause of their misfortunes[45]. Other examples are urban planning and architecture that shape people's surroundings for better or worse, or safety that is slightly compromised for the benefit of a more sustainable solution. There can be no doubt that today's and tomorrow's machines, gadgets and digital technologies and devices impact people's behaviour and wellbeing, and that education should make learners aware about the effects of technology on people's physical and mental health.

Other examples are the risks and vulnerabilities associated with the embedding of complex networked software systems in society in relation to a reliable and secure operation of software, the power of data science and AI, and secure communication. New computational techniques such as machine learning make it more difficult to understand the functioning of the software, while the high speed of development of novel techniques makes it difficult for businesses and policy leaders to keep up. The increasing power and pervasiveness of digital technology in every aspect of our lives means that risks that are not managed responsibly, can cause society great harm. It demonstrates why computer scientists and software engineers have to be able to take the responsibility of identifying potential risks of the technologies they use[46]. Engineering and design are obviously intrinsically value-laden and require ethical reflection[47].

Integrating a set of basic ethics competencies with an "ethics-across-the-curriculum" approach, where students learn to reflect about, evaluate and assess the ethical and societal impact of their work, is necessary at the bachelor as well as the master stage. It places the students in a position to decide and act responsibly with regard to the sustainability-oriented product development, safety, economic, and social welfare aspects of their work. The best learning gains are achieved when these responsibilities are integrated throughout the curriculum, as a crosscutting concern that is addressed in the immediate technical context of respective courses. The societal impact of a specific discipline is best understood in the context of the underlying technical details.

At TU Delft, all students take mandatory ethics courses that are either tailor-made for their discipline or run like a thread through their programme. In the latter case, ethics learning goals are integrated in technical courses or in a couple of thematic ethics courses that students from various disciplines can choose from in line with their personal interest and ambition. Examples of themes that are used for these interdisciplinary courses are geoengineering and space ethics, climate ethics, water ethics, energy ethics, computer ethics, ethics of healthcare technologies, risk and safety ethics, biotechnology and ethics, ethics of transportation technology and logistics, and science ethics[48].

This approach has been developed by the Ethics and Philosophy of Technology Section of TU Delft in collaboration with colleagues from the engineering programmes. In 2019 they initiated, under the umbrella of the 4TU.Centre for Engineering Education, a two-year research project to discover the 21st-century's ethical needs for engineering programmes, extended beyond Westernised content. The project is furthermore aimed at developing approaches on how to integrate ethics education meaningfully in disciplinary study programmes, as an integral part of the training for engineers and designers. The research will serve as a model that can also be followed by other universities worldwide. More information about the pioneering work in engineering ethics at TU Delft is available at www.tudelft.nl/ethics/.

A set of basic competencies, taken from TU Delft practice, consists of:
1. Moral sensitivity: identifying social and ethical issues in design, engineering and technology;
2. Professional and social responsibility: applying relevant codes of ethics; identifying the professional responsibilities of designers, engineers and students; living by these responsibilities; analysing situations in terms of responsibility distributions and allocating responsibilities;
3. Value-sensitive design and responsible innovation (moral creativity): a systematic analysis of relevant stakeholders and values, addressing direct and indirect stakeholders (anyone who could be affected by the development or use of a given technology, product or service (who is affected?), the identification of potential benefits and harms, and implicated human or social values (how are they affected?); trade-offs between values and if and how the potential harms can be designed out (what to do?);
4. Moral analysis skills: analysing the (moral) impact of engineering work and technical designs in terms of facts, values, stakeholders and their interests and responsibilities;
5. Moral judgement and decision-making skills: identifying the ethically relevant elements in different assessment tools and frameworks that are used in design and engineering (like cost-benefit analysis and risk assessment); making a decision in a given context, based on a reflection on different moral frameworks including professional ethics and common sense morality; morally justifying one's actions in terms of the mentioned ethical theories or frameworks and a reflection upon them.
6. Moral argumentation skills: discussing ethical issues with other engineers and non-engineers, reconstructing arguments in terms of premise and conclusion, identifying fallacies, listening to and taking the arguments of others seriously, including those of non-engineers.

With the advent of artificial intelligence in our education, privacy and other ethical concerns will be a challenge of a different nature. In 20 to 30 years' time, will intelligent machines be as effective at teaching moral values as humans? What about the machines that interact with students, that have information about students' strengths and qualities, their personality traits, and their vulnerabilities[49]? Our education has to


Ethics
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give more consideration to the ethical aspects of artificial intelligence and the putting in place of adequate oversight mechanisms in order to prevent artificial intelligence from being misused or from behaving in unpredicted and potentially harmful ways[50].

"AI will open up a Pandora's Box of ethical questions and we are a very long way from resolving them" Quote Anthony Seldon in his book The Fourth Education Revolution

In this age also the learning of the differences between experiment and simulation, between facts and norms, between scientific necessity and human choices is getting increasingly relevant. There is an increasing demand for the kinds of skills the intelligent machines are not good at: asking questions and thinking outside the box. This makes critical thinking, which is about asking intelligent and critical 'why'-questions, and understanding the sources and consequences of differences of opinion, the most important attribute socially responsible engineers shall have. Throughout the bachelor and master studies, students have to be trained in sound argumentation in engineering and societal matters, especially if it concerns the impact of the introduction, maintenance or tidying away of technologies[51]. Students have to be provided with skills and techniques to assess positions regarding these impacts, and produce balanced and defendable positions.

Learning to Innovate

The creed of modern industry is ***"Innovate or be history"***. The habitat of almost all engineering graduates is obviously in innovation, where understanding the customer and truly caring about their needs and experience is essential. Successful innovation lies in the ability to understand "what people will do with technology", and not "what technology will do to the people" [52]. Innovators need a people-centred mindset that goes way beyond technical expertise. In his 2016 report, Kamp identifies innovation, alongside employability and community, as one of the three cornerstones of future-proof higher engineering education programmes[53].

Innovation is about ***novelty and impact***, about meaningfulness, desirability and viability. It is the emerging key competency for engineering graduates and should run as a red thread through the fabric of the master. An interesting example of immersing engineering students into innovation has been implemented at the Skoltech university (Moscow)[54]. All its first-year master students enrol in an intensive one-month full time entrepreneurial boot camps, the Innovation Workshop, to instill an entrepreneurial spirit for the rest of their studies.

Engineers are best prepared for a leading role in innovation when they have learnt a high tolerance for ambiguity and have a good mastery of technical knowledge from peripheral domains. In their academic studies they will have learnt to connect and synthesise disparate pieces of information from different sources in new ways[55]. This is achieved by piquing their broader interest in learning environments in which they communicate and collaborate with various individuals who have technical expertise outside their own discipline. Not being made to follow a simple narrow discipline-focused trajectory in their curriculum, but having sufficient "sampling" time is crucial. Trying things out is the answer to finding one's talent. The more contexts in which students learn, the better they become at applying knowledge to new situations, and the better they see how their education fits into their overall learning trajectory and the labour market. Expert knowledge and skills, acquired in a narrow trench of a discipline, are not easily transferrable to designing solutions for tricky problems or innovating technologies in an uncertain context of the VUCA world. Only when we are prepared to deemphasise some of the deep and narrow specialisation in master curricula to free up space for learning in different contexts and making connections across other domains and ideas, innovation truly becomes part of a curriculum.

It is important ***not only*** to teach how to design and develop new products or systems, generate new knowledge or transform fundamental knowledge into applied knowledge for subsequent use in engineering. Two reports by Smulders et al (2018, 2019) state that it is also important to teach the ***process of technological innovation*** to our engineering students, to train them in how to innovate products, processes, systems and technology. This is all about value creation through the use and integration of various disciplines into joint solutions to complex problems, continuous experimentation, and the ability to find new patterns between cause and effects and the connections between multiple fields, where these patterns and connections have never been found before. So not only should we address innovations from the perspective of existing and codified technological knowledge, i.e. developing new products that work with existing and proven technology. It is equally important to address the development of new product ideas with new technologies, to consider what technological innovation is and how it unfolds over time in real life[56]. In this context we should discuss examples of innovations that have not paid off, but did enable the development of follow-up products that would not have been designed without the 'failed' intermediate step.

Almost all innovations with new technology require further development until their maturity reaches a level of readiness, when practice is able to use the new technology to design, engineer, build, maintain and dispose of the objects[57]. This type of innovation usually follows a ***technological innovation journey*** with numerous cycles of trial and error in science and in practice, with involvement and contributions of various disciplines and stakeholders. Integrating the perspective of such technological innovation journeys of the past in courses and design projects, brings the process of technological innovation to life and is input to scenario thinking.

Learning about Professional Engineering Cultures

Students are usually inspired to collaborate in teams that comprise different cultures, generations, physical locations and disciplines, preferably in collaboration with humanities and social sciences. In these environments they learn to transfer their scientific and engineering knowledge to the infinite contexts of real life. Students become aware of their own language, tacit knowledge and blinkered perception by seeing through the eyes of others. Connective spines of innovation, design or applied-research projects in curricula bring together students and staff from diverse disciplines, non-academic stakeholders of engineering business and NGO's. They stimulate community building and move towards more outward-facing curricula with impact. It is an important broader benefit of university life for the students to meet in physical locations.

As mentioned before, curricula in research-intensive universities often have rigid structures and leave little freedom of choice for the student. They force students to study subjects outside their prime field of interest. Many of today's master programmes are unduly scientific and theoretical, short-sighted and overly specialised. They fail to educate students in understanding the larger contexts, securing an interdisciplinary perspective, and they lack the opportunity for students to reflect or get to understand themselves. This understanding is crucial to build on and to find - or preferably - to create a new job when theirs disappears. The trend toward ever deeper specialisation and solitary work in the master degree programmes shall be overturned (read more in chapter Agile programmes). It unintentionally prevents talented students from reaching their leadership potential[58] and undermines the development of an innovator mindset[59]. Society wants research universities to create engineers who contribute to economic development and growth, are aware of real-life constraints like quality, risk and safety, and who understand the factors behind commercial success.

"You cannot understand or solve complex problems without the knowledge and tools of multiple disciplines"

Another important driving force for change is found in the need for multi- and interdisciplinary learning opportunities with student-led choices. As education shifts from standardisation to customisation, there need to be plenty of opportunities for students to personalise their graduation profile and pursue their own ambition and interests (see chapter about Agile programmes). In these learning environments it is the student who defines their personal learning goals and outcomes in relation to these projects, and determines how these will be achieved and reported on in portfolios throughout the entire study programme, with possible extracurricular experiences as well. The rise of the gig economy and the decline of lifelong professions are leading some young people to wonder if the three- or five-year linear campus curriculum is still worth it. Portfolios with a synthesis of accomplished skillsets and mindsets may soon be as important as university diplomas when looking for a job. The portfolio is a testimony to what a young graduate can offer future clients and employers.

The demand for differentiation is growing, not only from a student's point of view, but also from the job market. When properly integrated in the curriculum, the different roles in the engineering profession[60] that are geared towards future professional needs, may function as a magnet on and a guide for students. Engaging the students with specific roles they may play in their future profession in real-world open-ended complex problems, makes them adventurous, develops their self-efficacy, motivates them to take ownership of their study, and helps them to develop into leaders in society, not just engineers. Alternative schemes of non-formal differentiation may be found in digital badges that are a visual record of achievements and experiences. They acknowledge non-formal learning and education achievements, such as volunteering, activities in a particular student project, membership of a student body, extra-curricular courses or research activities, transfer of knowledge and experience, competitions and contests.

Learning to Fail, not Failing to Learn

We all know we are going to fail every now and then, so we'd better learn how to do it better. So why not reward students for (learning from) failure? Although risk taking and experiencing failure is not an objective per se at Google, this company explicitly promotes failure as a crucial part in its innovation process, and rewards people for it[61]. This is exactly what the more risk adverse Gen-Z students need, to take risk and be open to learn from failure. It is unfortunate that the academic culture has stigmatized failure to the point of instilling fear in students and putting the focus on passing tests and exams instead of learning. In academia, failure has a largely negative connotation. It influences how teachers use the words fail and failure and create failure experiences for their students. It would be better to replace "learning to fail" by "learning to understand failure".

Learning to understand failure is very important for engineering students, or anyone for that matter. It motivates to ask questions, to learn how to integrate feedback, change unproductive habits, and come up with innovative solutions. For a student a frank reflection on their contribution to failure is difficult, but necessary. There are usually many factors but the only ones they can control are those that involve their behaviour. They will learn to think about what they could do differently next time.

Understanding failure is directly related to taking risks. Innovation requires risk taking, trying something new, and possibly failing[62]. Engineering is all about transparent risk governance, identifying and acknowledging risks, experimentation and risk mitigation. Similar to learning about technological innovation journeys as described in the chapter Learning to innovate, learning to understand failure helps students to see learning as a personal journey rather than a matter of external performance only, in their studies, and later in their engineering practice.

It is important to discuss openly how each person contributed to failure and to develop an understanding of how failure is caused. Guest lecturers and coaches from the industry could talk about workforce issues. Case studies examining start-ups' high percentage of failure could also provide interesting insights into learning from failure. In discussions, students have to learn to focus on their own actions, to listen and avoid being defensive or apportioning blame. They need to remember that very few people act with the intention to fail. It is crucial to provide safe spaces where students can be empathetic and supportive when sharing their contributions, and where they can talk and write about what has been learned. This culture allows everyone to benefit from failure and makes these discussions more common, conventional, and constructive.

It is furthermore important for students not to rush into finding another solution, but to first explore the failure instead. In engineering practice there is a culture where learning from mistakes and failures is facilitated. In "after-event" reviews organisations make expert teams available to build capacity among staff to discuss and analyse what went wrong and why. In these exploration and failure analyses, the four key questions to be answered are: Why has it failed? Where did the failure develop? Why did it happen? How did it happen? Using a systematic approach like this helps us to understand failure, prevents it from happening again, and helps to design better solutions.

Learning as Inquiry

At many universities, traditional teaching-based education is treated as a series of steps to master, where the goal is to learn as much as you can as quickly as you can. Alternative learning-based education makes use of ubiquitous internet access and search engines at almost infinite speeds that enable the acquisition of knowledge about almost everything. Learning-based learning can be messy, social (learning with one another) and playful. It brings information and experimentation together and fuses the knowledge with the students' personal needs, desires and ambitions.

In the next sections we will discuss two examples of learning-based education: challenge-based education and making-as-learning. In both learning environments the student(team)s take full responsibility and ownership, which turns out to be a key success factor[63]. Their learning process is organic, it is not ***about*** solving problems about the world, but about defining the problem and designing solutions through engagement ***within*** the world. In both cultures it is the ***process*** that makes learning interesting and intrinsically motivating. Knowledge is reframed from a ***what*** question ("what is the information?", "what is it that we don't know yet?") into a ***where*** question ("where do we find information and what is the context?"). The role of the academic staff is to coach and advise the team, not to drive the engineering/design/research process or suggest solutions[64].

Assessments are not about the knowledge that has been successfully transferred, but about embracing the things students don't know, about understanding which questions are the better ones to ask, and how to ask them in order to learn more. This style of learning is called ***inquiry***. It is about asking the right questions about the things we don't know, in a continuously shifting context.

Challenge-Based Education

Students are intrinsically motivated to learn when they feel passionate and have the freedom to operate in a self-directed way within the constraints of a well-defined problem. Generation-Z students are highly motivated by working on real-world challenges and contributing to important goals, i.e. making an impact on the outside world. In challenge-based education, students learn new technical knowledge, or transfer disciplinary knowledge to a different context through the lens of practical, complex and volatile problems. It builds on the practice of problem-based learning in which student teams work on a well-defined design, research or diagnostic “problem”. Learning takes place through a structured process of working out the solution.

Challenge-based education is demanding. Only when students have learnt enough of their science discipline, they are ready to do science. Designing holistic solutions for open-ended multi-dimensional problems requires insight in deeper structures and the ability to transfer principles and methods from the own discipline to a different context. These competencies are usually not attained until halfway through a master programme.

The key asset of challenge-based learning is that it adds relevancy through impactful engagement with the outside world and a call to action that requires students to make something happen[65]: solutions are not only proposed as concepts but implemented as well.

Learning in challenge-based education: “Taking your knowledge and skills to a place that’s not doing the same sort of thing”

Challenges are “harder” than routine problems in problem-based learning: The starting point is an unstructured and extremely open-ended problem that has to be unravelled by generating a wide variety of key questions, discussion points and research. These steps make learning more challenging and slower, at times frustrating in the short term but more profound in the long term. The challenges are inherently interdisciplinary, but it is unclear on the outset which disciplines are needed. And the variety of disciplines obviously allows for a variety of solutions. In this situation, teams of students who have back-grounds in different technologies and who are able to tolerate ambiguity are much more likely to make a splash in solving problems than teams of similar-minded excellent students who have deep knowledge in the same field of expertise.

Key in designing creative solutions for complex problems is making analogies with past, real-world projects and consulting outsiders from other disciplines and (non-academic) organisations who have worked on a wide variety of technologies and used different approaches. The greatest strength of the teams is not their combination of narrow specialisations, but the ability to integrate broadly. The work not only focuses on the technical feasibility but also on the operability, economic viability and societal acceptability[66].

High ambitions about results are combined with a constricted time frame because students have to learn to meet hard deadlines and accept compromises by understanding and respecting arguments from other, possibly non-engineering disciplines. After arriving at a solution, students assess the outcome and provide a rational explanation for future steps. Thus the work asks students to reflect on their learning, to see how their teamwork is influenced by their own behaviour, to share their experiences, discuss the impact of their actions with academic and non-academic stakeholders, and present their solutions to a layman audience. As such it mirrors a 21st century workplace.

An element of competition may incentivise students to come up with visionary approaches, whilst still aiming for practical solutions. The key driver always needs to be the positive impact on society, not the winning of a competition.

Intended learning outcomes include the integration of knowledge and skills from different disciplines to do with conceiving, designing/research and analysis, and, at times, also prototyping, building and testing. Other learning outcomes are teamwork, (intercultural) communication and pitching, project planning, self-leadership, customer-awareness, reflection on critical factors, and understanding ethical, economic, and legal issues.

Project work in challenge-based learning can be enriched by scaffolding workshops[67] about design thinking, interdisciplinary collaboration, engineering ethics, innovation pitching, value-creation, agile project management (scrum), asking the right questions, leadership, prototyping and craftsmanship, etcetera.

In a challenge-based approach, staff has very limited influence on the precise content of a project[68]. Students take the responsibility to shape their own "living lab" and find the experts they need in the cross-disciplinary academic and business worlds, and in the wider community. In this way, they take on the role of change agents and connect what they are learning with their own experiences. Multi-dimensional problems by definition do not map to most academics' narrow field of expertise and fall outside their perceived responsibility[69]. Challenge-based projects can also be very dynamic with sudden unexpected moves.

Challenge-based learning therefore asks for a different kind of coaching and guidance from academic staff and industrial mentors. They are the side coaches in the classroom, allowing students to take the lead. The pay-off in terms of student engagement and satisfaction, and the spin-off benefits for the university can be high. At completion, students identify more strongly as engineers.

Since students in challenge-based projects follow a ***Let go and grow path***, learning outcomes cannot be detailed in advance. Assessing the achieved learning outcomes and awarding academic scores is therefore not straightforward. The traditional linear method of assessment of individual performance through rubrics proves less appropriate for measuring what each individual student has learnt. But performing in challenge-

based education without assessment could easily cause a movement away from the methodologies that have been adopted in accredited engineering programmes.

In challenge-based education the circular assessment model, known in industry and leadership circles as 360-degree feedback, is appropriate. Assessing the connection between the solution and the challenge is useful, including the solution's scientific and societal consequences (economic, social, cultural, environmental), the accuracy of the content, the clarity of communication, the likelihood of implementation, and the efficacy of the idea[70]. Then the process individual students and teams went through in working towards a solution, should be assessed. This captures the development of key skills like the ability to switch perspective, to independently apply theory and knowledge to design, to analyse and validate the solution, to collaborate and communicate in an interdisciplinary team, to plan and control the project efficiently, to demonstrate behavioural competences and skills, and to write concise reports and present to the community.

Making as Learning

The more modern universities have started to base their engineering programmes on three pillars: more self-directed, project-based curricula; flexible and innovative classrooms that focus on experiential learning; and more hands-on learning opportunities. These developments have come as a response to the demand by Generation-Z students who want to be exposed to the actual challenges and advancements of the industry and focus on real-world application of skills. It helps to narrow the gap between the academic and professional environments.

Universities have started to create learning and makerspaces (mostly machine-driven locations), in which students explore, experiment, and build their own projects by having the right facilities and tooling at their disposal, and the opportunity to meet, co-participate and ask guidance from academia and industry.
At the heart of every engineer is a maker-instinct! The maker movement is about the joy of exploration, about knowledge, and making and play. It is the hands-on and heads-on learning environment that really stimulates student investment in learning, because exploring, experimenting, playing, and making allows students to discover what is important to them, and what it is they actually want to learn. Which is crucial, because they learn best when they can follow their passion and let their imaginations run free.

> *"Hands-on discovery is an important part of knowledge development and a key creator in sparking a desire for learning"*

Creating is the most complex cognitive process in Bloom's Revised Taxonomy. The best way to learn is by creating, making, developing, exploring, trying, failing, and analysing the mistakes and failures, while making use of all tools and facilities the engineer has available.

Besides the benefits of intrinsic motivation and deep learning, makerspaces can also be a powerful expression of an institution's image and a unique selling point to attract students to a campus.

"Mindsets in curricula shift from "learning knowledge-as-a-thing" to "learning knowledge-for-purposeful-application"

Makerspaces create ownership of learning processes, even if it is not perfect (the "IKEA Effect": individuals value their own creation, even when flawed, more than those of experts)[71]. Makerspaces will become even more important when educational programmes evolve into a blend of off-campus, personalised online learning and hands-on experiential learning. But framing impactful experiential learning in regular curricula is still a challenge. It requires a mind shift in management, teaching staff, administrators, organisational bodies, and students as well.

Makerspaces are ideally placed to encourage students to adopt a holistic way of thinking that challenges conventional ideas and integrates fresh ones. They can really stretch and challenge students as they learn to alternate between the abstract and the precisely detailed, to deconstruct big problems and model real-life situations by simplifying assumption. They do this in fluid relationships that are a result of shared interests and opportunities.

The spaces themselves have to encourage creativity, give students a great deal of freedom, and provide conditions for invention. Increasingly students want to embark on challenges that relate to meaningful real-world problems or research questions that are expected to have a palpable impact on society. In multidisciplinary teams of students, staff and external partners they pursue creative and innovative answers to the world's challenges and open-ended questions.

As discussed in the Challenge-based education section, discussions about assessment of experiential learning in maker, or other, spaces and in circumstances that reflect real-life engineering situations ("BYOD[72]" exams for instance) are cumbersome. In today's test-obsessed culture we tend to measure the quality of intellectual development in the number of credits achieved and marks scored. But these are seldom an inspiration to further understanding and learning.

Makerspaces add more value and impact to learning outcomes when students take full collective ownership of the makerspace[73], and when tests and marks are replaced by portfolios that are reviewed and assessed by their peers. This way, students experience other perspectives and can compare these to their own. This approach will teach students to define personal learning objectives, write a portfolio of accomplishments and provide feedback to their peers. It will make them understand the importance of skills, get a better grip on their personal and professional development, and develop a habit of continuous learning. In engineering practice engineers learn from (senior) colleagues as well. Why not incorporate this dimension in our teaching through peer feedback for and by students?

Makerspaces are often linked to entrepreneurial environments in which teams of students develop and prototype their ideas. In these spaces students learn to remain flexible and to be prepared for constant change, be it organisational, technological, social or other. Based on specific coaching, start-ups can emerge or students are confronted with the life of a real company, with convincing investors, structuring a good business plan and adapting to an already existing market.

Makerspaces exist in different forms and sizes: they can be student-led or staff-driven, used within curricula or for extracurricular free experimentation, and facilitate single or multiple technologies. The Massachusetts Institute of Technology (MIT) Media lab was the first to establish makerspaces in higher engineering education. In 2002, they created Fablabs with equipment for students and staff to tinker and engineer their "product" solutions. It has resulted in a network of more than 1000 fabrication spaces in almost 80 countries[74].

The Singapore University of Technology and Design (SUTD) owns one of these Fablabs and a number of satellite Fablabs. Their website[75] reads "these labs allow students to design and build virtually "almost anything" with high-performance machines such as laser cutting and engraving systems, 3D printers, plastic injection moulding machines, vertical sanders, water-jet machining centres, vertical injection moulding machines, etc. Faculty, researchers and students are able to access valuable expertise and resources to transform their creative ideas into tangible products, and eventually, into meaningful outcomes and innovations to serve societal needs. The Fab Lab supports SUTD's strong interdisciplinary design-focused pedagogy that emphasizes theory and practical work." Their website lists various other makerspaces, such as an Innovative Digital Arts Lab and an Automation, Robotics and Mechatronics Studio.

"Knowledge comes from book knowledge and knowledge that comes from experience. Often knowledge developed through experience is what encourages us to go back to the book to figure out what's happening. Experience is our living textbook."

In 2007, Delft University of Technology (TU Delft) transformed an existing workplace of about 300 m^2 into the fully equipped, completely student-led D:DREAM Hall [76], a home for more than 400 students in the 12 student D:DREAM teams (D:DREAM stands for "Delft: Dream Realization of Extremely Advanced Machines"). A makerspace at TU Delft of a very different nature is a VR-Lab of about 40 m^2 for about 10 students. It offers opportunities to design for virtual reality. Another, the Collaborative Design Lab, is a state-of-the-art facility equipped for joint distributed teams who work with a network of computers, multimedia devices and software tools. It allows a team of students, academic staff and industrial experts from several disciplines, distributed all over the world, to design complex systems and advanced machines by applying the concurrent engineering method. The lab facilitates a fast and effective interaction of all parties involved and makes optimal use of multi- and interdisciplinary knowledge-based engineering, visualisation techniques and hyper-connectedness inthe digital engineering world. Rapid prototyping, i.e. the making, is not (yet) part of this lab.

Another leading example of a makerspace is Case Western Reserve University's Sear's Think[box] in Cleveland. It is a seven-story 4500 m^2 ecosystem of innovation for approximately 5000 unique users each year. It has gathering places for brainstormers, multimedia meeting areas, top-of-the-line prototyping tools, a high-tech workshop with metalworking and woodworking equipment, project spaces for formal student groups and design competition teams, all kinds of resources for turning an invention into a market-ready product, and last but not least incubator office spaces, faculty expertise and mentorship.

Diversity in the Classroom

Female Graduates as Ideal Candidates to Hire

Many countries in Europe have a low percentage of female engineering professionals and academic researchers. Engineering and technology have earned themselves a reputation of being a male bastion. We seem to forget that without the input from women, engineers have access to only half the total pool of creativity. We all know that we need varied, at times even conflicting, mindsets to come up with innovative ideas. No technology works optimally if fifty percent of the innovative capacity is excluded.

> *"If you want your company to be successful, if you want your company to operate with wisdom, with care, then women are the best"*
> *(Quote Jack Ma, Executive Chairman Alibaba, at the World Economic Conference in Davos 24 January 2018)*

And it is not only half of the creativity we are missing. How can commercial businesses be successful in understanding trends in customer needs, and in discovering new market niches, when they don't understand or have the skills to empathise with the female perspective? How can we be sure that learning machines, using complex algorithms that sort and sift data, are "colour-blind" and do not discriminate according to gender, race, political background, etcetera, when they are developed by a subgroup of individuals who all have the same background? Only 22% of the world's AI professionals are women[77]. It is a driving reason as to why women should become key in the development of algorithms for AI.

For too long traditional engineering studies have presented themselves as studies that recruit the best brains in mathematics and science and shape them into problem solvers who wear hard hats and work on-site.

Content in techno-science is mostly articulated in a ”subjectless”, reductionist mode that favours certainty, objectivity, distance and is non-relational. It makes engineering education masculine and hard to analyse in relation to gender[78]. Whilst female students want context and interactive and relational training, non-relational teaching is pretty much the norm in engineering academia.

“Integrating the knowledge and perspectives of gender and diversity studies as central approaches into engineering research and teaching as chance to foster social responsible research and innovation in technology”
(Vision Prof. Dr. Carmen Leicht-Scholten, Gender and Diversity in Engineering, RWTH Aachen)

Women, more often than men, want to become socially responsible engineers who solve major problems, and come up with design solutions that make a difference in people’s lives. They are interested in engineering work that is “socially conscious”. They feel, more than men, attracted to “purpose” and are less inspired by developing highly advanced instruments, optimising product or system designs, doing research without having the user or application in mind, and without any visible impact on society.

Sooner rather than later, engineering shall be reframed in a purposeful and creative profession that resonates with everyone’s interests. There will be an emphasis on engineering as a social activity, a shift from nerdy technology to contact and empathy with customers and colleagues. Any new technology, system, building or infrastructure we see in our daily world is the work of a team of engineers, customers and end-users. Rather than thinking of engineering capabilities as gender-related, engineering is highly person-related. Because women spend more time on social integration than men and perform better in interactive and social settings, they have adjusted better than men to the increasingly interactive world of work[79]. Women tend to outperform men on numerous leadership competencies, leaning towards inclusive leadership styles that improve the performance of diverse teams. Increased gender diversity is also connected to greater ethics and compliance, and women in leadership roles have been linked to increases in innovation and group performance, and greater effectiveness in solving difficult problems[80]. Since women are more adaptive to change, they are more suitable for the digital transformation and therefore the preferred engineers of the future.

In STEM fields, where purpose, relevance and social integration play a major role, female students often dominate the student population. For the more nerdy engineering disciplines the dominating population is male. We’d better aim for a balance in gender and a diversity in backgrounds so creative and innovative solutions are not only the most advanced in function or performance, but also acceptable to the customer and society at large.

Taking the accelerating pace of the changes in society, technology and student population into consideration, educational leaders may have to prepare to remedy big shifts in student populations, even in the traditional engineering disciplines. Soon they may have to mitigate a dominance of female students because of a sudden rise of female enrolments and an unexpected drop in males.

Generation-Z Students: a Different Breed

Universities, where mainly 18- to 25-year old students learn and live, are always on the frontier of generational change. In the changing landscape of higher engineering education, it is crucial to keep in mind the realities in which modern learning occurs, including the habits, behaviours and preferences of the students. The modern learner expects content that is consistent with the new format of digital learning, namely short, relevant, contextualised, personalised, available on their mobile devices, and committed to the learning goals that are relevant for their life and prospective career path.

"They are too busy messing with their iPhones, that have become a prosthetic part of Gen-Zers"

Generation-Z (Gen-Z for short) is the generational cohort born between the mid-1990s and 2015. They are the first generation comprising only of digital natives. From their earliest youth they have been exposed to the internet, social networks and mobile systems. They are so attached to technology that they don't necessarily think of it as such. Their life is a life lived online. This generation, also indicated by the iGen, sees technology as an extension of themselves to communicate, deal with friendships, shop for good value, consume information, portray personal identity, and learn. Never before has there been a generation so globally plugged in and so well informed. In 2019 18- to 22-year old Dutch teenagers on average spent 230 minutes[81] a day watching a screen for social media, gaming, texting, and browsing the internet! An estimated 96% of this group owns a smartphone, and for them email is ancient, and even old-school texting is getting less popular and is being supplanted with mobile video and image-based communication[82]. Voice and meetings are only for emergencies. Students in this generation are used to spending more time on their devices and social media than they spend in face-to-face encounters. Cryptic messaging keeps them in touch with one another but not close. It means they are technically very well connected but almost disconnected from human relationships.

The first wave of the Gen-Z generation has arrived on campus. They are a different breed to and definitely not a simple extension of the millennials who were born between 1980 and 1995. Gen-Z is tech-savvy, cosmopolitan (they feel European yet live in the Netherlands), fiercely independent and individualistic, engaged and realistic about the challenging world. They are very comfortable with collecting and cross-referencing many sources of information and with integrating virtual and offline experiences. They are less certain about dealing with failure and competition, are less risk tolerant, even more distracted than the millennial generation and eager for money[83].

An in-depth study of teenagers in the US by psychology professor Jean M. Twenge of San Diego State University shows trends that we also observe in Western Europe, and most likely in the rest of the world as well. The percentages and steepness of the trends probably differ per region and culture. In her book iGen[84] she reports an analysis of large-scale age-matched generational data, comparing Gen-Z now to previous generations when they were the age that Gen-Z is now.

Of course such generalisations have to be treated with caution. Belonging to a certain generation represents only one of many diverse factors that influences the behaviour of an individual person. And since the generation covers a period of 20 years of rapid and immense changes and developments in technology and society, and the composition of the group has become more diverse than ever in social and cultural backgrounds, Gen-Z is far from a homogeneous group. Generation-Z is still young. Their ideas, ambitions, worldviews and dreams have just started to evolve.

Today's students seem younger (Gen-Z 22-year-olds are like 18-year-olds of Generation-X and Baby Boomers) and so require more guidance and personal development than their predecessors of the millennial generation. They have not gained as much life experience as previous generations of the same age. During childhood they interacted less face-to-face than any previous generation. They have replaced time for friends in person with (virtual) friends online. In her book, Twenge explains how this has fundamentally changed the lives of these adolescents.

As a consequence, teaching staff must expect that particularly in the first years of study, more students will be hesitant to talk or ask questions in the class. They may be scared to say the wrong thing and are a little unsure about their opinions. We should not confuse this feeling of discomfort with the fact that these students profoundly believe in the importance of dialogue to solve conflicts and accept differences of opinion.

This generation is growing up more slowly than previous generations and takes more time to adopt the behaviours associated with adulthood. It means first-year students have had less chance to practice living independently, navigating relationships, or learning how to moderate high-risk behaviour (dating, having sex, drinking alcohol, doing paid work)[85]. As a consequence, on average they are less familiar with the norms and expectations of higher education[86]. For academic counsellors this will mean an increasing demand for advice from students who don't know how to manage their lives by themselves. Teaching staff may have to be reskilled to understand the incoming students and how to reach them. They must expect that these students need more guidance and want more frequent feedback, short and to the point, to adapt their learning approach. Also alumni from Generation-X (1965-1980) and the millennials (1980-1995) may have to learn about Gen-Z, well before they take for instance a mentoring role of Gen-Z students. Alumni often still view education and campus life at their alma mater in the context of their time at university.

"In today's world, it is far more important to know what you know about what there is to know than to know how to look something up"
Quote by Philosopher Laureate of the Netherlands Daan Rovers

Gen-Zers want an education they can apply, that is relevant and shows a clear pathway to a prospective career and sustainable employability through help with CVs, mock interviews, job market research, business simulations, industry exposure, shadow internships, and alumni mentorship. And although many Gen-Zers

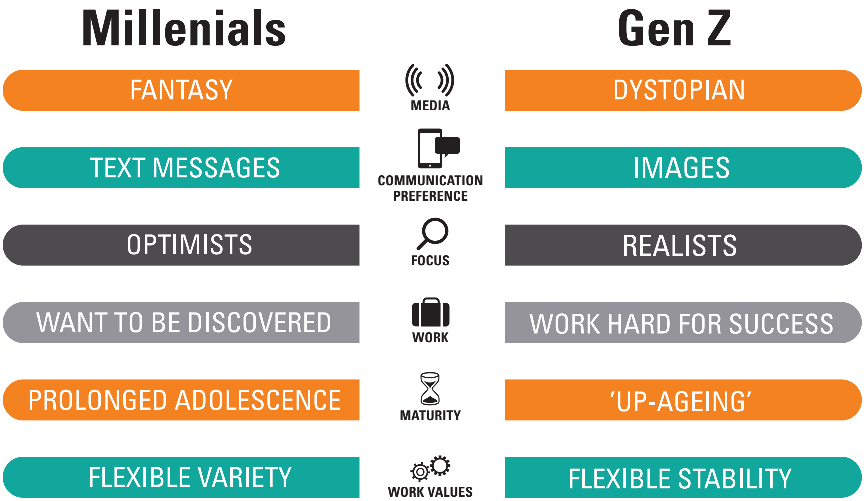


Figure 8 Graphical comparison between the Millennials and Generation-Z'ers (credit Summer Shaffer, source Colorado State University)

experience it as demanding and increasingly stressful, they look for alternatives within the curricula and in the arena of social and extracurricular activities, to build up a distinctive CV. Increasingly, prospective students of this generation base their decision about where to enrol on the opportunities of social and extracurricular activities and other aspects of campus culture.

Within the curricula these students increasingly look for opportunities to collaborate with fellow students, where they are stimulated and guided by academic staff or professional experts on interdisciplinary projects to design solutions for real-life challenges (challenge-based learning, makerspaces). The societal involvement of the Gen-Z students is strong. Already during their study they want to contribute to "the common good". Their mindset is a humanistic one, with responsible engineering, lifecycle engineering, openness and transparency as cornerstones. But reality is obstinate. A large discrepancy exists between their sustainability thinking and talking, and their sustainability acting. It might be interesting for educational programmes to make one or a subset of the UN's SDGs a driver for the curriculum, portray it as such, and make the sustainable development goals explicit in the engineering attributes to be developed. That way, they immerse students throughout their study in a sustainability-oriented engineering methodology. Since one of the cores of Gen-Z is manifesting individual identity, students may then use the sustainable development goals as an expression of their identity and as a matter of ethical concern.

Gen-Zers live in an instant culture. They are accustomed to find the information they need, when they need it through search engines or freely available online courses. They supplement their formal learning with mediums such as search engines, massive open online courses (MOOCs) on the edX and Coursera platforms, podcasts and by watching "snack-size" YouTube videos. This calls for new approaches to higher education, with options for students to discover study paths on their own and possibilities to tailor education to personal needs. They want flexible learning opportunities in blended formats of face-to-face and online, independent and group work, and of acquiring fundamental knowledge as well as training professional skills.

In this instant culture they are also accustomed to instant gratification. Gen-Z students almost panic when their study-abroad programme suddenly has to be adapted on the spot. They expect the availability of a dream internship when they need it, quick feedback on assignments, and almost instantaneous replies from academic staff to questions when submitted in an app or the digital learning environment.

Gen-Zers are the grazers of the internet and collectors of information and knowledge, using the digital world

The consequence of spending massive amounts of time online during their childhood is that they arrive at university with much less experience in reading and sustained concentration. Traditional textbooks with hundreds of pages on engineering fundamentals of mathematics, statics, thermodynamics etcetera, may have to be reformatted into e-textbooks, with chapters that are shorter in length, have a more conversational writing style, and include interactive figures such as video sharing and built-in quizzes. Only then will they be able to keep Gen-Z readers interested in delving deeply into a subject matter.

Gen-Zers are also the generation of "Being Woke": being attentive to inclusion across race, ethnicity, sexual orientation and gender identity. They embrace diversity and freedom. Although this is a liberation in itself, it can be a heavy burden for them at the same time by embarrassments on social media that can easily damage emotions and reputation. This is more expedient for Gen-Zers than we may expect. The higher level of diversity and freedom leads once more to a higher demand in enhanced advice from professional academic counsellors, who may be supported by virtual intelligent assistants on mobile devices that provide each individual student early alerts of trouble.

With the vast amounts of information at their disposal, learners of this generation are more pragmatic and analytical about their decisions than previous generations. Gen-Zers are optimistic about the world and excited to create in it. As knowledge, technology and society evolve, the traits and behaviours of these students will shift. Faculty may have to plan curricular transformations more frequently than the eight to ten year cycle that is, roughly, the current norm and make changes much faster[87]. Curricula have to be made more agile and easily adaptable to change. Senior academic staff has to be trained to better understand and communicate with this new breed of students. Academic counsellors have to intensify their services, and may consider integrating their counselling in the entire study programme.

Diversity in Portfolio

Agile Programmes

Today's bachelor and master programmes have been conceived and constructed in the eighties and nineties of the 20th century. They have probably been updated with programming, teamwork, communications skills, modern tools and state-of-the-art expert knowledge. But in many research masters students are still educated in the traditional setting of a rigid academic programme that emphasises hierarchically organised theoretical knowledge in a discipline. The curricula emphasise the academic nature and underplay the teaching of future engineers. They offer little support for growing "systems thinking" skills or for becoming problem analysts of complex unstructured problems that go beyond the engineering bricks. Master thesis research is often the first and only time during their studies where students get the opportunity to integrate knowledge and develop creative skills in a PhD-type of work. Often, students in master theses are treated as cheap research capacity.

With decades of accelerating change ahead, we cannot expect that the future will be a simple linear extension of the present. Science and technology are changing at an enormous pace. The needs of the job market are changing. The expectations and traits of the Gen-Z students differ from those of the baby boomers and the millennials, and are still evolving. Although we live in a world of ever deepening specialisation, the demand for generalists and more all-round engineering graduates, is growing[88]. They act as brokers who facilitate collaboration between specialists, and as agenda setters who know what questions to ask and how to address them.

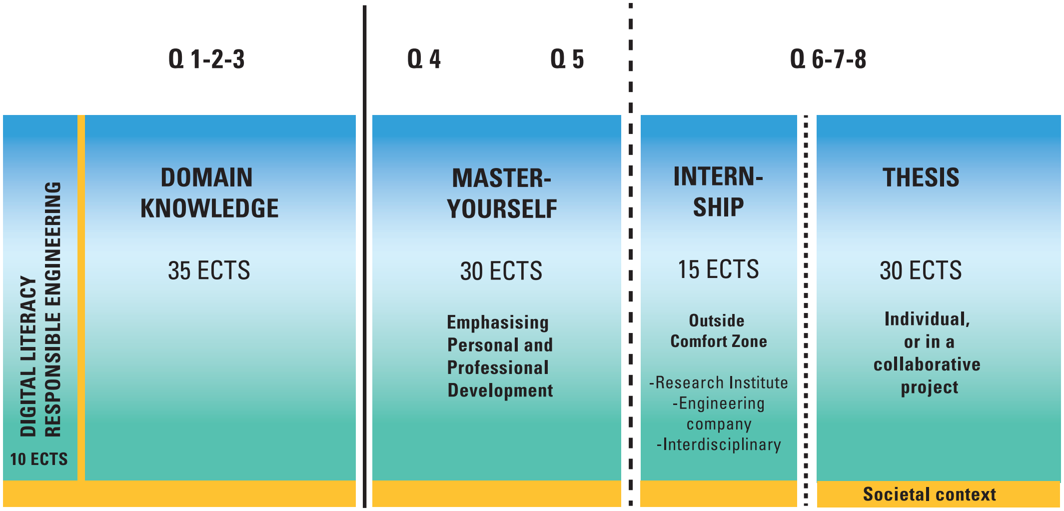


Figure 9 Example of a Master Yourself curricular framework

Many engineering programmes are not prepared or built for (responding to) rapid change. But we cannot avoid the fact that we have to make our science and technology curricula more responsive and adaptable to the emerging micro-credentials, demands for self-directed learning in individualised study paths, access to open-internet exams, the role of social media in student life and the market of continuous learners. If a curriculum does not have the capacity to change structure (including infrastructure), learning outcomes or educational activities in a timely manner, it may be good, but can soon become obsolete.

Agile (master) curricula do have this inbuilt adaptability. They enable students to build a personal identity profile. These identities and the associated individualised study paths may shift per cohort of the still evolving Generation-Z. Agile programmes have processes in place for strong academic and industrial stakeholder engagement in curricular change, and have regular dialogues to identify and prioritise the needs for change[89]. In these programmes, the development of competences and strong collaboration prevail over compliance and competition.

Employability and marketability of the graduate prevail over their excellent marks or publications of thesis research at a conference or in a journal. In agile programmes, the development of attitude and learning skills matter more than talent or a diploma. Last but certainly not least, at faculty level and across the institution, agile programmes demand a flexible and entrepreneurial mindset, away from administrative thinking, a culture of experimentation, initiative-driven change and fast approval processes for regulations. But agile (master) curricula also require overarching rules to assure coherence and quality at graduation:

1. A transparent framework of compulsory blocks and ample space for self-directed learning;
2. A harmonised, university-wide scheduling of the compulsory blocks and the space(s) for self-directed learning, to make projects, assignments, and other components accessible to all students of different programmes (common mobility window);
3. Uniform course size (or multiples), which enables the replacement or shift of courses without much administrative impact;
4. Integrated courses that address perspectives of different fields of expertise, instead of large numbers of separate small courses in niche areas of expertise. The detailed content within these integrative courses is changeable without administrative impact. It requires sufficient staff with an open and collaborative mindset who are able and willing to defend both the academic and professional values;
5. Multidisciplinary threads through the curriculum, which combat the compartmentalised discipline view of education and provide students with a clear vision as to the choices they can make to become an effective engineer who is prepared for sustainable employment;
6. Learning outcomes that are defined at a sufficiently granular level to leave enough space for different ways of implementation and avoid repetitive cycles of approval;
7. Narratives that guide students in their choices to build a self-directed learning path. The narratives include a prescriptive guideline about the competences that need to be developed within the space of self-directed learning and complement those already acquired in the compulsory parts of the curriculum or in the final thesis, of which the assignment should be aligned as much as possible with the personal learning objectives in the narrative;
8. Acceptability of stackable credentials, achieved by any means of learning and assessed through a robust, standardised process;
9. Guidance to support students in their choices;
10. Timely feedback that enables cumulative self-directed learning; the students need to be followed and coached at both the individual and the group level;
11. Portfolio of achievements (projects conducted and experiences gained) that enables students to keep track of their personal learning objectives and build and expose their personal identity, reflect upon one's practice, adjust the learning needs on the go throughout the degree, and eventually sell their competences to a prospective employer. Portfolios are an excellent starting point for setting up collaborative learning with peers. E-portfolios can be linked to digital badge technology for the recognition of competencies gained.

Agile master curricula very much depend on the DNA of the institute and the local context and culture of the programme. The example we will discuss in the following section considers a two-year four-semester engineering master programme of 120 ECTS-credit points (European Credit Transfer and Accumulation

Master Yourself section (30 ECTS total)	**Study load (ECTS)**	**Specialist 2.0**	**Systems Engineer**	**Front-end Innovator**
Capita Selecta To bring participants with different backgrounds at comparable levels of knowledge.	**10**	√	√	√
Additional disciplinary conceptual and procedural knowledge Additional courses to acquire in-depth knowledge in a specific field of expertise.	**5-10-15**	√		
Common tools for working Courses, masterclasses, activities to learn about systems engineering, computational thinking, (agile) project management, productivity, certification and safety, regulations of engineering, risk management, design thinking methods, making, experimentation and knowledge discovery, etc.	**15**		√	
Durable personal and interpersonal skills Courses, masterclasses, trainings to learn one or more subjects about personal leadership, leading engineering endeavours, creating a purposeful vision, strategic thinking, law, ethics, perspective taking, systems thinking, intercultural communication, academic communication, pitching.	**10 or 15**	√	√	√
Entrepreneurship and innovation Taking part in entrepreneurship, innovation and change courses, data-driven decision making (business analytics), and a business development lab or combined with an internship in an innovation department of an engineering business, or in a start-up company, to experience the enterprise and business context.	**15 or 30**			√
Interdisciplinary projects Taking part in a collaborative interdisciplinary innovation, joint interdisciplinary engineering or global humanitarian design project, commissioned by external clients, organisations or businesses, or an institute-wide discovery project, always involving public and private sector organisations, from conceptualisation to commercialisation.	**15 or 30**		√	√
Study abroad Taking courses at a foreign institute to complement home courses and to develop cultural agility.	**30**	√		√
Life and career Taking courses or masterclasses in job crafting, personal branding, engineering work ethics, proactive vision, self-reflection, initiative taking, decision making, and people and team leading.	**15**		√	√
Internship extension	**15**		√	
Thesis research extension	**15**	√		

System), subdivided in eight educational periods (Q1,...,Q8) of equal size and length of 15 ECTS each. Its aim is to prepare graduates for innovative and research activities and allow more mobility.

The ***curricular framework*** is identified by 3-2-1-2, meaning 3 educational periods for compulsory core courses (45 ECTS), 2 periods for a so-called Master-Yourself section of self-directed learning (30 ECTS), 1 period for an internship (15 ECTS), and 2 periods for thesis research (30 ECTS). The core courses provide students with thorough disciplinary, conceptual and procedural knowledge. 5 ECTS of the compulsory courses address engineering ethics, 5 ECTS methods of digitalisation and programming, and 5 ECTS domain specific digital engineering skills. The compulsory courses are ***scheduled*** in the educational periods Q1-2-3 of the academic year, the research thesis in periods Q7-8, the internship and space for self-directed learning in Q4-5-6. All courses are 5 ECTS or a multiple.

The ***self-directed learning space*** is offered in the choice-based Master-Yourself section. This section highlights the fact that students want to be in control, have to be determined to anticipate, take action, commit themselves and make decisions in order to make a challenging start to their working life. It provides excellent opportunities for self-directed learning, which ideally persists beyond the final thesis (lifelong learning). The aim of this section is to allow for seamless mobility and to increase students' individual awareness about human values, and how personal and professional skills are a useful complement to technical skills in life and work. Students convert their knowledge and competencies into action in appropriate situations and contexts. This personalised section is built up from different challenges and students work on a range of courses, assignments and projects, either of their own making or provided by the university, in a way that the personal learning objectives are satisfied.

In today's practice, students tend to select courses (or are instructed to do so by their supervisor) on the basis of disciplinary content rather than the competencies they can acquire. We also see that many students struggle to translate the feedback from one course context to another. It is therefore necessary to ***support*** the students in composing their individual Master Yourself section to ensure it offers ***repeated practice and evaluation for cumulative learning of personal and professional skills.***

In our example we use the attributes, required by prospective professional roles, to guide the students in their choice for the composition of the Master Yourself section. Students can use these roles as possible narratives: the Specialist 2.0, the Systems Integrator, and the Front-end Innovator, as discussed in the section Changing Roles, Skillsets and Mindsets.

The table on the opposite page lists a number of ways the Master-Yourself section can be implemented. It shows coherent thematic packages (with selectable items within some of the packages) that are made available within the programme, or better, at institute level for multiple programmes. Although these packages are not cast in stone, fragmented and incoherent Master Yourself sections must be avoided.

Neither shall students be allowed to do cherry-picking, nor shall they be overloaded with an endless number of options. A plethora of possible narratives, thematic packages, and combinations exists. Sources for inspiration are plentiful. Just to name a few that caught my eye: the Airbus Minds! [90] programme in Spain, the six personal development programmes GIFTed, GUIDed, WANTed, INSPIRed, UNITed and ACTIVATed at KTU in Lithuania[91], and the Danish KAOSPilot leadership programme[92]. Eventually it is up to education management to decide how much freedom of choice students get, and what level of agility is desired at programme and institutional level.

Lifelong Partnerships with Students

In today's practice, after graduating from an institution, a student becomes an "alumnus", a former student who is no longer a daily part of the community. Yet there is a growing trend that a degree is no longer the end of the relationship but, rather, the passing of one phase of that relationship to another. More and more older working adults return periodically throughout their career for short courses or other professional development opportunities.

Continuous learners are an emerging segment. Getting a better job is their top objective. In theory there is a huge demand for lifelong learning and upskilling, yet demand is still latent. Individuals tend to undervalue the long-term benefits of upskilling in the trade-off against short-term investments in time, effort and money[93], and the provision is still scattered and fragmented.

For companies to work on relevant problems, lifelong learning programmes for professionals need to provide state-of-the-art knowledge and perspectives to their employees. Rather than a nice add-on to the current formal three- or four-year degree programmes, upgrading and gaining fresh perspectives need to become a concept around which university systems are organised. Thus universities will develop into an active learning partner for a person's entire (working) life, stretching beyond the classroom and their occupational knowledge and skills.

At the same time however, engineering businesses do question whether universities are the most appropriate partners to upskill their professionals. Companies are at the forefront of the digital transformation for instance, universities are lagging seriously behind.

Portfolio careers and the need for workforce agility in the gig economy increase the demand for continuous development. Continuous learners have different demands and expectations than regular students who are young and enrolled in on-campus programmes. New-age learners are more "consumerised", want a quick return on investment and full control of their learning path because they may already be working or have a family. They want, even more than regular students, learning that is learner-centred, affordable, technology-enabled, accessible at any time across the globe, and preferably creative and innovative. They want to follow separate packages of knowledge, delivered by the best lecturers and available from a pool of modules, and re-bundle them into personalised curricula and stack credits gained from on-campus courses and lab work with new credentials such as open badges, nanodegrees or micro-credentials.

> *"The illiterate of the 21st century will`not be those who cannot read and`write, but those who cannot learn,`unlearn and relearn" (Quote Alvin Toffler)*

Universities that aim to make continuous education part of their mainstream activities, will have to co-design curricula and courses in close partnership with employers and students. It will lead to a more intense involvement of engineering businesses in education.

Blended and Online Education

As described above, an increasing number of face-to-face universities consider continuous education as an interesting complementary offering besides their regular degree education. Although a sustainable revenue model is still a challenge, the development and delivery of complementary online courses can have interesting spin-offs for the existing on-campus education and the institution as a whole. The extremely high quality standards that apply to online education (not the classroom, but the world is the audience), can lead to a surge in educational innovation and put education higher on the university agenda. The worldwide exposure boosts the visibility and reputation of the institution, and attracts more talent.

Online and open education are seen as modalities that provide flexibility to the educational system for off-campus students. Too much emphasis on online learning carries the risk that universities develop into conveyors of online courses, transforming the face-to-face university into a digital factory that serves the digital economy, emphasising digital job creation and using platforms to launch new digital services and apps.

Blended education is the dominant trend of innovation in on-campus curricula, as universities do not (yet) abandon face-to-face education for their bachelor or master students. Online education is one of the tools to better align with student needs: less facility and time constraints, better situated contextual learning, more exposure to the real world of companies and technologies, improved learning experience like self-directed learning with 24/7-style communication and access[94]. It is seen as a promising field for universities for increased offerings to lifelong learners[95]. They have to be aware though, that lifelong learners have different needs and wishes than regular students, as do different companies. Developing online courses for diverse audiences requires customisation of content, assignments and assessments. To be successful in this market, universities have to expand their traditional view of a ”learner” and seek new customers like multinational companies, industry professional associations and other online-content providers.

The developments in online and open educational resources already have a significant impact on the evolution of STEM education. Fundamental engineering knowledge is increasingly commoditised, and learning is shifting to blended learning. In 10 to 15 years' time it may be too expensive and time consuming for young students to learn basic engineering fundamentals and other content that can also be picked up online through personal learning with the support of learning analytics. These analytics provide solutions that use cognitive and biometric data about learners, their personalities, their habits, goals and feedback from others, and drive personalised learning and provide coaching and connections.

Bachelor curricula in particular are expected to evolve into a blend of off-campus personalised online learning and hands-on experiential learning in lab spaces on campus, in companies or makerspaces. There is a growing need for more personalised mentoring as well as synthesising group work and student interaction across disciplines and borders. We will see a stronger sense of peer-to-peer learning and one-on-one counselling provision through the wider use of social media networks that offer a *learn-when-you-want and how-you-want* model, a highly personalised approach[96]. Thus we move toward a technology-enabled era of learner-centred learning in which the student gets what they specifically need and in which they largely teach themselves the fundamentals of engineering, the skillsets and the mindsets. Intelligent virtual assistants (avatars) make education smarter and enable personalised learning, and they do most of the personal lesson planning based on learning analytics.

Different kinds of players may enter this online education business. For example, recruitment and human resources companies have an obvious entry point, given their expertise in student employability and strong links with employers. Corporate universities and global tech giants, with their digital know-how, may dive in too. Universities will need to forge strategic partnerships to grow their online presence.

Reframing Engineering Education with a Time Horizon of 2050 [97/98/99]

Like never before, science and technology universities have to push for a comprehensive conception of what they should look like in 20 to 30 years, and what an engineer's profession will look like. Will a future engineer have the same meaning, do the same activities, need the same skills as today, or will they be something fundamentally different? Will a future engineering student still be intrigued by technological objects and phenomena, or will they find their motivation and purpose in designing solutions for salient societal challenges?

These questions are very much a present-day priority for universities around the world. Do we know what and how we will teach science and technology two or three decades from now? It is easy to fall into the trap of thinking in terms of linear extensions of the present or past top-down approaches. Universities need to take on more responsibility in educating entrepreneurial minds that understand the entire spectrum of societal and technological challenges, students that are willing and capable to live up to these challenges on a daily basis[100]. To do so, universities need to embrace innovative ways of teaching or they may even have to be restructured.

"When people talk about the future, they tend to pinpoint a few big trends and then try to relate those ideas, to those trends in isolation. We don't want to do that; we want to try and understand the coherence between everything"
(Quote Matthijs van Dijk, Reframing Studio, 2019)

Answering what the engineering profession will look like in 20 to 30 years, working out what engineering roles might be expected and desired by society, requires an understanding about what our future society might look like, the context in which engineers would play their roles.

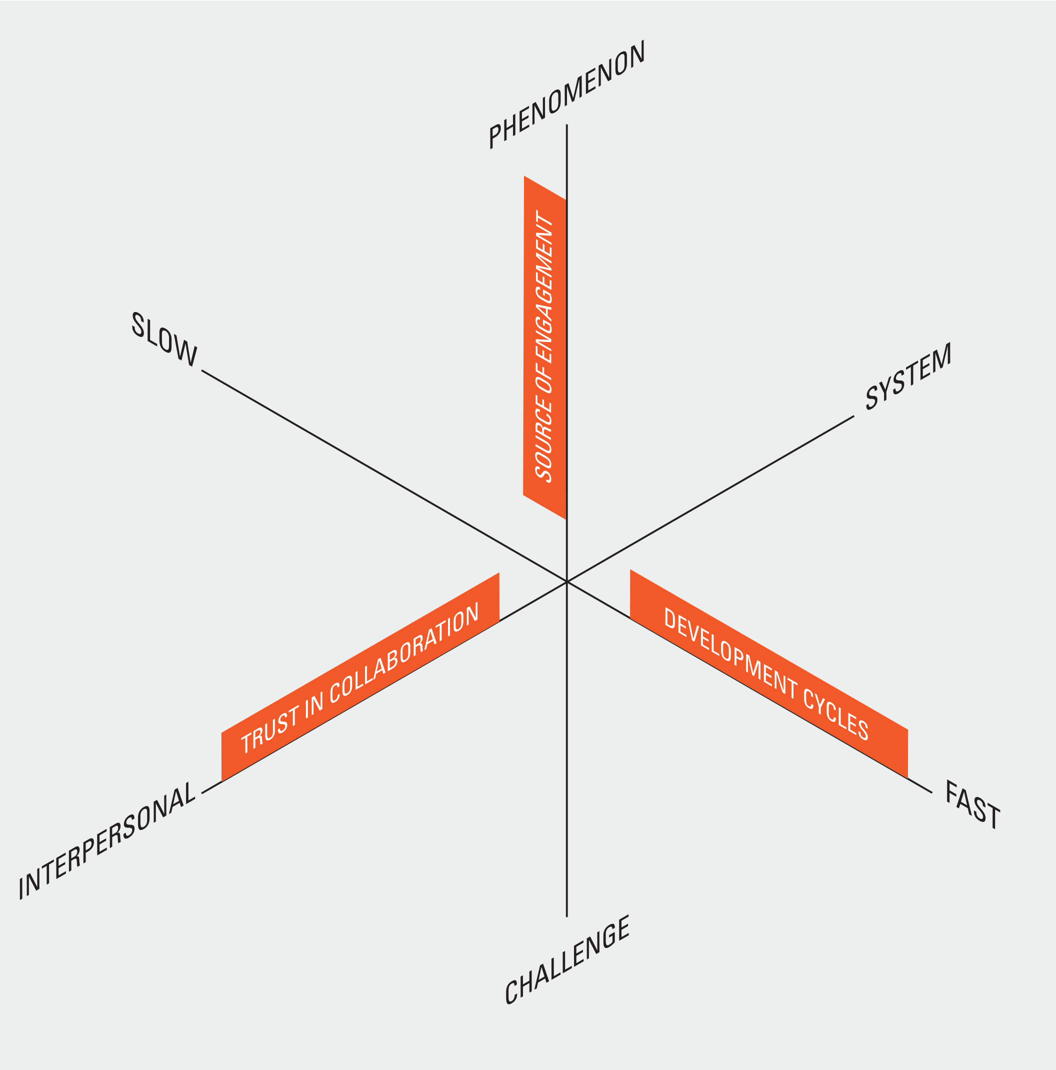


Figure 10 The framework showing the three driving dimensions that are likely to determine engineering behaviour[102]

A study at TU Delft/4TU.Centre for Engineering Education (Kamp et al, 2019) tried to build a picture of that future context by gathering as much information as possible about a specific future, and then "working backwards" to the present-day, identifying policies that would get us to that desired future. The result of the study is a ground-breaking concept in which the drivers for curricula are no longer the engineering disciplines, but the engineering behaviours that are expected by future society.

This comprehensive out-of-the-box thinking identified three dimensions, revealing eight new meanings of engineering in the future:

1. the way engineers engage or get involved with science and technology (source of engagement). It is about the intrinsic motivation for a person to choose to study and work in science and technology in the first place. For some, it's the quest for technological solutions driven by the major societal challenges; for others it's the desire to explore and thoroughly understand in depth a particular technological phenomenon in or across disciplines.

2. the way engineers work together with other people in society (source of trust and collaboration). Some engineers thrive when they work in a large, less personal system. They may not know their colleagues at first, but trust that they have the expertise necessary to work on the job, just as they trust the system in which they work. These people are engaged with incremental, technological improvements as part of building an even better system. Other engineers thrive in small entrepreneurial teams, where interpersonal trust is based on intuitive judgment, proximity and personal contact. These people are proactive, have more an entrepreneurial mindset and are at their best when they work in a close-knit dynamic group of like-minded innovators and technology start-ups. They like to work in interpersonal networks.

3. the way engineers apply or create new knowledge. It is about the speed of the development cycle. Rapid innovation cycles demand a fast response to urgent dilemmas and the creation of rapid results. Engineers in this frame need the ability to navigate difference and manage change, and a willingness and ability to recognise and pursue opportunities for new value creation and problem solving in any organisational setting[101]. Entrepreneurial behaviour is my catch-all term. The need to stay up-to-date with the latest innovation stimulates lifelong, personalised learning and retraining for engineers at every stage of life. Other engineers feel more comfortable in long-term technological advances that have a much slower cycle of change. It requires patience, endurance and sustained attention to aspects like the implementation and systems adaptation, governance, legal and policy issues, and cultural and ethical norms and values.

Each of these three dimensions represents a new and independent area of knowledge and can be seen as a scale of different ways of working, with different needs for behaviour and competencies. The extremes mark the ends of each scale. So an engineer might be motivated by either societal challenges or technological phenomena, by working within a solid system or an interpersonal network, within fast or slow development cycles, or anywhere in between. The beauty of this three-dimensional framework is that it is relatively straightforward to envisage different professional profiles that are based on every possible permutation of the extremes of each dimension (see Figure 10). For example, a professional or engineering student can map their personal identity profile by being motivated by a societal challenge, work best by collaborating interpersonally and at a slower developmental tempo. This helps to define their specific professional profile, and optimise their specific competence strengths and preferences.

But how can science and technology universities incorporate this concept in their formal engineering education? The study suggests to flip the university organisation. The traditional disciplinary departments may remain, but they need to transform into providers of disciplinary conceptual knowledge to the three educational institutes that focus on educating the engineering profiles. Engineering education might thus be organised in line with the concept of the dimensions by turning each dimension into a separate educational institute:

1. Engagement Institute – teaching the ability to study scientific phenomena in depth, and building cross-disciplinary knowledge bases to address societal challenges;

2. Decision-making Institute – teaching how to work together in a dynamic entrepreneurial team on multiple thematic projects simultaneously, and how to collaborate in network-based open innovation systems, using open-source, open-data and open-standards and ethics of science;

3. Pace Institute – teaching the ability to respond to urgent dilemmas and produce rapid results, and continuously reframe, learn and develop ways to understand the changing world; learners are involved in shorter time cycles as well as long term developments of both human and material affordances, systems and products.

Taking the idea of these three institutes one step further leads to the concept of the “Personology Arena”. It is an alternative organisation for future engineering education at universities of science and technology. The Personology Arena is a concept for a scientific playground for lifelong learning in a melting pot of research-intensive institutions and career-focused institutions. The word ‘personology’ is derived from personality and technology. It emphasises the fact that the students will be taught how to create a relationship between self-growth and societal purpose, giving them the ‘agency’ in building their own career path whilst ensuring societal relevance. In the Personology Arena, students learn to play different engineering roles in shared learning environments of universities and companies, both face-to-face and online, national and international.

It is not only meaningful for students who want to become a professional with a specific professional profile, but also for people who are professionals already. It gives them the opportunity to re-think and re-frame the position they already have in society.

For sure this study does not pretend to define the one and only concept of future engineering education. It is an inspirational and out-of-the-box example of how we might re-imagine engineering education in the future, when the position of universities, industrial and societal needs, and the expectations from the engineering profession have dramatically changed.


GENE 3

Learning, Unlearning and Relearning Staff Competencies

When Student Knowledge Outstrips that of Academic Staff

For almost more than 200 years, universities have focused on content and exams. For too long they have been "fixing the teacher" to teach content better and in a more contemporary and time-efficient way, i.e. they have been fixing the system by refining and perfecting it. Academic staff at research-intensive universities are by definition subject matter experts. They often lack the method to teach engineering fundamentals and disciplinary knowledge ***in combination with*** training social skills ***and*** fostering mindsets in a coherent ensemble. These higher social skills and mindsets will be essential for a successful career in the field of science, technology and engineering in the emerging artificial intelligence age of learning machines, avatars, automation and robotisation[103].

It is this digital world that creates its own challenge. The rise of technologically-supported "brains" and the growth in artificial intelligence and virtual reality may revolutionise learning design, delivery and assessment. ***Under artificial intelligence, the knowledge of students could easily outstrip that of the academic staff who have been educated under the old system***[104]. Staff have to recognise the need to advance their competencies in digital literacy and see the potential for how it may improve teaching and learning for students enrolled at their university.

The only thing that can make the difference in higher education is the people. They are confronted with a plethora of tools and applications that are rapidly improving in terms of quality and applicability. Taking the innovations in pedagogy into consideration, a strengthening of didactic professionalism and a high degree of professional autonomy for teaching staff have to become the norm. The role of the teacher is changing from the teacher-oriented knowledge deliverer (the "sage on the stage") via a more learner-centred "guide on the side", to a coach, peer, mentor and learning facilitator. Their focus is to equip students with the ability to discern between relevant and irrelevant knowledge, to identify gaps in their knowledge, and devise strategies to fill those gaps, all in the context of engineering practice problems. Staff not willing or able to think, act and deliver this "differently" may soon be redundant.

One of the biggest challenges for universities is their agility and the fostering of learning, unlearning and relearning of academic staff, motivating them to co-design with non-academic institutes or industries more learner-centred, self-directed and expansive curricula, and focus on research and design questions that have the potential for societal impact. As already discussed, Gen-Z students and lifelong learners are a different breed with different expectations, aspirations and needs. They are more "consumerised" than universities are used to and may not have the patience to wait around for universities to figure out their market and adapt their programmes to teach new skillsets when an online learning platform somewhere in the world is offering that possibility already.

Academic Careers with an Emphasis on Education[105]

The educational systems at many engineering and technology universities may need a wholesale change to accommodate teaching and learning for the future. There is little practical motivation for either novice graduate students or experienced lecturers to take time out to learn how to teach better. Staff incentives have been low for many decades as educational achievements are highly undervalued in research-intensive universities. Many are comfortable with what they are doing and can't see, or choose not to see the future ahead. There is a growing urgency to flip the existing culture of promotion on the basis of academic excellence (read: research) and create a culture and structure in which engagement in educational development work, excellence and leadership in education will be weighed on par with research achievements. Career paths shall be developed and implemented for academic staff with an accent on education. The Royal Academy of Engineering (UK) recently launched a teaching framework[106] that enables universities all over the world to implement academic careers with an emphasis on education.

One of the challenges is that traditional engineering sciences and technology universities have of an old-time focus on the academic profession of conveying theory, and have been structured in mono-disciplinary faculties and departments. They have to transform and deliver interdisciplinary education without being highly interdisciplinary themselves. Staff has to prepare for new learning and teaching environments in which they will address professionally relevant aspects that are not necessarily part of the current teaching traditions of disciplinary concepts and theories[107]. This not only requires curricular transformations, but also a major mind shift and upskilling of staff, higher management and programme bodies, in combination with the establishment of compatible organisational structures. A successful transformation is achievable only when enough people are prepared to defend both the academic and professional values, and when they collaborate across organisational boundaries.

Academic Staff as a Role Model for Students

Research-intensive universities are full of scientific staff with diverse backgrounds. Most of them do not have an industry perspective or have never been an engineering practitioner. Academic staff increasingly lack practical skills in engineering design processes, systems engineering, project approaches, entrepreneurial thinking, and in social or professional skills of team coaching, conflict management, negotiation, and professional behaviour. It leads to a disconnect between the academic world and the world of engineering practice. This is a growing challenge at research-intensive universities. While senior faculty staff control appointments and promotions, change will not come from within, and thus the templates for recruiting academic staff are getting narrower. It reduces the chance for people with a non-academic background to bring their experience, tacit knowledge, role models, empathy and creativity in engineering practice to the classroom.

Increasingly, this discrepancy is mitigated by hiring mentors and project tutors from engineering companies to supplement the lack of professional engineering competencies in academic staff [108]. Universities are also more and more involving alumni in engineering education, and they are attracting more engineers with personal experience in the private sector to becomes role models[109]. They are in the position to give valuable counselling, supervision, consultation or intervision[110] in project work that can be messy, social and playful. A strong involvement of engineering practitioners helps the establishment of a culture of constructive failure.

Strengthening University-Industry Collaboration

Where science and technology are an academic discipline, engineering is geared towards a practice-based profession. Engineering students need to prepare for this future by getting a taste of genuine research, engineering and design through learning-by-doing, and meeting their role models in universities and the industry. They have to become aware that universities and companies have very different timescales. In today's world, the pace of engineering and innovation projects in companies has become really fast. There is not always time to envision all the consequences of a new product or service on society, or how customers will respond. Universities teach students over a generally longer period of time, and students doing their thesis research often spend half a year or more on their project.

> *"The university of the future will derive its right to exist primarily from being active in the world and by producing knowledge for the world"*
> *(Quote by Bert van der Zwaan in his book "Higher Education in 2040")*

Such relatively long periods should be used to bring students and experts from engineering practice together from different fields, for example social science and engineering students, industrial experts and teaching staff, in seminars or in joint reviews. It provides great opportunities to practice authentic and respectful communication with different audiences and environments and it creates a mindset of empathy, necessary for working in communities with various stakeholders, including academic staff, industrial experts and technicians from the shop floor, representatives from governmental bodies, as well as friends and family.

Universities have to address the strategies employers are seeking to accomplish and the ways technological change and innovation shape the industries. With the shifting position of the university in society, it is expected that degrees of the future will become more employer-led. Academia for academia's sake will end[111]. Educational programmes shall therefore not only be aligned with the latest developments in research and science, but also with those in engineering practice[112]. Engineering companies need engineers who go beyond disciplinary and digital skills. They want young graduates to have an understanding of customer intimacy, product costing, manufacturability, project management, strategic planning and industry-specific knowledge. An enhanced cooperation with companies in engineering business could render university systems dynamic and needs-oriented, to better align curricula with their needs.

In lifelong learning models, universities will also have to aggressively engage with industry. To ensure that education does not lag behind developments in engineering business, the skills of academic staff need to be constantly updated, for example, by arranging exchanges with the industry.

Engineering professionals should also be involved in the co-design of curricula and course content, collaborate on applied research, and offer work-integrated learning. The involvement of industry professionals is absolutely crucial in the development of successful industry-linked curricula for Continuous Professional Education. Professionals want to use hardware and experiment for example to make concepts that are conveyed in lectures more tangible. In this age of acceleration and digitalisation, a strong and enduring partnership between industry and academia is more essential than ever.

Empowering Leadership

The role of education institutions is shifting from being a repository of knowledge to teaching learners to curate, challenge and extend knowledge, and by redefining research and teaching methodologies via technology[113]. New players on the educational field from all over the world, arrive with breakthrough models, such as the NMiTE[114] initiative in the UK, or the 42born2code school[115]. This 42 non-profit organisation, funded by a French billionaire, has 4000 students and is disrupting engineering education and the tech talent pipelines by an innovative peer-learning concept. It has two main campuses in Paris and Fremont (Silicon Valley) and partnering organisations in France, Belgium, Marocco, Finland, the Netherlands, Russia, Brazil, Indonesia, Armenia, Japan, Columbia, Spain, Canada and Italy. It doesn't have lectures, teachers or MOOCs but a 100% project-focused curriculum, based on peer-to-peer learning, where students learn to create advanced software solutions and resolve different development challenges.[116]

> *"Engineering education must empower the students to be leaders of innovation and to be able not only to adapt to the uncertain world and changing work environment, but also to change that world"*
> *(Based on a quote by Cathy N. Davidson in her book "The New Education")*

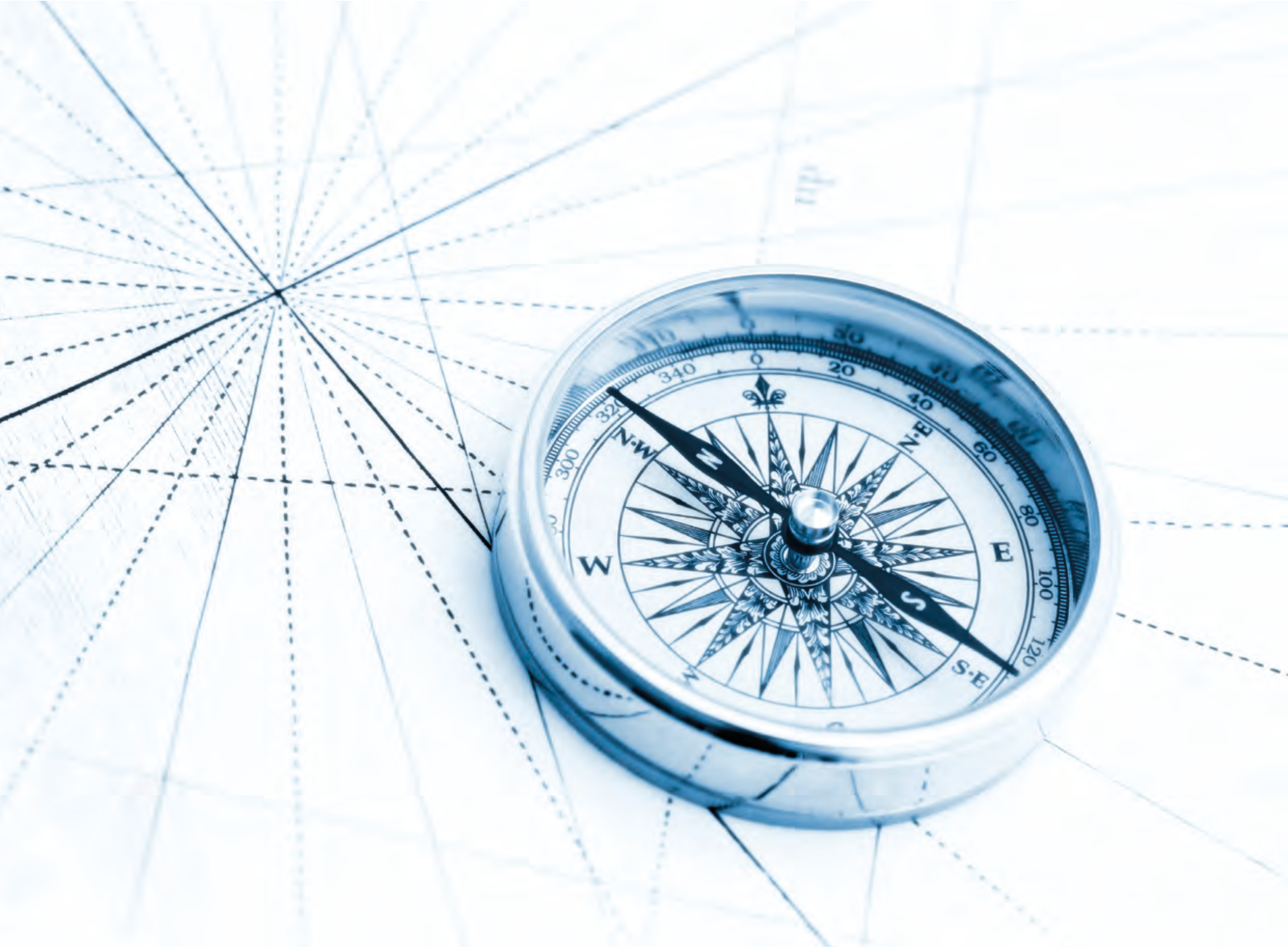
Traditional universities will need all their capacity to transform themselves in order to serve a changing society and a profoundly changed world, and to stay relevant and meaningful for next generations. To achieve a major transformation like that, we need strong entrepreneurial leadership on all levels at our universities, and a culture, capacity and capability that can thrive in highly uncertain and unpredictable learning environments.

Change in education is often at risk because it is hardly the focus of any "ranking management". Specific barriers for change include the fact that educators and administrators are cautious about change and have limited tolerance for the uncertainty that any important innovation causes; there is also a lack of trust when it comes to initiating innovation. Establishing a new paradigm for engineering education at science and technology universities demands a clear educational vision and strategy, where management has to demonstrate personal commitment[117]. It is often the young academic staff who is not yet tied to the old ways of doing things, who can make change happen in close collaboration with more senior students.

Educational change has to be drawn on feedback, evidence and ideas from across and beyond university hierarchy. Enabling leadership by higher management has to nurture an educational culture of continuous experimentation and innovation, and an acceptance of failure.

In the Netherlands, the 4TU.Centre for Engineering Education[118] has proven to be an excellent enabler of innovation, experimentation and action-based research in subjects that are specifically relevant for engineering education. Its current themes are future engineering roles, interdisciplinary engineering education, engineering educational ecosystems, emerging technologies to help students maximise learning, responsible engineering, intercultural skills for engineers, and the development of a career framework to award teaching excellence. The virtual centre is based on trust, knowledge sharing, dissemination, and it involves PhD students, postdoctoral researchers as well as teaching and supporting staff from the four research-intensive technology universities in the Netherlands.

Deregulating the environment (flexibility in rules and regulations), and last but not least, incentivising staff to experiment and innovate are important enablers for changing educational culture. It's not the institution that causes change, it is the people.



A Compass for Educational Vision and Strategy

Educational change is not driven by science and technology but by university strategy, the changing nature of the student body and the decisions of individual faculty members. Where most academics are brilliant experts in their discipline, their education is a mechanistic solo-activity that remains largely didactic and is more likely to emphasise content coverage than the acquisition of lifelong skills and tools of thinking that will serve graduates in every area. Their institutions revere their traditions and habits. In the preceding chapters, we have seen how they keep the focus on content and exams and decide not to think (deeply enough) about innovation in curricula or courses, simply because it is a departure from the old ways. They neglect the mismatch between graduate competencies and job market needs and keep the focus in current curricula on easy-to-handle technical knowledge.

We have entered an era that will rock the foundations of engineering education. Making fundamental changes is the only way to reap the benefits of pedagogical and technological innovations in education and better prepare graduates for the increasing and very different demands of the new world of work.

University management have to envision these changes and make choices on how to adapt. In this section I present a set of 24 high-priority recommendations. They are clustered in four compass points, the key directions for action. Together they provide a compass for strategic planning and updating educational visions. It is not a matter of reacting to change, but taking the lead in the future of engineering education. The variety in the recommendations illustrates that updating higher engineering education is a complex, multifaceted challenge that requires a complex solution.

This solution consists of a combination of measures, each targeted at specific aspects of the overall challenge, which is unique for each institute. The measures are not presented in order of importance, but clustered around the four compass points of ***Skills and mindsets***, ***Pedagogical and technological innovations in education***, ***Continuous/lifetime education***, and ***Educational strategy and leadership***.

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1) ***Skillsets and mindsets for 21st century engineers***
   a) nurturing mindsets and meanings in curricula.
   b) celebrating out-of-the-box thinking without the stigma of failure.
   c) making innovation the major thread in the fabric of master curricula.
   d) integrating scientific and professional integrity and business ethics in engineering curricula.
   e) embedding technical, interdisciplinary work in curricula so that students learn to work “at the fringes and on the crossroads” of disciplines.
   f) embedding non-technical courses in the context of technical content/knowledge, in the areas of quality, risk and safety; project management, knowledge of other (business) cultures, innovation-related competences and emotional intelligence skills, and by treating them as equally important.
   g) making the culture of data literacy tangible in all educational programmes.
   h) empowering students, as discoverers of their future career, as designers of their educational experience, as change agents and co-creators of education, in labs and makerspaces (intra– and extracurricular) to foster leadership, ethical behaviour, deep collaboration, interdisciplinarity and creativity.

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2) ***Pedagogical and technological innovations in education***
   a) developing agile education that is able to accommodate shifts in a timely manner and to respond to rapidly changing industry and employer demands.
   b) empowering students and shifting the focus from teaching to learning, i.e. giving them flexibility and freedom of choice to structure their individual study paths; encouraging them, with time, resources and space, to explore various career options through all kinds of courses, seminars, internships, and other real-life experiences.
   c) fostering scholarly teaching that is evidence-based, reflective and peer-reviewed.
   d) nurturing a “take the lead and lead the change” culture that encourages initiatives, experiments and innovations that promote an educational system that is responsive to change.
   e) empowering staff to improve and innovate education in short-term agile iterations in a data-driven manner, and to disseminate the outcomes.

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3) Continuous/life time education: continuous upskilling and relearning

a) incentivising innovative approaches in education and investing in the (continuous) professionalisation of staff in concert with academic career opportunities in education.
b) developing an innovative capacity by giving autonomy and trust to self-regulated teams of young, excellent teaching practitioners (typically less than 37 years of age) who have proven their passion, ambition and expertise in education.
c) stimulating faculty members to gain professional engineering experience and expertise by sending teaching staff to industrial companies to get insights into the latest developments, while inviting people from companies (role models) to regularly teach in the classroom.

4) Educational strategy and leadership

a) empowering a flexible and entrepreneurial mindset for students and staff on an institutional level, away from administrative thinking, with supportive policy interventions and leadership to incentivise change and upscale innovative evidence-informed learning and teaching approaches, making sure they become mainstream.
b) expanding digital learning environments and capacities to enable a fast upscaling of large computer simulations and the analysis of massive amounts of data, machine learning and artificial intelligence for big student cohorts.
c) developing large flexible learning spaces to enable educational activities that have a high degree of interaction, physically or digitally, with representatives from industries and other external institutes or organisations; and working in (distributed) teams with a network of computers, multimedia devices and software tools, possibly supported by a hybrid virtual-physical space where students can model, build, test and evaluate prototypes.
d) recruiting staff from multiple disciplines to develop range and build capacity for interdisciplinary education, including education beyond engineering, in monodisciplinary departments.
e) developing educational leadership to create vision, strategies and incentives for the changing paradigm of higher education, and to promote innovation in teaching.
f) intensifying the collaboration between educators and employers to share resources (engineering practitioners in the classroom, engineering projects and internships at companies), set priorities together and support employees, the self-employed and those without employment (either in a sector or at all).
g) exchanging experiences and fusing local, regional, national, international and multidisciplinary perspectives by forging strong partnerships through distributed collaborative networks between universities via joint platforms, thematic networks, etcetera, possibly also including corporate universities.
h) promoting impact-focused education through interdisciplinary learner-centred projects with societal relevance (where societal relevance is the centre of engineering).

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About the author

Aldert Kamp has been the Director of Education for the Faculty of Aerospace Engineering of TU Delft since 2007. He is deeply involved in the rethinking of engineering education at university level with a horizon of 2030. Over 20 years of industrial experience in space engineering and 18 years of academic experience in teaching and educational management have given him an excellent overview and understanding of the academic and professional capabilities that engineers need for a successful and sustainable employability in a volatile and uncertain world.

He is the author of the influential report "Engineering Education in a Rapidly Changing World", first published in 2014, later revised in 2016. Taking a horizon-scanning approach, the report articulated vision statements for the attributes that engineering students will have to acquire for a successful career. The report stirred considerable debate across and beyond TU Delft and is being used by many universities to inspire educational leaders and teaching staff to rethink their programmes.

In his 21-year industrial career, Aldert was the Systems Engineer for the design and development of extremely complex space instruments, working in interdisciplinary teams of national and international industrial expert engineers, finance and project controllers, government space agency customers and scientific end-users. In earlier projects he was responsible for the engineering management of the design, development and environmental testing of advanced satellite systems, collaborating in multidisciplinary teams of international expert engineers.

At TU Delft he has been involved in university-level education policy development, the reconstruction of engineering curricula and audits of Dutch and international academic engineering programmes. He taught bachelor and master courses on Space Engineering & Technology, History of Spaceflight, and Space Instrumentation Engineering and professionalised project education.

Since 2011, he has been actively involved in CDIO, the global innovative educational framework for producing the next generation of engineers, and has been its Co-director since 2017. He is TU Delft Leader of the 4TU.Centre of Engineering Education (4TU.CEE), which explores, researches and facilitates innovations in higher engineering education at the four research-intensive universities of technology in the Netherlands.

He is a member of the CESAER Task Force “S&T Education for 21st Century” and the Academic Liaison for the Global Engineering Education Exchange (Global E3) consortium. Last but not least he is Chair of the Board of the Educational Leadership Course produced by the Erasmus University Rotterdam, TU Delft and University Leiden, and trainer of its module “Curricular Change is not Rocket Science”. Since July 2020 he is self-employed as a freelancer in his one-person *Aldert Kamp Advies* business.


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