Engineering Education in the Rapidly Changing World
Rethinking the Vision for Higher engineering Education

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ENGINEERING EDUCATION IN A RAPIDLY CHANGING WORLD

Rethinking the Vision for Higher Engineering Education

Second Revised Edition

SECOND REVISED EDITION

TU Delft Delft University of Technology

4TU. CENTRE FOR ENGINEERING EDUCATION

Colophon

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"Our situation is not comparable to anything in the past. It is impossible, therefore, to apply methods and measures which at an earlier age might have been sufficient. We must revolutionize our thinking, revolutionize our actions, and must have the courage to revolutionize relations among nations of the world. Clichés of yesterday will no longer do today, and will, no doubt, be hopelessly out of date tomorrow."

Albert Einstein (1948) in
"A Message to Intellectuals"

Foreword to the Second Revised Edition

When drafting the first issue of this document it sometimes felt like I was manoeuvring a small canoe through a highly viscous fluid of conservatism and complacency, with everybody bogged down by today's thinking, preparing next Tuesday's nine o'clock lecture, aiming for the best learning experience by optimising teaching and assessment. The issues of the day are about the "how next week", not about the "what next year", let alone the "why in the next decade". After publicising I was happy to discover that I had been somewhat mistaken in my impression. Many people in universities, industries and research institutes across the globe informed me they are with me in my canoe, or want to be. That they want to rethink higher engineering education and help initiate change to enhance the effectivity of engineering study programmes and professional training. Like me, they are concerned about as well as challenged by the technological revolution that will rock the foundations of engineering education in the coming decades.

The first edition inspired many conversations about "The Future Engineer" at my home university and many partner universities and institutes abroad. The "Free Spirits" Think Tank of the 4TU.Centre of Engineering Education in the Netherlands, which investigates the rise of new engineering profiles in the coming 10 to 15 years and develops matching scenarios for campus education in 2030, has taken my vision as a source of inspiration. The numerous meetings and workshops I attended between engineering academics, industries and engineering consultancies in the Netherlands and abroad, and the conferences and panels of the global CDIO Initiative and the World Engineering Education Forum (WEEF) in Florence (2015) all discussed the subject of the engineer and industry of the future. They addressed the impact of the changing global economy, the fast pace of change, the limited shelf life of specialist knowledge, the university's role in innovation, the need for an interdisciplinary mind-set, the global interconnectedness, the rise of machine intelligence and the use of open standards. These are all aspects that shape the rapidly changing world in which we live and in which we educate tomorrow's engineers, who might be a different breed than the ones we have been educating over the past 50 years. These factors set the scene for the "why" and "what" of our future education.

My personal interest in the changing world and its impact on engineering education was piqued in 2013. First David Goldberg of iFoundry visited my office and talked about "The 7 Missing Basics of Engineering". Then I attended a keynote speech at the CDIO Annual Meeting also in 2013 at MIT by Tony Wagner of Harvard's Innovation Lab about "The Seven Survival Skills", which, by the way, have nothing to do with the seven missing basics Goldberg speaks of. More recently a keynote presentation at the World Engineering Education Forum 2015 in Florence by Sabina Jeschke, Vice-Dean of RWTH Aachen University, and the discussions in the World Economic Forum in Davos in January 2016 forecasted the systemic impact of the Fourth Industrial Revolution on society as a whole. There can be no doubt that higher engineering education is not keeping up with these rapid technological, societal and economic changes. In the 21st century, 20th-century solutions and thinking are not going to get the job done. Pioneering schools in Asia, such as the Technology Leadership and Entrepreneurship programme and the Individualised Interdisciplinary Major at the Hong Kong University of Science and Technology, as well as the Outside-In Curriculum in Engineering Systems and Design at the Singapore University of Technology and Design (SUTD), the Renaissance Engineering Programme at Nanyang Technological University (NTU), and the Center for Entrepreneurship and Innovation at the Skolkovo Institute of Science and Technology in Russia, all experiment, develop or innovate, emphasizing interdisciplinary opportunities and opening up career prospects to innovation and advanced technologies. I realised that the engineering and academic worlds around us are changing rapidly, but that many engineering programmes seem little aware of the impact this has, or that they show a dangerous degree of complacency.

This document provides a lens through which you, the reader, can look into the engineering future so as to foresee trends in or concerns about your engineering education. It does not consider what the jobs of the future will be, but rather looks at the future proficiencies and professional capabilities that will be required for the various jobs in the field. It concentrates specifically on the "why" and the "what" of our education. I start with a conceptual mission statement for engineering education at TU Delft in the 21st century, which functions as a beacon for my investigation. In line with this mission statement I establish vision statements for a number of attributes that our engineering students have to acquire in order to secure a successful career in the future. They are the attributes most frequently addressed in literature, conferences and workshops about innovative (engineering) education, societal challenges and developments with regards to engineering sciences. They are highly relevant for students we educate in the Masters and prepare in the Bachelors. My vision statements are based on the vast amount of sources used to generate ideas and "read around" the topic (listed in the bibliography): literature, personal notes of presentations, roundtable sessions, panel discussions and workshops with universities and global players[1] in business and development, mainly at European conferences and in workshops on engineering education and skills. In that sense the visions in this report are multi-sourced and leveraged with my personal touch.

"Engineering is much more than what engineers do."
Trevelyan (2014)

Since Boeing issued a list of "Desired Attributes of an Engineer" in the nineties, changing higher education in engineering has been the subject of an on-going discussion among industries and engineering universities in the US and Western Europe. In many organisations, project teams of wise men and women have elaborated on and specified the engineering attributes and the attainment levels in ever greater detail. But it is achieving the change that has become the serious barrier. Many engineering programmes have hardly changed over the past 30 to 40 years. We can no longer stick our heads in the sand and refuse to see that both technology and society are fundamentally reshaping the engineering profession. There is a growing concern that universities perpetuating an old paradigm may cause future engineering graduates to become employees who have difficulty dealing with the pressing demands of the fast-paced global market place, and may even end up as a commodity. Can our programmes absorb changes in the world, 10 to 15 years from now? It is the joint responsibility of the academic and supporting staff and the student body to become aware of our rapidly changing world and make conscious choices concerning if and how we want to reflect major shifts in engineering attributes in the learning outcomes of our programmes.

In this revised paper I have added material from about 50 new sources that analyse and document the changing societal needs regarding solutions to complex interconnected challenges, as well as the necessary adaptation to globalisation and the confluence of emerging breakthroughs in technology. The chapters on creativity, global mind-set and employability have been completely rewritten. An anthology of the impact of the Second Machine Age

1 European Space Agency (ESA), Airbus Industries, ASML, Advisory Council Aerospace (TUD), Boeing, General Electric (GE), German Aerospace Centre (DLR), National Aerospace Laboratory (NLR), Philips, Rolls Royce, Royal Netherlands Airforce, Safran Group (France).


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(Erik Brynjolfsson and Andrew McAfee, 2014), also known as the Fourth Industrial Revolution (World Economic Forum 2016), which discusses globalisation and digitalisation, the horizontalisation of the socio-economic world, and the blending of the technical, economic and societal cultures has been added. It paints a kaleidoscopic and fractured view of the world of tomorrow's engineer. In a new overarching chapter, I connect the many dots of knowledge and skills mentioned in this paper and map them back to programme and university levels in a Mind-map. This reveals the three cornerstones of tomorrow's engineering education: Innovation, Employability and Community. For ideation I have included an Appendix that describes three practices I have used in workshops or panels with academia, industries and high-tech start-ups to initiate change.

I hope this second revised edition will inspire and motivate many people to get in the canoe with me, that it can provide a sense of direction, and keep up with the pace of change in engineering and society in our educational programmes. The future may arrive long before we have begun to change.

Aldert Kamp

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Council member of the Worldwide CDIO Initiative

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Mission Statement for engineering education TU Delft

TU Delft's Mission Statement "To make a significant contribution towards a sustainable society for the twenty-first century by conducting ground-breaking scientific and technological research which is acknowledged as world-class, by training scientists and engineers with a genuine commitment to society and by helping to translate knowledge into technological innovations and activity with both economic and social value" addresses societal relevance, the 21st century, a commitment to society, and translating knowledge into solutions of value.

But because statements concerning research, education, and enterprise and research commercialisation ("valorisation" in one word) are all rolled into one here, this mission statement does not stick in the mind, reflect TU Delft's slogan "Delft Engineers: Making ideas work", or show the ambition that our educational programme should be a place where students learn to stimulate their creativity and develop their talents.

In order to find my way around in a changing world that will potentially impact engineering education, I needed an education-oriented Mission Statement. This can serve as a beacon for both the author and the reader to identify the key attributes of tomorrow's (Delft) engineering graduates, and forms the basis of the development of vision statements for these attributes.

The following Mission Statement for TU Delft's education, which I have formulated in a strictly individual capacity , is not only in line with the existing TU Delft Mission Statement and dominant university culture, it also reflects TU Delft's slogan and sticks in the minds of students and staff.

"To produce self-motivated and responsible engineers of the highest quality who are able to help solve the societal and engineering challenges of the 21st century through creative workable solutions."

A world of Volatility, Uncertainty, Complexity and Ambiguity

After 2500 years, the observation of the Greek philosopher Heraclitus seems more relevant than ever: “The only constant in life is change.” We have entered a threshold decade in which three converging driving forces are changing our world into one full of Volatility, Uncertainty, Complexity and Ambiguity, a VUCA world. These forces are:

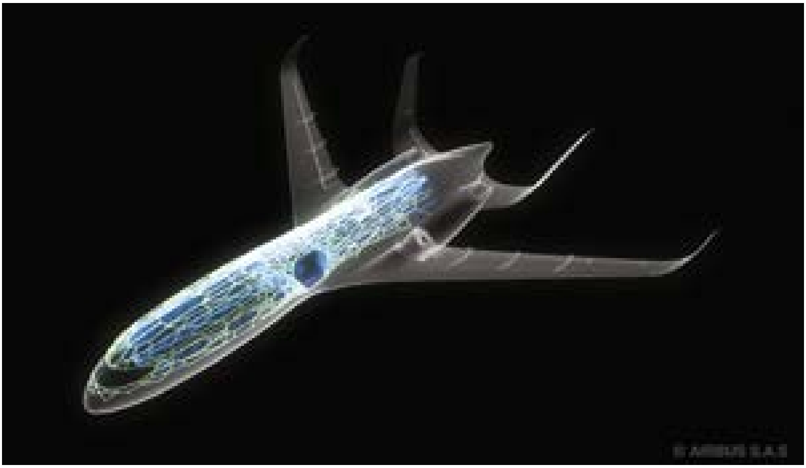
1. globalisation and digitalisation,
2. the horizontalisation of the socio-economic world,
3. the blending of technical, economic and societal cultures.

The impact these forces are having on technology, business, organisational and social systems today, forecasts the kind of world we will have in 2030, a world in which future generations of students will have to study and graduates work. The best way to learn about the future is to immerse yourself in this VUCA world. I will therefore paint a kaleidoscopic image of its landscape, not read from a crystal ball but largely based on the analyses and syntheses found in “The World is Flat” by Thomas Friedman (2007), “The Second Machine Age” by Erik Brynjolfsson and Andrew McAfee (2014), “The Future of the Professions” by Richard and Daniel Susskind (2015), and the “Portrait de l’Ingénieur 2030” of L’Institut Mines-Télécom (2014).

Globalisation and digitalisation actually impact any job and any problem, solution or innovation in any engineering discipline. A common thread in this world is the blurring of boundaries – between nations, disciplines, and professions, between academia and industry, and between applied science and engineering. Everybody and everything is networked and connected. Distance, space and time are no longer boundaries for the practice of engineering or innovation. Mobile communication, social media, cloud computing, big data analytics, smart devices, connected objects and sensors fundamentally change the way people live, work, communicate, travel and play.

Digitalisation leads to an exponential proliferation of knowledge and information, characterised by flux and glut. Big data is a major opportunity for the engineer to improve process, for instance design and maintenance processes and applications. But as big data continuously redraws the line between public and private personas, it is also a major challenge for engineering to assure digital wellbeing and cybersecurity. Big data analytics and the hyper-connected environment of the Internet of Things play an ever-increasing role in the development of products and enterprises. They empower data-driven management and re-shape engineering and business processes. Information, interconnectivity and search engines are revolutionising the way people innovate, engineer, design, think and live. Machines are increasingly capable of making predictions and generating new knowledge, relying on different kinds of knowledge and information, and using different approaches than human engineers would do in tackling the same problem. Intelligent machines learn at an accelerating rate since they are uplinked to the cloud and incorporate the experience of every other machine of their kind almost instantaneously. They complete more and more non-routine cognitive tasks and develop broad abilities in domains that used to be exclusively human. The potential rise of quantum computing and simulation may further enhance the computational power that enables the simulation and behaviour prediction of highly complex systems and solutions to fundamental problems that are beyond the realm of digital computers today. The improvements in computational power is taking engineering away from the classical trial-and-error methodology.

Success in the engineering business depends on developing well-performing products with zero defects right the first time and on-time. Even greater success can be obtained by partnering up, offshoring certain R&D (Research and Development) activities, or joining open innovation labs. Research is increasingly detached from production and for their R&D, enterprises seek out pockets of excellence from around the world. As activities are broken down into smaller activities or digitised they are easier to share out. More and more projects draw on disparate networks of qualified experts who work together to solve engineering problems that are posted by companies, or compete to offer alternative and better

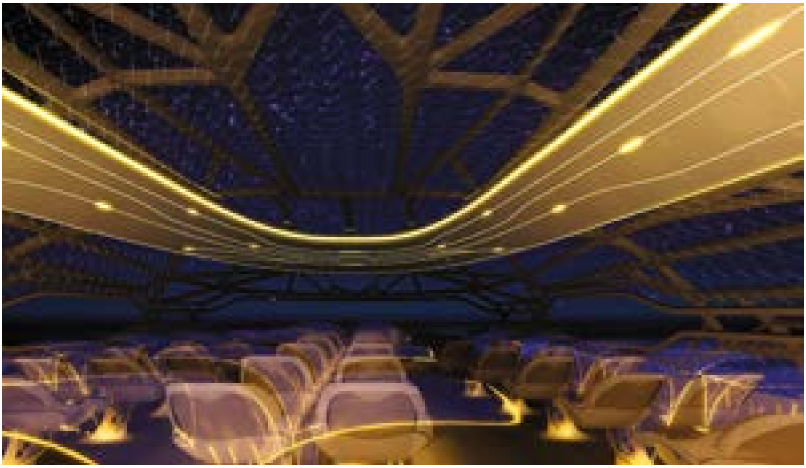


The future by Airbus - The Airbus Concept Cabin Xray: Airbus predicts that aircrafts in 2050 will have a bionic structure that mimics bird bones to allow for a lighter weight structure and open panoramic views (source: Airbus S.A.S.)

solutions. These open-sourced networks have their own models, collect their own data and focus on specific aspects of a system to be designed or researched. They deliver services in a decentralised pay-per-task structure. These "open-collar" workers form the bridges between individual designers or scientists (who need not know one another) and companies with specific or urgent research or engineering needs.

The race to find talented students, professors and young scientists is a global one, and can be summarised as a "commodification of higher education". Talent mobility is an important driver for creativity and innovation. Mobilising talent means moving jobs to where the talent is instead of recruiting talent for where the jobs are.

Globalisation is boosted by the growth of science in emerging countries. It opens up vast talent pools of young engineers who may be equally or even better skilled and more productive than people from the industrialised world. People in emerging countries are on an equal footing when it comes to competing for global knowledge work such as large-scale engineering and research projects in urbanisation, coastal management, and energy transition. Research funds for projects related to global challenges such as the scarcity of resources, or those related to emerging technologies of functional bio-inspired materials and



The future by Airbus - The Vitalising Zone by Night: Passengers in 2050 sit back and enjoy the night sky when travelling to destinations due to the bionic structure and interactive membrane of the Airbus Concept Cabin (source: Airbus S.A.S.).

structures, additive manufacturing, or designing beyond nature, are acquired in competition with companies in emerging countries. Engineering sciences in Eastern Asia are rapidly becoming bigger and better. More lenient regulations and higher public investment means innovations in these emerging countries can accelerate faster than in Western Europe.

The horizontalisation of the socio-economic world transfers power to consumers and end-users. They demand that products and services that are marketed on a global scale feel local, personalised and one-off. Those products compete on a global scale by customizing them locally. In 24/7 discussions on social media, consumers compare prices and deals online and determine in real-time the essence of products and brands. There is an increasing demand from governments and markets for sustainable processes and products. Innovations not only depend on Technical Readiness Levels, but also on Technology Acceptability Levels, and enterprises are called upon to be transparent at every step of a product's life cycle.

Horizontal communication through interdisciplinary networks and collaborative models has taken the place of hierarchic layers, thereby removing the disciplinary compartmentalisation in engineering institutes and companies. Angel investors, crowdfunding and crowd-sourcing are increasingly used to obtain funds for services, innovative ideas or content by soliciting contributions from large groups of people, especially online communities. Larger organisations sponsor smaller entrepreneurial teams within their own walls ("intrapreneurial" projects) to help generate new ideas and spur innovation. The ease with which smaller companies can be set up makes employees less captive to a single employer. This has led to a liberalisation of the world of work where hierarchies have become fluid. Open sources and common standards are frequently used.

Traditional innovation models, with all of the relevant disciplines in house, are shifting to more open innovation models that make use of a supply chain for specific knowledge and prototyping. Open innovation is particularly useful at the lower levels of technology readiness. In open-innovation spaces, the resources for innovation are available almost instantaneously to anyone with access to the cloud. "The other" is not necessarily a rival but may be an interesting resource instead. In this horizontal world, the road from science to innovation, and from invention to market penetration is much shorter. Incubators are often supported by accelerators.

Horizontalisation is not only taking place in the world of engineering. The liberalisation of research is facilitated by the low-cost accessibility of information to almost anybody across the globe. The university's leading role as a producer of new knowledge is under attack. Higher education is being liberalised, monetised and privatised by means of online courses by renowned professors. Learning analytics are transforming traditional courses into ways of advanced personalised learning. It makes education more technological, and less student and teacher centred. New additive manufacturing techniques enable the liberalisation of the manufacturing of intricate industrial parts or replacement parts of human bodies, using 3D-printers as portable factories.

The blending of technical, economic and societal structures is leading to business and innovation approaches where technology-driven innovation is replaced by more client- and consumer-driven approaches. The successful marketing of mass consumer products is often about launching beta-versions instead of products with zero-fault performance, as was the norm in the 80s and 90s. For the manufacturing and servicing of capital goods such as commercial aircraft, success obviously still depends on zero defects and low recurring cost. But the conceptual thinking of engineers has become much more linked to the customer and the end-user. More and more, the engineer is becoming the mediator between technical specialists and daily life.

Access to easy-to-use, powerful software, tools and equipment, along with online access to market and funding data, skills and knowledge, are revolutionising the way things are designed, developed, manufactured, financed, sold and consumed. Prototypes are being designed by teams of experts, engineers, students, entrepreneurs, financiers, crafters, suppliers and customers in makerspaces while the specification is still being written. And instead of innovation work happening in isolated research laboratories, entire organisations and all of its employees engage in trend spotting and ideas generation. The high speed of change and innovation implies short-term thinking. Businesses and organisations are overexposed to intense competitive and operational disruptions, which requires greater resilience, also of their employees.

Enterprises choose diversity-in-thought as their strategy to innovation. The enterprise that generates the most "wows" wins the day. Teams of different backgrounds exploit differences in culture, politics and socio-economic environments for the benefit of technological innovation, product design and engineering business. MOOCs, makerspaces, international campuses and group projects: lifelong learning is produced in formats that assure diversity so as to meet the needs of the technical, financial or governmental stakeholders and different cultures.

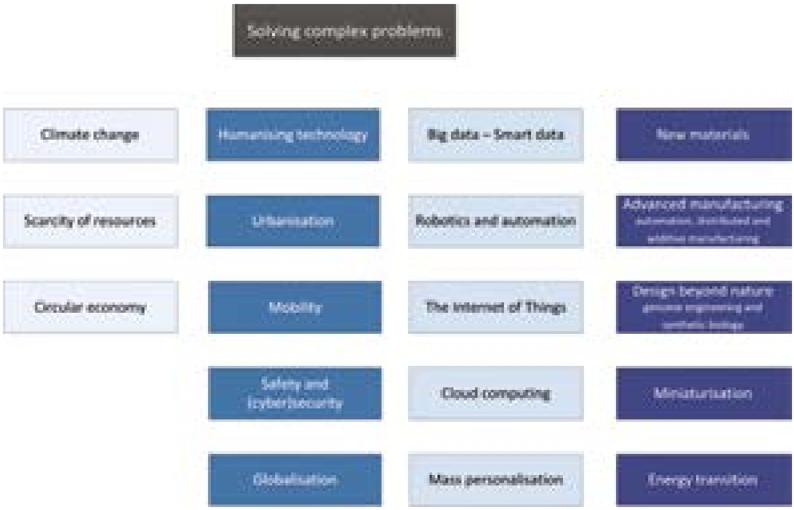
The above is a kaleidoscopic preview of tomorrow's world of work for our engineers and shows the many flavours of the VUCA world. Innovation drives growth but also leads to instability. It is full of dangers and sparkling opportunities. In the coming decades, we will undoubtedly see that we have failed to spot new important developments that will further reshape the future, such as a failing to solve world's challenges, a slowing down of global integration by the rise of protectionist barriers, or a repositioning of China's economy.
The VUCA world is uncertain, complex and continuously changing, and our educational programmes are part of it. Universities have to rethink their role in teaching engineering and the associated professional capabilities. No matter how uncertain or complex the future may be, our novice engineers have to be ready to deliver and get things done in the New Economy.

Engineering education at a crossroads

Between now and 2050, the world's population will increase from six to more than nine billion people. Eight of those nine billion will live in the less developed countries of Africa, Asia, and Latin America, whose economic growth is expected to be only slightly less than that of highly industrialised countries. They present future society with enormous challenges on many fronts, such as energy transition, infrastructure in urban settings, mass migration, mobility, climate, healthcare for an aging population, and social as well as cybersecurity and safety. Regions and cities will encounter their vulnerability and inability to respond to all these crises. And because they are so deeply interconnected, the landscape of these challenges is dramatically different from that of the 20th century. They require solutions that balance technological innovation, economic competitiveness, environmental protection and social flourishing. To understand and solve them, incremental solutions will not always be enough. The approach to these problems must be holistic, flexible and adaptive, integrating many diverse opinions and interests.

> *"Nowadays we attempt to educate 21st-century engineers with a 20th-century curriculum taught in a 19th-century institution."*
>
> *Grasso and Burkins (2010)*

The accelerating technological revolution is the other side of the equation. We are on the brink of a period of irreversible change in technology, with new ways in which engineering expertise is made available to society. The exponential growth and fusion of emerging breakthroughs in sensor technology, artificial intelligence, robotics, the Internet of Things,



Megatrends in engineering (adapted from Kamp, Klaassen, 2016)

bioengineering, etcetera, converge because of the hyper-connectedness of the digital world. This revolution will transform our life, world of business and the global economy as we know them today. Huge steps in scientific discovery and innovation in many fields must therefore be expected over the coming decades. Technology, the domain of engineers and engineering scientists, is an essential component in making these innovations possible. Our graduates will be at the heart of this revolution. By 2040, the students of today will be halfway through their career and operate as specialists, integrators and innovators of ideas and technologies across the public, private an academic sector. They will need cross-cutting capabilities and a mind-set beyond technical expertise to link disciplines and industrial sectors. Many of today's engineering tasks (and curricula in higher education in engineering) still focus on typically 20th-century how-to-do-it activities, associated with product and service design, manufacturing and support. They made sense in the 20th century, but tomorrow's engineers will be called upon to perform an increasing amount of what-to-do functions, and engage with experts from multiple fields. This new breed of engineers will not only need to be comprehensive problem solvers, but also problem definers, leading multidisciplinary teams in setting agendas, and fostering innovation. They will produce many new technologies that will change the world. But this change will only occur when people adopt these new technologies. Engineers will therefore also need to be able to influence their colleagues, customers and business managers and develop an entrepreneurial attitude during their study.

Backward mapping these perspectives to higher engineering education, shows us an increasing need for training in creativity and innovation skills, "out of the box" thinking, and a learning environment where divergent thinking, opinion generating, and subjective interpretations are encouraged. These ingredients will have to complement, and partly replace, the styles and skills that are traditionally associated with engineering, such as abstract thinking, a focus on correct and precise answers, and a disposition toward objectivity. Engineering education must be regarded as a strategic foundational element, alongside technical research, in building innovation capacity. Engineering is the social practice of conceiving, designing, implementing, producing and sustaining complex technological products, processes or systems. But many of the societal and engineering challenges are so complex and multidimensional that they cannot be unlocked with the old-fashioned key of sciences and technology alone. This high level of complexity is often caused by the emergent behaviour of system development, which changes with time and cannot be predicted from its constitutive parts. Uncertainty and delay are mostly caused by the never-ending input of new information, which requires the engineer to constantly adapt their behaviour and strategies. This is especially true when human behaviour, interpretations and decisions play a key role in solving the problem. Solving complex systems therefore not only requires a solid foundation in mathematics and natural sciences, but also an understanding of human nature. Familiarising students with human risk aversion for instance, makes them aware that technical problem solving in engineering is usually avoided. To lower uncertainty and development risk, solutions that have been tried and tested in the past are used instead. And familiarising students with the fact that different people view the same thing differently, makes them see how human diversity in teams lessens the consequences of uncertainties caused by human behaviour. The skills of tomorrow's engineer must clearly go beyond the technical domain.

> *"There has never been a better time to be an engineer with special skills or the right education, because these people can use technology to create and capture value.*
>
> *However, there has never been a worse time to be an engineer with only "ordinary" skills and abilities to offer: Employability competition is worldwide. Engineering students all over the globe, computers, virtual assistants and other thinking machines are acquiring these skills and abilities at an extraordinary rate."*
>
> *Brynjolfsson and McAfee (2014)*

It is not trivial that the technical universities are capable or willing to accommodate the rapid changes in their educational systems. Research-intensive universities are often con-

Main knowledge and capability areas for three career choices of an engineering graduate, adapted from the Well-Rounded Engineer in McMasters (2005).

sidered the foremost places to pursue ideas in forward thinking. In reality, however, many of today's discipline-oriented, research-intensive universities are not really designed for students to play or experiment in the true sense of the world. Nor are they compatible with teaching students complex, multidisciplinary and practice-oriented problem solving. Yet both are essential for innovation.

It is TU Delft's goal to enable its students to maximise their potential contributions to the wider society and make a difference in the world by creative solutions that work. Its science- and research-dominated engineering curricula should therefore not only achieve technological depth in the engineering disciplines, but enrich and broaden the students' background as well. Our goal is to help engineering students think about the bigger picture, to let them see how social, cultural and historical contexts influence the objectives, process and outcome of their research or design work, and that their work is affected by global and social trends which may create unintended consequences. Engineering no longer operates in a vacuum, separate from society. Attaining communicative, creative and interdisciplinary capabilities, and a flexibility to accommodate easy mobility and adaptability, becomes increasingly important for students. It will involve major pedagogical changes, for instance by introducing immersive, integrated problem- and challenge-based learning around historical cases and issues that are of personal and societal significance in the real world. Students who view the world through the lens of such contextual problems and solutions, deepen their understanding of the achievements in engineering. These are situations where students use disciplinary knowledge beyond its boundaries, and lecturers move away from rote and lecture-driven modes of teaching.

Defining and enabling capabilities lie at the heart of every engineer. Engineering students are not only students of engineering, but also of the problems and solutions that may well go beyond their own engineering expertise, or even engineering as a whole. We have to prepare them for, broadly speaking, three different engineering roles they may play in their careers. Firstly, we have to enable our graduates to develop into expert, world-class engineers with strong integrator capabilities to use and advance disciplinary expertise on its fringes, or fuse technological breakthroughs in one discipline with other disciplines. Secondly, engineering graduates should be able to develop into integrators who synthesise, operate and manage across technical or organisational boundaries in a complex environment. Thirdly, our graduates should be able to take on the role of change agent, which means they must be prepared to provide the creativity, innovation, and leadership that is needed to guide research and industry to future success. During their study they must learn how to link science and engineering to the needs of society, and how to communicate this to the public. Most of today's engineers work in industry and research institutes and rarely interact on a one-on-one basis with people who directly benefit from their products or services, unlike, for instance, physicians, lawyers, and teachers. This explains why at present the public, even prospective engineering graduates, are pretty unclear about what most engineers do.

"Many programmes seem not even aware that there is a problem in focusing almost completely on technical knowledge and processes in their engineering curriculum."

Grasso and Burkins (2010)

"Technical expert knowledge can be learnt, its shelf-life is short.

Personal and professional capabilities cannot be learnt but have to be developed; they last a lifetime."

The first challenge in education has always been to anticipate the capabilities graduates need in their future jobs. "We have to educate students for jobs that don't yet exist, using technologies that have not been invented, in order to solve problems we don't even know are problems yet" (YouTube: Did You Know 3.0 - Shift Happens). What we do know is that tomorrow's world will be an intense VUCA (Volatile, Uncertain, Complex, Ambiguous), digital and hyper-connected world. Although great advances are unpredictable, and future scenarios thus full of uncertainty, it would be naïve to let that paralyse us. We might miss a next revolution, but we can be pretty sure that engineers will be better off when they master common engineering methods and tools, a set of common engineering languages like mathematics, algorithmic thinking, systems thinking, collaborative design thinking, ethics and visual literacy (3D spatial sketching, reading graphs and charts, using mind maps, thinking aloud), and when they can work across cultures. Speaking and understanding these common languages enables cross-disciplinary communication and collaboration. Most importantly, students must learn to use their imagination and have agile and resilient abilities. They have to be prepared to learn about the engineering landscape, and the kinds of practical questions that engineering scientists and professionals in their domain repeatedly face.

The second challenge is how faculty staff can teach and students can learn all that is needed to meet society's needs and help solve societal and engineering challenges in the coming decades. Transferring engineering knowledge requires different teaching and learning styles than training and fostering professional skills. Technical theoretical knowledge can be transferred and learnt, but professional skills can only be developed.

"80% of our economy is now information-based. Yet, if one would pursue an engineering degree from our university, the result would be many courses which are not significantly different from those offered during the middle of the past century, when Western Europe was largely a manufacturing-based economy."

Grasso and Burkins (2010)

We are speedily moving towards a global collaborative society, in which traditional power structures are challenged by new market developments and values. No longer can engineering education be about assimilating knowledge alone, and no longer can we be satisfied when only our smart students learn how to apply this knowledge to solve open-ended real-life problems. Our future education needs to focus on how to apply knowledge to complex, unstructured problems in a connected world. A world in which it may be neither apparent where the heart of a problem lies nor how and where interventions should be made to find a solution.

And future education will have to do more than that. Personal attributes like autonomy and empathy are increasingly important in the job market. Academic engineering education does a poor job of helping engineering students think about their own lives, their career goals, their desire for intimacy, or their plans for a productive and meaningful life. All-round engineers with these capabilities can only be produced by educational programmes that are enriched to develop breadth, both on a professional and a personal level, through capabilities such as self-regulation, relationship management, self-awareness, empathy, and social and emotional intelligence. Novice engineers not only have to be technically adept and broadly knowledgeable, but also culturally aware, able to demonstrate leadership, flexible and mobile, and have a concern for ethical issues, and able to work collaboratively and think and design creatively. They should have learnt how to communicate with the public. These requirements in itself are not new, but their importance is shifting, also in the eyes of hiring companies. The reasons why an employee is successful in his job is only partially tied to his disciplinary knowledge. More elusive factors like ambition, creativity, patience, perseverance, international orientation and social intelligence become at least as important as a diploma in engineering. For companies and organisations with their own training centres or corporate universities, recruitment on the basis of specific knowledge becomes less important than recruiting someone with great potential. It matters less that a graduate has a deep knowledge of signals and systems or microsystems engineering, if he has shown that he is a fast learner, a hard worker, an excellent communicator and intensely loyal to his employer. Companies indicate they can repair a deficit in technical knowledge much easier than they can adapt a young employee to fit in.

"Engineering students and graduates are so focused on what they are doing, they sometimes forget to look at where they are actually going or ask the question if that is even where they want to go."

Vera, Honours student TU Delft Aerospace Engineering (2015)

Some things never change. An academic engineering degree still remains a good preparation for a working life and continues to be seen as a good investment for employability. It looks almost unavoidable, however, that major parts of our science and technology curricula have to be transformed to meet the growing demand for a new breed of modern engineers and to make optimal use of new pedagogical approaches and insights. Curricular reforms should, however, not adversely affect technical depth, as we do not want to endanger the strengths of our current education, scientific research and expertise in engineering and technological specialties. In other words, adding the required breadth and enrichment should not lead to teaching less and less about more and more. In the coming decades, education in the engineering sciences must also keep its emphasis on engineering fundamentals, but in a more balanced partnership with human factors and business acumen. The two latter aspects shape the landscape of engineering practice as much as technology does.

Students need to see the engineering profession as more than just excelling in technical rigour. Sceptics often point to extracurricular activities, sidesteps, a gap year, or the first five to ten years of a career as the place where the personal and professional abilities should be developed. Indeed, expert levels in many skills can only be gained by years of experience in engineering practice and not in a university classroom. But tomorrow's job market expects that young engineers are capable to build up experience rapidly, with little support from their employer. Young engineers will therefore only be successful when they have mastered the basics of these (inter)personal and professional skills at graduation. Since the residue of knowledge and habits of mind that students take away from an academic degree programme are greatly determined by how, and how well, they were taught, the how we teach will become equally or even more important than the what and how much we teach.

Engineering education in research-intensive universities in the 21st century, adapted from E.W. Ernst; Irene C. Peden (1998).

Emphasis remaining on	Shifting to more
Monodisciplinary expert thinking	Multi- and interdisciplinary systems thinking
Reductionism	Integration
Analysis	Synthesis
Abstract learning	Experiential learning; common sense
Developing order	Correlating chaos and resilience
Techno-scientific base	Human factor and empathy; business acumen
Convergent thinking	Creativity
Understanding certainty	Handling ambiguity and failure
Rational problem solving	Complex problem solving
Independence	Collaboration
Rounded expert	Employability and lifelong learning

More than just cool technologies

The mission statement I defined in my individual capacity earlier for TU Delft's engineering education, combined with the trends and developments in higher education, the world of work and society, set me thinking about a vision for engineering education in 2030 that encompasses eight key aspects:

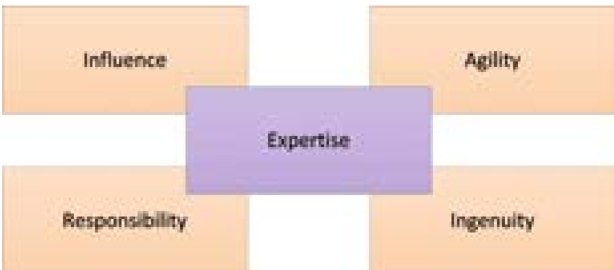
1. *Rigour of engineering knowledge*
2. *Critical thinking and unstructured problem solving*
3. *Interdisciplinary and systems thinking*
4. *Imagination, creativity, initiative*
5. *Communication and collaboration*
6. *Global mind-set: diversity and mobility*
7. *Ambitious learning culture: student engagement and professional learning community*
8. *Employability and lifelong learning*

These aspects are neither exclusive to TU Delft nor to the future. They largely concur with the categories of the Technical, Professional, Personal, Interpersonal and Cross-cultural Engineering Criteria of the Accreditation Board for Engineering and Technology (ABET) and the Revised Attributes of a Global Engineer by the American Society for Engineering Education (ASEE). In the Netherlands they have been described and elaborated in the "Criteria for Academic Bachelor's and Master's Curricula" by Meijers in 2005. These criteria have been the reference point for the final qualifications of most if not all TU Delft

Bachelor, Master and Excellence programmes. Over the past decades, most of the attributes have been mentioned in surveys and analysis reports about what universities think is best to teach, and what the world of work thinks is necessary. Although the attributes in itself are not new, it goes without saying that their relative importance shifts in our changing world, which is a result of the exponential growth of technological breakthroughs, of globalisation and digitalisation, the explosion of knowledge, and the increasing complexity of engineering and societal problems.

Engineering has always relied on knowledge and expertise that is unevenly distributed among the engineers and non-engineers in project teams. Engineers usually gain access to the required knowledge and skills by mobilising the right people when the need is there. The exploitation of available diversity becomes more important with the increasing complexity and interdisciplinary nature of the problems at hand, the larger cultural diversity within enterprises, and the further deepening and narrowing of specialisations in technology. It can therefore not be emphasised too often that tomorrow's job market not only demands engineers with the rigour of engineering fundamentals and technical expertise, but also with proven abilities of ingenuity, agility, responsibility and influence. It has become a cliché to argue that twenty-first century engineering curricula need to be reformed to shift the focus from "knowledge" to "capabilities".

"We have the choice of what type of engineer we want to educate: ("routine design engineers" - merely technically competent and designing complicated systems, "engineering scientists" – pursuing an academic career , or "holistic engineers" - trusted to make the important decisions in solving complex problems."



The five main areas of the future engineer's transversal capabilities (source: L'Institut Mines-Télécom, 2014).

In the past 15 to 20 years the accelerating rate of change in society has transformed our lives, business and economy, but has hardly influenced the engineering educational programmes. Universities hang on to past practices and change very slowly. In some ways this conservatism is positive; it encourages teachers to build upon well-established methods. But conservatism may go too far. Today is the worst time for complacency. We have entered an era where higher education in engineering may have to undergo fundamental changes, not only to benefit from pedagogical and technological innovations, but also to align with the attitudes and capabilities of today's generation of students, and better prepare the graduates for the increasing and different demands of the new world of work. Rather than wait for time to pass and then try to respond, it is better to envision these changes, forecast the capabilities needed by tomorrow's engineers and make choices about what type of engineer we want to educate (operative "routine engineers" - merely technically competent to create, perfect and operate technologically driven processes, "engineering specialists" – pursuing an academic career, or "holistic engineers" - trusted to make important decisions in solving complex problems and taking on non-technological tasks of leadership). Education has to change with the changing times. This time it may have to change more profoundly and rapidly than it has in the past 40 years in order to strengthen the position of our engineering profession as a competitive, cost-effective, highly respected and attractive option in the new world of work.

1 *Rigour of Engineering Knowledge*

Mastering depth in technical engineering disciplines and logical thought is without doubt necessary for successfully solving complex problems and advancing knowledge, now and in the future. To prepare students for the knowledge-based economy, engineering education has to focus on the acquisition and development of codified core knowledge and capabilities in the domain of the engineering sciences: to discover, analyse, conceptualise, design, develop and operate complex systems. These attributes are hard won and only come with practice and experience. Future curricula can keep their emphasis on discipline-based learning. But they also have to focus on the holistic view of a product and system life cycles, in which the students acquire a conceptual understanding by learning about the theories and principles of physical phenomena and engineering sciences, about modelling real-life problems by simplifying assumptions, so as to transfer their knowledge into solutions and feasible designs of an appropriate level of complexity. This way, they learn to alternate between the abstract and the precisely detailed, to deconstruct big problems and accept failure.

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

We should also teach our students the value of tacit knowledge, common sense and "ignorance". Not everything they will need as an engineer to design, develop and operate complex products and systems is always explicitly known. And not everything we teach is known and certain, and physical phenomena and failure are not always fully predictable, no matter how detailed and extensive our simulation models. Teaching ignorance and incomplete models leads to curiosity and students learn to cope with failure as a normal and valuable part in the development of products or services, as well as their personal development. It teaches them that aiming for the best in engineering and design is not always the best thing to do. When is good good enough?

Specialisation is needed to be competitive in innovation. In the 20th century, expert knowledge used to be the core capability. Nowadays, however, knowledge is no longer the end goal of an engineering study but an on-going activity of learning-to-think and learning-to-learn. Tomorrow's engineers no longer have to memorise everything they learnt at school. The half-life of cutting-edge specialist technology information is less than, say, five years, and much of what students learn today in a specialisation Master's is obsolete within a couple of years of graduating. Graduates become the "grazers and collectors" of information and knowledge, using search engines that highlight fragments of text that are relevant to whatever they are searching for, but unfortunately provide little incentive for taking in documents as a whole. It is becoming increasingly important to shift our educational methods from cramming large amounts of expert knowledge into the heads of our students, which primarily serves the needs of a minority of students who pursue an academic career, to learning how to acquire knowledge from the surging sea of data, and how to find out what to make of it when it has been found. In the future, the internet will be the true heart of the modern university, with YouTube and Google as omniscient librarians.

"Graduates will be the 'grazers and collectors' of information and knowledge, using the digital world."

Engineering is not only a matter of applying science, or solving problems using the theories and methodologies of math and science, but also of advancing knowledge through research and experimentation. Besides learning how to acquire and apply knowledge, it is also essential for students to develop their independence, autonomy and critical attitude.

"The core of engineering is not simply applied science, but the application of design and creativity to science."

Grasso and Brown Burkins (2010)

When we take a look at the changes in subject matter, we should expect environmental literacy, new-media literacy, and especially digital literacy to become basic literacies in higher engineering education. The massive increase in sensors (10 trillion online devices with digital sensing, computing and communications capabilities by 2030) will unleash a vast amount of data and information ("big data"). Data is the new oil in engineering and business, but is only useful when it can be refined. This requires expertise and capabilities in data analytics (control and manipulation of big and small data through algorithms, programmes and scripts), cybersecurity, cloud computing and optimisation techniques in design, engineering and research. Any engineer will therefore have to be data literate, i.e. have a good working knowledge of and skill in algorithmic thinking and programming, statistics, domain knowledge and data visualisation techniques in order to operate successfully in an increasingly "data–rich" engineering environment.

2 *Critical Thinking and Unstructured Problem Solving*

Engineering sciences are often seen as the "troubleshooter" when it comes to solving problems. However, problems are becoming increasingly complex and their solution requires engineering capabilities that are different from the rational problem-solving methods that we currently emphasise in our curricula. These complex problems do not respond well to most traditional decision analysis tools.

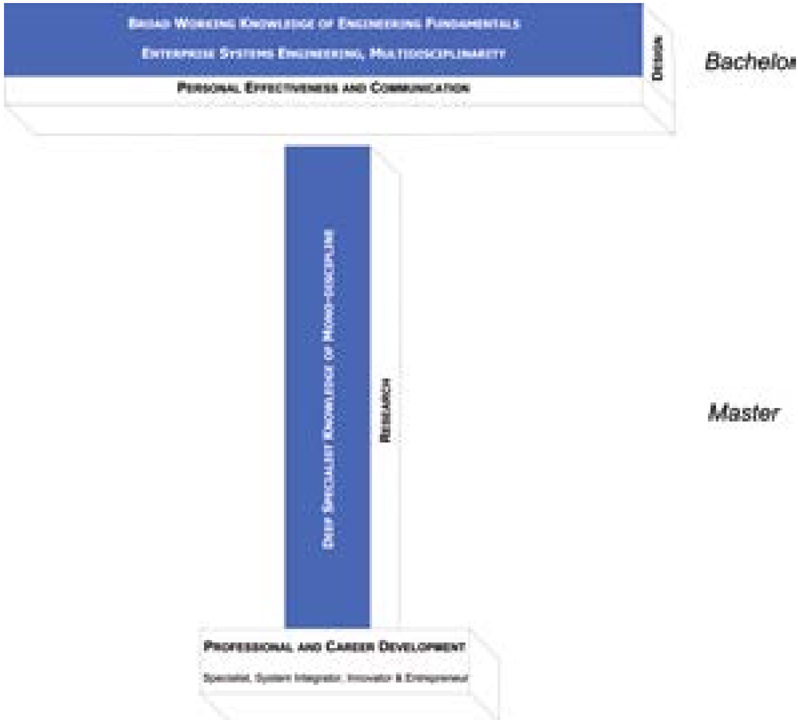
Whereas structured problems have a clear connection with a finite set of solutions that essentially occur every time, most problems in real life and business are not that straightforward and often involve economic, technical and human aspects. Seldom do they have one unique "correct" solution. Sometimes formulating the right question, or knowing how to avoid a problem rather than having to solve it, can already be a significant step in the right direction. Critical thinking is about asking the right questions. A more complex problem leads to more data, which makes the ability to ask the right questions of vital importance. Asking critical and intelligent questions helps engineers to formulate new directions and new ways of operating. It helps them to look outside the box and rethink the purpose of certain existing processes. This "question thinking" requires courage and imagination. Taking some humanities courses or collaborating in educational design or research projects with people with a background in humanities, is a highly effective way to develop these questioning and critical thinking capacities. Now and in the future, not only knowing "what", but also knowing who to ask, is one of the most effective ways to find solutions for a technical problem. Training engineering students in these simple, basic professional (communication) skills makes a lot of sense.

Computer-based, design-build engineering will become the norm for many product designs of the future. Engineers and designers will be increasingly supported by virtual assistants - smart thinking machines that take on cognitive tasks by employing artificial intelligence. In a radical concept of future "algorithmic design", an engineer sets out the design criteria for a product or systems, and algorithms sift through and iterate every parameter value possible to generate a system that best fits the design criteria. There will be an increasing demand for the kinds of skills these machines are not good at: asking questions and thinking outside the box. This makes critical thinking the single most important attribute novice engineers should have when entering the profession.

The three most common kinds of problems that practicing engineers solve are in the field of decision making, troubleshooting, and designing. For any of the three, solving the problem is more or less the same as defining it: there exists no black-and-white termination criterion. Engineering students need to learn that solutions to engineering problems are mostly true or false, are defined as good or bad, and that the termination criterion is often "good enough". They have to be made aware that engineering problems do not have an enumerable set of possible or permissible solutions. More emphasis in our curricula on solving unstructured real-life problems by combining fact-based data analysis and highly subjective and even intuitive judgements about aspects of a problem, should make the students more familiar with the uncertainty of real problems.

3 *Interdisciplinary and Systems Thinking*

Most graduates do not become discipline-based academics, and most promising breakthroughs in technology will take place at the intersection of advanced specialties. Breakthroughs in one discipline rapidly fuse with advances in other disciplines. A broad and strong intellectual base should therefore be the foundation of any educational programme. Many TU Delft programmes have adopted the T-shaped professional as a reference: with deep specialist knowledge in one technical area and a broad working knowledge and communicative skills across some other (mostly technical) areas. The T of the T-shape in Delft often stands squarely for Technology. In order to come up with valuable breakthroughs in the future, engineers must be able to combine specialist mono-disciplines (such as composite materials engineering, nanoengineering, digital signal processing, genome engineering), cross borders and respect other people's views. This calls for expert thinking, but even more for an ability in complex communication. Collaboration and multi- and inter-disciplinary thinking that cross the borders of engineering become increasingly important. This is reflected both in the arm of the T-shape as well as the bar at the bottom of the stem, which represents non-technical capabilities, particularly related to innovation, marketing



The model of the T-shaped professional as used in discussions about the profile of the TU Delft programmes in Aerospace Engineering.

and services. Students who pursue a career in engineering business management combine deep specialist knowledge in an engineering domain with deep expert knowledge in business functions (MBA), which makes them into so-called Π (Pi)-shaped engineers.

Today's inclination towards deep specialisation in the Master degree programmes, where students become expert in technical analysis through individual intellectual efforts in ever smaller corners of their discipline, with little communication with neighbouring fields, discourages multidisciplinary collaboration, and leads to a lack in holistic thinking and relationship skills. This is in stark contrast to the world of engineering practice, where engineers with highly specialised fields of expertise collaborate and rely on other people to provide the comprehensive set of knowledge and expertise that is needed to resolve multidisciplinary problems. The trend toward ever deeper specialisation and solitary work in the Master degree programmes unintentionally prevents talented students from reaching their leadership potential.

In high-tech industries that design complex products, systems or machines, the trend of deep and narrow specialisation leads to a higher fragmentation of the design work, which in turn results in a growing unawareness of value creation by the individual engineer, "over-engineering" and higher cost. Paradoxically, narrower specialisations lead to a higher demand of system integrators in industries. High-tech enterprises increasingly look for engineers who can develop the outline for an integral design, keep the overview and keep an eye on system design consistency. These system architects and integrators not only need solid fundamental knowledge, but must understand "the big picture", have a sense of the multidisciplinary problem domain and a good awareness of the business side and human context. They must be able to reduce the complexity, uncertainty and ambiguity to workable concepts, and create value for the enterprise and customer.

System architects attain their higher rank by years of experience in the field – something that cannot simply be taught at university. And yet the speed of gaining experience during their career can be accelerated by acquainting students with interdisciplinary and systems thinking at college. They have to learn the different methods of inquiry and arguments that exist in different disciplines, and how tools and materials of one discipline can illuminate the subjects of another. They need to learn how and when to incorporate social elements into a comprehensive systems analysis of their work. In other words, they have to learn how to solve complex problems from a systemic perspective, drawing on multiple disciplines, seamlessly integrating multiple perspectives and methodologies by synthesising information, data techniques, tools and perspectives, and concepts or theories from two or more disciplines. Although the trend in research and higher education towards further specialisation continues unabated, many employees cry out for synthesis. The synthesising mind will become highly valued in the 21st century. It is essential that we teach students how to acquire more than one perspective on the same subject – something that does not happen in the current curriculum. Simply educating students in more than one engineering discipline, though, is not the solution to learning how to synthesise different disciplinary insights.

Different perspectives are also found in interdisciplinary engineering. Systems engineering and technical management have been a major foundation for technical leadership in complex systems design in military and space systems, particularly since the middle of the 20th century. Systems engineering has been a vital component of engineering that helps solve complex multi- or interdisciplinary problems. But the technically oriented systems engineering of the future may have to shift to Enterprise Systems Engineering. In order to design systems that function as elements of comprehensive complex enterprises, future systems engineers must know how to look beyond the system in isolation, and be able to consider the characteristics of the enterprise in which the system operates as well as the context in which the system is developed. These systems engineers will work closely in online service networks with disciplinary experts and data scientists who master the tools and techniques that are required to capture and analyse large amounts of information, in order to identify trends and correlations in product and process performance and behaviour over time. These data scientists and experts are for instance capable of turning raw manufacturing process data or product usage information from data communities or the Internet of Things into actionable insights for an enterprise.

This makes systems engineers no longer architects who guide engineering projects for clients from concept toward strategic goals, but leaders who are capable of balancing their technological skills with the demands of restricted budgets, regulations, collaboration complexity, public safety impact and public understanding. It is these "people" components that introduce much of the uncertainty and complexity into engineering projects. Systems engineering methodologies currently taught will therefore need to transform within a framework of complex systems science that comprises social, operational, and economic aspects, as well as engineering. With more resources being devoted to solving complex engineering problems from the microscopic level of information and communication technologies, new materials and nanotechnology, to the macroscopic level of complex systems of mega cities, wind farms and global systems such as cyber-infrastructures and civilian airspace navigation, there is an increasing need for Enterprise Systems Engineering and technical management to become essential interdisciplinary elements in the academic life of each and every engineering student.

> *"The days of engineers creating systems and processes without an understanding of the impact created by the end product are over. Engineering no longer has a life of its own."*

Learning interdisciplinary and systems thinking will not be limited to the engineering domain. Engineering can no longer operate on its own. Almost any engineering practice involves team-based, cross-disciplinary projects with contributions from engineers and other human actors such as contractors, customers and governmental agencies who often have a background in humanities or social sciences. A team that exploits the differences in thinking and acting styles of people with diverse backgrounds, will outperform a group of the same kinds of individuals. The ability to apply theory to difficult and unstructured problems in collaboration with other people is a key attribute for engineers who want to be innovators. Data scientists, for instance, combine technical skills, analytical and industry knowledge and business sense to turn data into value for innovation and productivity. Learning-by-doing (-together) when it comes to tackling real-world, authentic problems and encouraging risk taking becomes an important aspect of future educational programmes. Interdisciplinary thinking requires the synthesising of disciplinary knowledge and stakeholder knowledge (pulling together what is known about a problem from both academic knowledge and practical experience) and the understanding and managing of various unknowns (appreciating that not everything about a complex problem can be known and that the remaining unknowns must be taken into account in the decision making process). Future education has to address interdisciplinary problem-solving techniques that do not only involve different engineering disciplines, but also the social and human factor. It may require a change in educational approach, with students taking courses from fields that traditionally are not taught in engineering programmes. But this enables them to compare, contrast, connect and adjust disciplinary concepts, theories and methodologies. These courses help students form a deeper understanding, see the bigger picture, make the curriculum more relevant to them, and build connections between central concepts within mostly mono-disciplinary engineering and at its fringes. These capabilities provide our graduates with integrated engineering and research approaches that give all stakeholders a better understanding of a problem and supports them in making decisions.

4 *Imagination, Creativity, Initiative*

Where "global knowledge" and convergent thinking were once essential for leaders, "creativity" is the most important leadership quality for the engineer of tomorrow.

> *"Creativity will be the most important leadership quality for the engineer of the future."*

Creativity involves the ability to put things (words, concepts, methods, devices) together in novel ways. It involves divergent thinking and depends on connecting disparate dots of knowledge. More often than not this is driven by collaboration as much as, if not more than, by solo work. Creativity is not only instrumental in finding more solutions to engineering problems or never-before-thought-of solutions, but also in building agility, i.e. looking at the world in more than one way, and with a greater awareness that change often creates opportunities.

We have to familiarise our students with integrative thinking, in order to mesh together different perspectives and disciplines to build a resourceful, resilient and open mind. Given the speed of change and the resulting complexity, students have to learn to go beyond knowledge, expertise and logical analysis, and develop a courageous attitude towards being creative and addressing different ideas. Progress in science and engineering are often the result of unexpected leaps of the imagination that are made intuitively. Intuition requires an open mind that asks about the "what" instead of the "how". It is often associated with the concept of entrepreneurial engineering. Engineers will only excel at creative problem solving and different ways of thinking when they have learnt to sketch a problem in their brains, see the world through the eyes of a practitioner from more than one discipline, and master the ability to combine logical analysis with intuition. However, generating innovative ideas alone is not enough. They have to be carried through to their final form. Creative solutions have to be analysed and weighed up with a critical eye, which requires convergent thinking. Engineering education therefore has to provide instruction and practice in both modes of thinking.

> *"Bachelor student experience has to bear out the creativity and innovation promise of careers in engineering."*
>
> *Grasso and Burkins (2010)*

In the future world of work, engineering activities that can be deconstructed into a sequence of clearly defined (but not necessarily simple) actions, are ultimately easily duplicated, and therefore likely candidates for automation or outsourcing to low-cost countries. A wave of technological progress may dramatically accelerate the automation of brain-work. Particularly the big data that an exploding number of sensors provide, combined with emergent artificial intelligence offer solutions to many of the engineering problems that hindered sophisticated algorithm development for robots in the past. Engineers of the future will be increasingly supported by robotic personal assistants, or cognitive computing systems, who get to know their controller through continuous interaction or via a network of similar robots via the cloud. They will be able to complete more and more non-routine cognitive tasks. They will learn to offer guidance and forewarning, even before designers or engineers know that a problem or opportunity has arisen. They will gradually redefine the relationship between the engineer and his pervasive digital environment.

The relatively low susceptibility of engineering occupations to computerisation is largely due to the high degree of creative and social intelligence they require. Thinking machines will be crunching data, sure. But they still have limited skills in recognising patterns from sensory input, making smart choices or pulling out concepts at higher levels of abstraction, something humans excel at. They are good at interpolation, but stumble when a decision requires intuitive steps beyond the data available or a consideration of social aspects or other contextual arguments. Thinking machines are bad in emergent thinking and cannot tell the story about why they did what they did, nor do they have the slightest idea what they are thinking. And so, ideation, coming up with new ideas or concepts, and taking social or contextual aspects into account is something that computers cannot (yet) do. What-to-do engineering that is combined with technological excellence, is a skill difficult to duplicate, automate, or outsource. It is to be expected that what-to-do engineering will become a core capability for tomorrow's engineer. As intelligent systems become more skilled at performing more complex tasks in the coming decades, it is up to the engineers to develop the mathematical framework and programme, and manage these machines so that they are able to build models about their own "thinking". The talents of a robot end at the limits of its programming.

Although the world is changing rapidly it is unlikely that the practice of engineering will be completely recast in the coming decades. Original creative designs are not always the preferred option in engineering business. They are time-consuming and expensive and introduce uncertainties in their development and implementation. Also, creativity in future engineering practice will often lie in modifying existing and proven designs, and in knowing how to work within a set of constraints that are imposed by applicable engineering standards, rather than start designing creatively from a blank sheet of paper. In the eyes of the novice engineer standards inhibit truly creative designing. In reality standards represent an accumulation of experience that saves on development time and reduces cost and risk. Intelligent systems will acquire these accumulated experiences as well and support engineers during the creative design work. In the coming decades, increasingly capable non-thinking machines are expected to perform more demanding tasks and outperform human engineers in solving the kind of problems that used to be their exclusive domain. These machines build neural networks by seeing the world and consuming data, which enables them to learn like human beings. Other types will operate in entirely different ways. By using statistical modelling and making sometimes unthinkable connections, learning patterns, correlations and rules, they will, through their spectacularly forceful processing power and limitless storage capacity, produce probabilistic outcomes that may seem ingenious, even creative or innovative to today's engineers. These non-thinking machines might yield creative designs, novel ideas or "unthinkable art" by making combinations that the human brain will never make.

The fact that creativity will become the most important leadership quality, should imply that its value is explicitly communicated to students. Engineering education has to shift from predominantly feeding information, to stimulating the student's right hand brains. This can be done by creating strong relationships rather than executing simple transactions, tackling new challenges instead of solving routine problems, synthesising the big picture, and considering problems from different perspectives, rather than analysing a single component. Seldom do passive learners yield creative engineers. To awaken curiosity and stimulate an open mind, we need to really challenge our students' brains. Only then will they develop the required level of creative thinking.

Academic staff often feels that creativity cannot be taught and that it should not be part of the engineering curriculum. Even though they are partly right – creativity cannot be taught as subject matter, it can be nurtured in the course programme. Creativity is not simply a set of skills, familiarity with a certain behaviour or knowledge. Creativity cannot be taught, but it can be learnt, and it is not 100% malleable because it is limited by personality. But we should awaken it via interventions, preferably for the full duration of a student's time with us. "If you don't educate creativity, you kill it, and if you don't use it, you lose it."

Engineering students develop creative thinking by progressing through different levels in their study. Taylor and Getzels (1975) distinguish five such levels. The most elementary level is expressive creativity and reflects the ability to develop unique ideas with little concern about its quality. This level is stimulated in icebreaker projects, practicals and experimental lab work or assignments that are prescribed and have known solutions. The second level is technical creativity and is about creating designs and products that meet technical requirements but have little expressive spontaneity. This level can be obtained in early design courses at undergraduate level. It involves applying recently acquired knowledge to pretty straightforward situations and contexts by following structured design methods and prescribed procedures in order to obtain known solutions. The third level is inventive creativity. It is the ability to re-engineer designs or develop new products by linking science and engineering to customer needs, and following a structured research or design methodology to obtain an unknown solution. Inventive creativity often involves the communication of the result to a non-expert public, for instance by demonstrations of functional prototypes. The fourth level is innovative creativity. This is the level where students think outside the box and move beyond the current strands of engineering thought. At this level they should be able to establish a school of thought or formulate innovative departures by a self-regulating diverse team that explores unknown ways to obtain solutions for a complex, mostly interdisciplinary, open-ended problem. This level is usually the highest achievable in engineering education. A fifth and highest level is the level of emergent creativity.

" If you don't educate creativity, you kill it. If you don't use it, you lose it."

As an example of the above, students could advance their thinking level from technical to inventive, and from inventive to innovative by advanced design courses and projects. To enhance their creative thinking level these courses would have to address universal principles which are independent of context and steer clear of a set of heuristics - codified rules, rules of thumb, or checklists that are commonly used by professional engineers and are highly context-dependent. Such recipes or checklists, typical examples of the technical creativity level, are predictive in the sense that the expected outcome is obtained when certain ingredients under particular conditions are combined and certain prescribed techniques used: tried-and-true solutions. They do not enhance student's creativity or curiosity. For inventive and particularly for innovative creativity, design courses or projects should stimulate creative thinking with open-ended formulations and questions, and even require out-of-the-box thinking, taking jumps that might seem absurd. Engineering requires not only "designing things right" but also "designing the right thing".

> *"The more possible concepts or solutions you think of for a design, the more likely you are to come up with the best solution."*

To nurture creativity, it is essential that we offer students self-directed learning environments in which there are no "stupid" questions and no "right" answers, with a high level of self-regulation and much hands-on learning: Projects where students learn to conceptualise, design, build and test experiments, machines and systems. Where they obtain the level of inventive creativity by following a classical methodology of compartmentalising by function or discipline, thinking before you build, writing it all down, following a plan, and keeping everything as organised as possible. Or where they acquire the more advanced level of innovative creativity by an agile methodology like Scrum through cross-functional team work, rapid iterations (learn-on-the-fly), rapid prototyping (fail early and cheaply) and continuous customer involvement. This methodology is particularly suitable for solving complex adaptive problems.

The presence of inventive and innovative creativity in the young generation is clearly illustrated by the renewed desire for more authentic products of quality, the abundance of user-generated videos, blogs and apps on the internet, the "maker" movement in which enthusiasts use their own 3D printers to make products out of local materials, and last but not least the extracurricular student projects. This generation spends its time and effort for free on these activities because it enhances a sense of identity and community, and because it is fun. Creating more of these study environments would provide students with a nurturing environment for creativity and the freedom to take risks, whilst at the same time allowing them to discover and develop their own intelligence.

Innovation requires whole-brain thinking – right-brain thinking for creativity, imagination and holistic system thinking, and left-brain thinking for logical reasoning, analytical thinking and planning. Creativity can also be stimulated by taking students far out of their comfort zone, by bombarding them with things they have never encountered before, and by adding challenges to their design projects. Such an "immigrant mind-set" can be created by taking students beyond the comfortable cocoon of the university: by stimulating them to study abroad, take up a placement in industries or institutes in different domains, cultures or environments, and by encouraging them to put themselves "out there" and try new things and by feeling comfortable with risk. These are conditions where students learn to network and can practice fast learning. By extracting meaning from their experiences, they will develop learning-agility, which is a key competence for personal leadership in the VUCA world.

Classroom environments themselves also create ambiances that either encourage or discourage imagination, creativity and innovation. Some environments squelch new ideas; some others seem to breed them effortlessly. Spaces that engender creativity, innovation and problem solving must be autonomous and give the students a great deal of freedom. We may benefit of the experiences in arts education where students are commonly provided with creative prompts in studio workspaces, which give them a starting place for creative design.

5 Communication and Collaboration

The internet leads to more emphasis on knowing how to find and extract information, and less on actually knowing facts. The future world of work will be characterised by an even greater reliance on breadth of comprehension, rather than depth of knowledge. Design and engineering teams are getting smaller and more agile. The opportunities and problems that future teams will have to deal with are more complex and of a much broader range than today. Solutions are likely to involve third parties and elements that are beyond the area of expertise of the technical team in question. The key to working in the new world is to master the art of working in a truly flexible and collaborative way, which requires being able to listen and teach well, to multi-task and to prioritise. Communication and collaboration are widely regarded as key assets for engineers. In today's workplace social interactions dominate the practice of engineering: an engineer spends at least sixty percent of his time interacting with other engineers, clients, supervisors, specialists, and many other people who have specialist knowledge and experience (Trevelyan, 2014). There is no reason to expect that this will change any time soon. A good fluency in the English language is absolutely essential but not sufficient to communicate in the engineering field. Recruiters of Small and Medium Enterprises (SME) prefer multilingual employees who also master the local language. Their engineers are often in contact with merely local customers and end-users. Multinationals favour multilingual employees because of their international business and expatriation strategies. They achieve good communication and adoption to the local habits and cultures by immersion, which needs a mastery of the local language. A high level of proficiency in English in combination with the mastery of another world language like Spanish, Mandarin Chinese or Arabic opens up international career prospects, also in future.

In practice, most engineering consists of team-based, cross-disciplinary projects. Engineers work in a globally connected world with international and multicultural collaborative teams, whose members may work on different continents in different cultural settings and with different time horizons, with different incentives and conflicting interests. They use complex communication techniques through social networking and interaction, both virtual and face-to-face, with ever changing tools, from email to Skype to virtual meetings and more. Advancements in technology continuously redefine how engineers communicate, as global collaboration, mobile computing, and 24/7 product development permeate practice.

> *"The way an engineer interacts with other people determines how effective his or her engineering contributions will be."*
>
> *Trevelyan (2014)*

Digital work, however, makes working relationships more complex. Although the teams are more connected, the social relationships are more fragmented and impersonal than 20-30 years ago. The ever increasing deconstruction of project work into smaller activities that are conducted simultaneously in several different locations leads to numerous specialised networks of engineers. In combination with the social media these networks will lead to rapid dissemination of personal achievements, of excellent personal leadership, or of unethical behaviour with global reach.

At university or college, students have to learn how to choose which medium, including in-person meetings, is suitable for what. The emergence of new technologies means that communication is no longer confined to oral presentations and written technical reports. Communicating face-to-face in teams or through interactive screens requires excellent nonverbal perception and skills like listening, reading and seeing. Another crucial skill is the ability to sketch and diagram solutions to problems that show the relation between mathematical models constructed in the academic mind and the physical world. Besides these basic communication skills, engineers need broader basic communication abilities. They need to master skills like writing e-mails, synchronous chat technologies, virtual conferencing systems, mobile phones, web-based collaborative tools, cloud data management, and whatever the next wave of technological development will bring. As communication technologies continue to shift, and work becomes increasingly distributed, engineering students have to be trained to develop a fluency, not only in written texts on paper, but in the full range of communication media. It is therefore of great importance that our students are taught the impact of the human factor in communication, and experience how different media support or hinder an effective workplace.

> *"Students have to learn the language of discourse of their own engineering discipline and the ones that interface; how to explain difficult concepts to different audiences."*

Students have to learn the discourse of their own engineering discipline and the ones that connect; how to explain difficult concepts to audiences with different backgrounds and what misconceptions, preconceived notions, and biases people bring to learning. Learning to communicate as an engineer is strongly related to learning to think like an engineer. It is therefore essential that we create an environment in which students learn to work with diverse groups and learn collaboration techniques. These skills are invaluable for careers in academia, industry, government, as well as not-for-profit organisations. In their future engineering practice, they will rarely be in the position to choose their team mates, and the mastery of social and technical interactions in a team setting is therefore of the utmost importance. Students have to learn that data can be interpreted in various ways, and that they need to convince others that their designs or services are efficient, useful or otherwise sound. They have to be made aware that innovation will only be successful if ideas are converted through clear communication and pitches. Given the high stakes associated with communication in engineering and the rapid technology development cycles at play in global engineering, it may no longer be feasible to allow students the luxury of time on the job "to figure it out for themselves", sometimes even without more senior engineers to imitate or provide guidance. Employers are willing to invest in training only for those skills whose value they can fully capture, but are less willing to invest money on knowledge or basic skill development, since employees are not around for long, especially in their early years of employment, and take these skills elsewhere.

Nowadays, engineering students mainly learn to collaborate in engineering teams and discuss matters in their own vocabulary. They usually impress with their technical abilities, but are often mute when it comes to discussing "the big issues". They often feel more comfortable with numbers than with words and think that non-engineering people cannot think logically. As technology is becoming an ever greater part of every facet of our lives, the convergence between engineering and public policy is expected to increase. This level of interrelatedness will force engineers to develop a broader sense of how technology balances with public policy. It will become increasingly important to give students a zest for reasoned and informed debate of societal issues. They have to be trained in how to participate in debates about more controversial areas of engineering, not only with engineers but also with laymen, business leaders, politicians, financial managers and lawyers, people with backgrounds in social sciences and humanities, from different cultures, or with different needs and interests. Engineering students have to understand the strengths and weaknesses of human nature if they want to climb the ladder and appeal to colleagues, supervisors and leaders in their future workplace. This requires discussion and empathy rather than a didactic approach. When graduates master this wider range of communication skills, they will find it easier to persuade, influence and lead.

"Our Master's is just two years. In their career they have more than 40 years to learn those skills. It's not our responsibility to prepare them for a career."

Professor in Aerospace Engineering, Management Retreat March 2014

6 A Global Mind-Set: Diversity and Mobility

The practice of engineering is no longer bound by distance, space and time. Innovative sectors design and adapt complex systems, products and services, conduct marketing campaigns and organise production projects in environments in which engineers work in diversified teams of disciplinary specialists, design engineers, system integrators, customers and business and people managers of different social backgrounds. The horizontalisation of the socio-economic world and the interconnectedness of the world of work intensifies the demand for engineers who are capable of performing in culturally diverse contexts. More and more, products, systems and services that are being designed and built will have global or cross-cultural aspects that strike everybody. Engineering students therefore need to learn about diversity-in-thought and what it means to operate in different realms.

Innovation needs diversity, because diversity provokes thought and enhances creativity. Diversity improves the way people think, not only because people with different backgrounds bring different information to the table, but also because interaction between people who are socially different changes expectations and disrupts conformity. Workplaces, teams, and organisations that are highly diversified make people believe that they will have to deal with many different perspectives. This makes them work harder both cognitively and socially because they assume they have to deal with a richer variety in information, opinions and alternative viewpoints, which, to reach consensus, requires more effort and better argumentation on their part. The simple fact that diversity promotes harder work leads to better, more creative and innovative results, whether the people like it or not. Diversity in the classroom and in collaborative projects are therefore essential. It prompts students to scrutinize facts, think more deeply and develop their own opinions. Students come to understand that engineering strongly depends on social interactions that are influenced by the prevailing economic and social cultures. With the increasing diversity in team composition and globalisation of project work it becomes important for students to learn how differences in age, gender, and ethical, legal, religious, social, environmental and political backgrounds all influence communication and teamwork and the resulting quality of work.

University students, whether they prepare for an international career or not, live and work in a context that is highly international and are surrounded by people of various cultures. In their prospective jobs they will operate in, mobilise, inspire, and manage a multidimensional and multicultural workforce. Engineering is definitely not the same everywhere. Engineers in different countries define and solve problems differently, and these differences create problems that have to be taken into account while working on global teams. Particularly non-verbal communication is culture dependent and easily leads to misunderstandings. Information technology creates immense opportunities for collaboration across time and space, but also generates boundaries that inhibit interpersonal interaction.

"Cultural awareness and creativity are essential capabilities for engineering students to develop in order to compete in a globally integrated society."

An international atmosphere on campus where students experience intercultural encounters may help, but it does not automatically lead to intercultural learning. Aspects of intercultural collaboration and globalisation should be explicitly embedded in the content and the delivery of engineering curricula of all students. This allows an "internationalisation at home", where students can learn how to effectively deal with ethical issues arising from cultural or national differences, understand the implications of cultural differences on the way engineering tasks are approached, and understand cultural differences relating to product design, manufacture and use. Encountering international students "at home" creates a personal sensitivity for one's own cultural background and values, and initiates the development of a positive attitude towards other cultures. Our multicultural classrooms are good resources that we should use purposefully in developing these intercultural skills. It teaches students how to work effectively in multicultural settings and develop a global mind-set. In class students have to learn to be agile, open to change and adaptive to new cultures and get their first experiences in how to collaborate in teams whose members have different levels of knowledge, backgrounds, attitudes and habits, and operate in different economic, political, legal and social and information environments. The available diversity on campus offers creative intercultural opportunities, and this route to enhancing intercultural learning is on our doorstep already.

Tackling and surmounting new challenges and unfamiliar situations increases students' self-confidence and ignites their curiosity. Personal leadership, responsibility, social and cross-cultural skills are, for instance, enhanced through the experience of studying abroad, which gives students opportunities to reflect. This is already accommodated by working with partner universities, but could be stimulated even more by setting up a network of TU Delft project centres around the world to facilitate on-location intense experiences of interdisciplinary project work, typically involving a high degree of interaction with local people and cultures. A boost in the development of interpersonal skills and adaptability greatly increases the agility of engineering students. Such a boost only happens when the international experience is "purposeful", in that it not only exposes students to, but also immerses them in new cultures, for instance through team building, collaborative learning, and interdisciplinary exposure. Students become aware of the

"Besides technology, I have always been interested in social issues, international affairs, arts and culture and I think these will be essential in my future job. I wish I could develop these interests to a higher level, but being a student at a technical university makes this difficult. Aerospace Engineering is challenging and very interesting but does not include any of these topics."

Yvonne, student MSc Aerospace Engineering, Delft (2014) full complexity of integrating social and societal contexts in engineering and design processes, in which a variety of stakeholders are involved who all have different ways of prioritising time, making money, reducing cost, taking risks and having an awareness of quality and customer needs. It puts the students in the shoes of the people who will make and use their products. Such immersive learning sometimes leads to disorientation and students may claim to know less upon their return.

Universities that attract an increasingly diverse population of foreign students should prepare these students for the local labour market. For instance, by offering opportunities to learn the local language, immerse them in the local culture, and teach them the differences between western and non-western engineering ethics, design methods, standards or business practices. In this respect we should also stimulate teaching staff to actively engage much more with the international engineering world. Peer learning is achieved by sharing the best practices with academic colleagues abroad and industrial professionals.

Globalisation enhances the number of potential students who "shop" globally for the best offerings in higher education. Technical universities are becoming more diverse because of, among others things, the international influx and increase in student exchange. This diversity enriches the study culture. Diversity is expected to further increase because of an ongoing process of individualisation through the DIY approach (Do It Yourself), in which students start to learn more and more off campus through media, online distance learning, the internet and from the different social networks to which they belong. Information technology and innovation create increasingly attractive alternatives to existing educational formats, and students are quick to learn how to take advantage of these alternatives, with or without academic credits. Just like buying individual songs on iTunes instead of entire albums, students shop around, pick out the best and most desirable components of education from different sources (cherry-picking), all in service of their individualised approach to "being educated". They use the world as their classroom. Student engagement that is currently achieved by following standard curricula, will soon change into more personalised learning, with individual learning plans that ask for high degrees of flexibility.

"Diversity is expected to increase because of an ongoing process of individualisation through the Do It Yourself approach."

As students spend an increasing amount of their private lives online, they expect of their study environment to have a similar online presence. This raises questions about how our curricula should respond to these demands. Unbundling part of the content is one of the available options. Integrating content, tools or labs that are made available by other universities is another one. It allows students to assemble the capabilities from different universities, which may range from on-campus education to self-directed study that is not bound to any structure. New opportunities will emerge from combining online learning technologies and face-to-face pedagogical strategies by adopting new models for blended learning, possibly in collaboration with organisations that provide corporate university teaching. They may turn out to be an effective means to enhance flexibility and accommodate the larger diversity in learning styles and study cultures.

> *"How do we educate our students so they have skills on offer that are not available on the global market at a fraction of the cost?"*

Young engineers of today are within reach of jobs and potential customers anywhere in the world. But this also means they are in competition with the best talents in the world. Engineers are proliferating at an enormous rate in the global job market because of an enormous massification of higher engineering education. Currently, over 40% of the global total of higher education students study in low-cost countries like Brazil, China, India and the Russian Federation. How can we improve the quality of our education and train our students so that they have skills on offer that are not available on the global market at a fraction of the cost? It goes without saying that our graduates should have a strong profile and be well-connected to the global market.

7 *Ambitious study culture: Student Engagement and Professional Learning Community*

Engineering education has to be engaging, compelling and motivating, and create a learning community that stimulates all students to discover their talents. The aim is to create a climate in which students are encouraged to develop ideas, both big and small, and bring to the market creative solutions to real world problems. Such a climate can be achieved by focusing on the student as the key player in the learning process (student-centred learning) and by an emphasis on experiential learning: a hands-on approach in teaching and learning of specific knowledge or skills when students feel the need for it. This is a basic premise of the CDIO Initiative (www.cdio.org), which states that hands-on experience is a vital foundation for engineering students on which to base theory and science. Exploring how one believes a system works, creates a knowledge-building relevance to the lecture or video that is then presented. Exploration, inquiry and problem solving are therefore not just "nice to have" in the classroom but an essential part of a future-proof curriculum.

Curricula have to focus on coherence, leading to a degree and a connection between courses and (sub)disciplines. They have to connect the subject matter to the context of the students' lives and the engineering profession, like the pressing issues of environmental awareness, social responsibility and entrepreneurial thinking ("People, Planet, Purpose"), away from the disciplinary monocultures. These issues connect with many young hearts and minds of the Millennial Generation in Western Europe. Students of this generation with birth years ranging from the early 1980s to the early 2000s, have a different set of values. They demand purpose in their lives, want to know who they want to be, not what they can do. Their motivation is self-driven, and they thrive on the ideas of being connected and of co-creation. They do not respect or trust authority or institutions. They want to be involved, make a positive difference, maximise their lives and have fun: "party-ci-pation" (van Sark, 2016). These students no longer want to be taught, but instead want to be allowed to learn their own way, knowing that somebody at the university cares about their development. Millennial Generation students have a growth mind-set and want to develop their strengths, for which feedback on progress is much more important than feedback on achievement. These characteristics are proven by the great interest, passionate exploration and commitment of the multidisciplinary D:DREAM ("Delft: Dream Realization of Extremely Advanced Machines"; http://ddream.tudelft.nl/en/ student projects, as well as excellence programmes that offer exactly these opportunities, unfortunately for a limited few.

"Millennial Generation students in the Western European world no longer want to be taught. Instead they want to be allowed to learn their own way, by co-creation and a Do-It-Yourself approach."

All engineering students have at least a touch of a maker instinct to build, test and operate things. Experiential opportunities in labs and project and makerspaces foster strengths beyond technical experiences, like leadership, ethical behaviour, deep collaboration, interdisciplinarity, and creativity. Such integrative aspects in a curriculum address real-life concerns, present opportunities for hands-on experimentation, prototyping, design thinking and problem solving. Hands-on discovery has been and will remain an important part of knowledge development. It sparks the desire to learn, promotes independent learning, and offers a more effective involvement with the

"The physical labs and makerspaces are key motivators and remain essential for learning how to engineer, and more importantly, may be a place for idea incubation, innovation and experimental play."

engineering environment and society. It is absolutely essential that universities unite and address the engineering practice, and that they do not divide their teaching and research. Students have to experience the real world of engineering and get a taste of genuine research by learning-by-doing and by being lectured and coached by professors, experts, researchers and engineering practitioners from the industry. Research, experimentation in labs, hands-on design projects on authentic problems, building and testing projects in project, production and makerspaces, and internships in industry and institutes enhance student engagement and teach students how to develop and monitor their own development and learning. It also allows for a better application of learning outcomes in real life and the building of tacit ingenuity in the practice of engineering. Through trouble-shooting and the production of a design, students are brought face to face with the social purposes and consequences of engineering - the technologies it creates, the practice of manufacturing, the management of people, and the personal skills involved.

At a time when the classroom environment is evolving from a room-with-a-blackboard to a laptop-with-a-network connection to the cloud and an online forum, the challenge is to find ways of bringing design-oriented, project-based learning and hands-on experiences to online learning, blended with in-person, hands-on activities in real labs. The rise of new technologies of virtual and augmented reality (overlaying digital information on the real world) will make it easier to simulate in-person experiences remotely and to such a high level of detail that the human brain can no longer distinguish them from reality. This technology, along with an all-pervasive content and multiple instant channels of communication, possibly supported by tactile sensing, will deliver an experience of rich interaction in a lab or a classroom, regardless of location and time. Virtual and remote research labs for education will provide better access to experimental set-ups in labs, and remove the need to be on campus for experimentation and design-build-test projects all the time. Virtual research labs for education are simulations that provide realistic learning experiences through photo-realistic computer-simulated 3D images or holograms of conceptual designs or experimental set-ups. They may include online interactive user interfaces and synthetic measurement results that rival the behaviour or performance of a design, or in case of experimentation, a physical laboratory. They mimic shapes, devices, components and physical phenomena, thus providing students with the mental engagement necessary to successfully complete experiments outside the walls of a traditional laboratory. Virtual labs will increasingly be used to immerse students in realistic yet low-risk engineering environments with all the "real" dilemmas and practicalities of experiments and design work. Combined with the use of so-called avatars and affective computing, working with virtual labs will support students in their social emotional development, by managing their emotions, and by developing collaborative capabilities and empathy for fellow students. Avatars are 3D virtual chat personalities who speak naturally and respond adaptively to students' knowledge and behavioural reactions. Head-mounted displays allow for strictly personal experiences. Mixed reality labs, where virtual projections on the walls of a space that is large enough to accommodate a group of people are combined with avatars and a physical presence of some attributes, will create intensive levels of realism (Louwerse, 2015). They may be used to practice presentation or negotiation techniques in a setting of a meeting room of an international enterprise. Teachers operate as game masters, continuously resetting parameters of the experiments to stretch the students to their limits. Virtual labs will develop into high-return learning media that provide students with at least the same level of understanding of experiments as a real laboratory environment.

"Students should at least once have the experience where something they design or test fails. This grounds them, shows them the importance of understanding the basics and makes them use common sense: is this really going to work? Students tend to get tangled up into super complex theories without understanding the basics."

Industrial internship supervisor Delft Aerospace Engineering (June 2015)

Remote labs provide an interface through internet to remote equipment in real experimental facilities, using live video streaming of experiments with real hardware under real test conditions. Neither the virtual nor the remote labs can ever be a substitute for an in-person experience and should therefore not be simply cut-and-pasted into a curriculum. They may, however, support the achievement of certain learning outcomes. Part of the hands-on learning experience may be transformed into hands-off learning by serious game simulations of lab environments. We can make them an invaluable tool for supplementing existing laboratory work for large numbers of students. In the near future, remote labs will shift from using a specific piece of equipment to accessing a network of shared facilities between universities. As discussed above, we should avoid situations where students who use hardware simulations lose sight of the real hardware being simulated, and instead get caught up in a "computer game" attitude towards the software. Above all, it should not be forgotten that engineering students bring ideas to life and share their passion for making and testing things by means of real fabrication and experimentation in lab spaces. Hands-on learning in physical labs remains appealing for the sensing, visual, active and sequential learning styles. This generation of students

"Universities are transitioning from institutes of knowledge to institutes of connections.

The challenge for the university campus is social cohesion and belonging, not the transfer of knowledge."

does not only attend university for their engineering degree, but to develop personally as well. It is in classrooms and physical labs, where they learn by practicing and working together.

Much that they learn is not strictly academic. What sets a young engineer apart from his fellows is often not degree-related. Empirical research by the Center for Creative Leadership in North Carolina shows that experiential and social learning contributes to more than 80% of the learning gain, against 20% for formal learning. Students gain the most from one another if their classmates have different interests, experiences, talents and beliefs. This sharing makes physical labs and makerspaces an important place of community, even more so when they provide opportunities to mingle with engineering practitioners from industry and young entrepreneurs. Spaces for hands-on discovery and exploration will therefore remain essential for learning how to engineer and to accept failure, and more importantly, they are places for innovation and experimental play.

To immerse students in authentic, complex problems, we can also use case histories and global challenges in interdisciplinary minors or projects. Integrating case histories into the educational process promotes a positive engineering identity and a sense of tradition—things that engineers often lack in comparison with, for instance, medical doctors and lawyers. In a variety of ways, case histories often show how social systems or technical infrastructures have compromised the success of a seemingly appropriate technical approach. Studying the successes of innovative engineers may help students to understand the roots of imagination and innovation. It could also be interesting to have students work on design projects, whilst a competing team checks for weaknesses in design and analysis. The competing teams would discuss these weaknesses until the debate is closed. This way, students learn that mistakes and weaknesses can be signalled by peers, maybe even from other disciplines.

When immersed in authentic complex problems, students grapple with the uncertainties of evidence, the construction and communication of scientific positions and arguments, and the societal and ethical contexts of the emerging developments in science, engineering and technology. This shows them that appropriate solutions do not always just rely on hard facts or cold numbers, but that emotions and values also play their part. In the VUCA world, breakthroughs in technology push engineers to new ethical frontiers, and developments in ethics will in turn require technological innovations. Students will have to ponder the benefits and risks of potential technological breakthroughs, ones that, for instance, extend life, advance digital intelligence, and make digital copies of our minds, and realise that such discoveries could also be manipulated to serve special but risky interests. Our technological revolution brings engineering into uncharted territory. Every now and again, engineers will be forced to do things that violate their own values. Discoveries in neurotechnology may blur the lines between man and machine, 3D printing of more personalised products may result in an increase of waste, and artificial intelligence and robotics may become incomprehensible and suffer from cybercrime. The standard reaction of engineers is to try and weigh the different considerations and establish which values are more important for the task at hand. But with the increasing complexity and interconnectedness, and the intense blending of our technical, economical and societal cultures, the engineer will not always be able to satisfy every moral obligation at the same time, and experience a moral "overload" (Van den Hoven, 2012). Addressing the technical breakthroughs and their accompanying unsolvable moral dilemmas in education, highlights the crucial role the students' own discipline plays in thinking about these challenges, whilst giving them a perspective on the system they will be part of. It stimulates thought about careers beyond academe and provides them with the insights, skills and confidence that can even help them to succeed at job interviews. Conveying role models and knowledge about professional and moral requirements will become an increasingly important task in our educational approach. It is unlikely that moral decision making in the near future will be handed over to intelligent machines. People will retain that advantage.

To capture student interest and respect, these ethical responsibilities should be more interwoven with subjects that are already taught instead of being condemned to the margins of the curriculum. To develop a good sense of ethical accountability and social responsibility, students need to come in closer contact with engineering professionals with whom they can identify and who they can try to emulate. Long-term strengthened relations between university teachers and the labour market that graduates are expected to enter are therefore essential.

Student engagement requires a professional learning community of lecturers where teaching is sparked by personal knowledge and the ability to engage others with passion and creativity, and where teaching staff take on a joint responsibility for learning outcomes and study results. This requires a culture and climate where the staff are willing and able to work as a team, serving as a powerful role model for the students. Since engineering is a practice-based profession, a strong and enduring partnership between industry and academic staff will remain essential. Although academic staff currently have a tendency to develop into mono-disciplinary specialists throughout their career, they will have to develop a more holistic engineering mind-set. This should enable them to enrich the learning process and demonstrate that engineering is not only about mastering a fixed and known body of knowledge, but also about the integration and effective use of that knowledge. They have to shift their teaching from transferring traditional knowing, to trusting and unleashing their students, helping them with their personal development into self-efficacious lifelong learners. But the teachers' input in filtering, structuring, sharing and explaining content will remain critical in 2030. This is going to require significant personal changes for many lecturers who have not kept their didactic professional skills sufficiently up-to-date, especially when it comes to such major changes. Strengthening the didactic professionalism of and trust in teaching staff has to become the norm. Since the TU Delft Graduate School is an important source of new academic staff, its training programme and that of the Tenure Track Development programme must be carefully examined and attuned to the problems and future needs of education at our university.

Will we enter paperless classrooms in 2030? A major challenge for academic staff is the rapidly developing digital world. With the proliferation of the use of mobile devices, the growth of social-media connectivity has exploded, and the penetration rate of mobile devices among students has reached a record high. Young people are addicted to social media and students are lightyears ahead of academic staff. They cannot remember a world without these tools. Social media like YouTube, Instagram, LinkedIn, Facebook, and Twitter are increasingly used to bridge the gap between the lecturer and the student, and between the student and the rest of the class (social learning). There are some attractive benefits to interactivity, hyperlinking, searchability and multimedia, but they also promote cursory reading, hurried and distracted thinking, and superficial learning. Frequent interruptions scatter deep thinking and weaken memory. Digital textbooks are increasingly used to share notes or passages in social-media applications. Integrating technology and pedagogy in new teaching and learning facilities allows staff to teach differently, perhaps by abandoning the linear and hierarchical world of the book and by using richer media, but it has to be taken into account that a frequent deciphering of hypertexts or studying multimedia fragments distracts students from reading and deep learning. Online tools and apps have the ability to bring the world into the classroom and they enable the sharing of expertise with others on campus or thousands of kilometres away. These emerging tools make it easier for students to ask and respond to each other's questions and for teachers to provide real-time feed-back. State-of-the-art real-time response systems will allow faculty staff to better monitor student learning and to provide immediate advice during live classes (personalised learning). Although much of the senior staff in today's education is not a digital native but more likely a digital immigrant, they can no longer afford to ignore these tools. With the revolutions taking place in the technological landscape, digital media literacy will only become an increasingly important key skill for our lecturers and professors.

Academic staff may be apprehensive of having to become fluent in these new technologies because many of them are no longer in their formative years. Since the young generation is much more digitally literate and social media savvy, reverse mentoring , whereby students coach their teachers, might be a solution. A major effort is needed in the near future to ensure that staff can support students in developing and using digital literacy skills across the curriculum. The rise of data-driven learning and assessment (learning analytics), whereby data on personalised learning experiences and study results can be mined for new pedagogical insights, also poses new demands on staff abilities regarding learning analytics.

Teaching an international classroom is another major challenge for academic staff. Apart from a different language, teaching in an intercultural setting requires specific qualities and skills, such as dealing with cultural differences, teaching and learning styles, the use of media and technology, and knowledge about the international labour market (Teefkens, 2000). Staff will have to learn that student learning in an international context is determined by instruction models that have been nationally and culturally defined. Domestic staff and foreign students may have different views on the meaning of the relative social position of lecturers and students in their cultures, on the relevance of curricular content, or on the expected patterns of student-lecturer and student-student interaction or assessment. These different views can easily lead to dissatisfaction, clashes or demotivation. Using cultural diversity as a resource and seeing its potential for enriching the learning experience requires reflection by the teaching staff on their role and responsibility in this complicated process.

8 *Employability and Lifelong Learning*

Employability is about the ability to find employment and remain employed. At tomorrow's university, students will need to be prepared for the realities of work with a

> *"It is not what you know, but how you learn what sets a young graduate apart."*

balanced mix of theoretical and practical training. The role of higher education in building and developing of employability has been a subject of debate for as long as universities have existed. University and the workplace differ in purpose and activity. Many capabilities that are critical for the employment in flat or less structured enterprise organisations can only be developed on the job and not in the classroom. But universities cannot simply neglect to prepare students for the future job market. Aspects of employability have to be considered when matching professional engineering skills to industries and institutes. They should, however, never be a dominant driver for the intended learning outcomes of an engineering programme.

Engineering knowledge and know-how is limitless in scope and detail, and engineers never know what they will need or be asked for in the next step of their career. And it is even less clear to students what it takes to start a successful career. Learning to manage continuous change and uncertainty is a key qualification in modern life. One of the most important employability skills is "learning how to learn". Employees will face challenges in many facets of their work, making lifelong learning more important than ever. Over the course of their careers, they will have to make demanding choices and change jobs more often than in the past: gone are the days of the "corporate ladder". Engineers may, for instance, need to switch to multiple fields of expertise for multiple companies over the course of their career, with international colleagues and activities in different countries. The fact that engineering-based jobs are transferrable across different sectors and businesses makes this even easier and more probable. The contemporary workplace is becoming increasingly complex, with more competitive companies and a more global landscape. New technologies appear in the blink of an eye, forcing out older ones. Future engineers have to be capable of dealing with rapid, sometimes unexpected challenges and changes. Resilience and agility are therefore indispensable skills to move quickly and flexibly and to take advantage of opportunities and avoid negative consequences of change. Such adaptive capacities are also valuable for learning a new job when the one they are in becomes redundant. The economists Frey and Osborne made a forecast that over the next two decades 47 per cent of the current job profiles in the US could disappear as a result of computerisation and robotisation.

Engineers will undoubtedly require a wider and more uniform form of knowledge than in the past. Hence, an important challenge is to design curricula that do not only prepare for an initial job or a career in a particular discipline, but rather provide a foundation for a lifetime of continuous learning. It will require a change in the mind-set of traditional engineering professors, who have to learn to think outside the box of their own discipline, and get a better insight in what engineering looks like in the real world of engineering practitioners. The emphasis in our educational system will have to shift from the mastery of subject knowledge to a mastery of the learning process itself. Students need to become self-motivated, proactive people who are prepared to take responsibility for their own learning and the development of professional skills. They need to understand how they can create value, receive value and act as the entrepreneur of their own career.

In the new world of work, it is not only what you know, but how you learn that sets you apart. Education, with an emphasis on broad skills, enables students to go through life acquiring new skills. At graduation, students should have learnt to be adaptable and versatile: to apply the depth of their skills to a progressively widening scope of situations and experiences, thus gaining new skills and building relationships. These are the tools that enable novice engineers to take on responsibility early, to have diversified career paths and meaningful work, meeting ethical standards with professional responsibility. They make them more employable throughout their careers, and abler to acquire the knowledge or the experience that is needed to be a good adapter, synthesiser and collaborator.

"The challenge is to design engineering degree programmes not as a preparation for a career in a particular discipline, but rather as the foundation for a lifetime of continuous learning, in preparation for their last job."

Students need to be made aware that they can only succeed in their profession if they develop their own personal abilities. Young adults need to prepare themselves for a lifetime of continuous upgrading and development, by not only applying the knowledge they have already learnt, but also by acquiring new knowledge as and when needed. Internships for instance are a form of practice-based learning and ensure that students emulate the daily working habits and methods of experienced engineers, acquire an up-to-date insight into the practice of engineering and make it more likely that they understand the bigger picture - the particular knowledge and professional capabilities required to becoming an engineer - and the need to learn continuously. Only on the job can they learn how context shapes tasks, how the use of standards and design guides saves time and reduces uncertainty, and how contingency factors have to be integrated into performance. Combining tacit knowledge and other learning experiences of (industrial) engineering practice with theoretical knowledge taught in the classroom, makes for internships with very rich learning outcomes. Employers and recruiters recognise internships as a substantial source of learning. Particularly internships abroad have a strong impact on learning, even more than studying abroad at a university. More often

"Students have to learn that they only succeed in their profession if they also develop their personal abilities."

than not these are life experiences that challenge students to go beyond who they think they are, what they know and have learnt in the safe environment of the university cocoon, and work in service of the real world.

Students working in the industry may by chance also be exposed to innovative and entrepreneurial activities, and learn how they can translate ideas arising from research into products suitable for commercial exploitation. Along the way, they get acquainted with the skills and experience of entrepreneurial engineering, like strategic technology planning, development processes, new concept ideation, technology needs assessment, and technology road mapping. Interaction with modern engineering professionals in design or research projects is the key to providing students with role models and it exposes them to real-world professionals and the problems engineers face every day. The ERASMUS impact study “Effects of Mobility on the Skills and Employability of Students and the Internationalisation of Higher Education Institutions” shows that one out of three students who did an internship were offered a job by their host company, and one out of 10 started their own enterprise. Industrial internships not only have a more positive impact on the development of professional and personal skills, they also create better employment and career prospects.

Practicing engineers value lifelong learning skills. Every day of their careers they learn from more experienced people by building cooperative and helpful relationships with colleagues and supervisors, and asking them for help. Students must be made aware that access to shared knowledge is a key asset in design processes to meet the tighter time and cost constraints of a highly competitive world. Novice engineers must be prepared to continue to learn proactively and plan for self-improvement and their future career. Reflective skills in particular are critical to becoming effective, self-directed lifelong learners. They should always be hungry for feedback and spend focused energy on processing information so as to better understand their own assumptions and behaviour. As professionals move through their careers, they direct their own learning, in future even more than at present.

To ensure we are educating the most talented and effective engineers, universities have to ensure continuous professional training throughout the careers of their alumni. Universities will transform from a “university for a Master’s degree” into a “university-for-a-lifetime”. Professional education of this kind has to be tailored to each company’s mission, vision and culture, and correlate with a company’s continuing professionalization scheme: highly specialised knowledge for experts for one company, a balance between academic rigour and business relevance for another. Universities have ample opportunity to create multiple options of face-to-face, blended, and online courses, focused on learning- by-doing, individual, group and peer learning, and produce these courses on campus or online.

Classroom populations are changing and becoming more diverse in background, knowledge and age. Computer-based training will become common practice in lifelong learning. Raising awareness about their future career and what they need to be successful, and instilling an attitude of lifelong learning should start in the first year of our students' university career. Preparing lifelong learners to identify and ask their own questions is probably the most useful skill they can have in their career. Elements of open-ended project learning as well as lectures from senior engineering practitioners expose students to the possibilities of career progression and show them the different learning paths in multinational enterprises for specialists, system designers or management functions. At graduation, students should have learnt to develop a personal career and personal development plan.

Lifelong learning also applies to the teaching staff, who should routinely update their pedagogy and develop new learning environments based on proven practices. They should be able to incorporate changing demand in their subject matter, perform synthesis in balance with analysis, act as a catalyst and an integrator in multifaceted interdisciplinary projects, and build connections between the world of learning and the world of work. They have to develop their pedagogical knowledge and skills in relation to their personal needs and stay up-to-date with the developments in engineering education, such as intercultural learning, advanced personalised learning, digital literacy, the flipped classroom, the blending of MOOC material into campus education, and going from "assessment of learning" into "assessment for learning".

Connecting the dots and backward mapping

Now that I have addressed many elements of knowledge, skill, attitude and know-how, it is time to connect the dots in a mindmap on the two facing pages on page 62 and 63. Most of these elements are related to our rapidly changing world and higher engineering education. Mapping them back to a programme and university level reveals the three cornerstones of future-proof higher engineering programmes: Innovation, Employability, and Community.

Innovation

The traditional task of universities used to be to educate and research. But times have changed and universities are no longer the only centre of knowledge. In the meantime, the transfer of knowledge and technology to industry, and the commercialisation of knowledge and research have become added responsibilities of research-intensive universities. This holds particularly true for high-tech knowledge-intensive sectors, where scientific inputs are of key importance in innovation. Research-intensive universities play a very important role in the system of knowledge generation and dissemination. They are the main source of highly qualified labour, a knowledge provider in university-industry relationships, and an incubator for high-tech start-ups. Engineering graduates fuel high-tech innovations by their up-to-date scientific knowledge and industrial ingenuity and are the most powerful mechanism for the transfer of knowledge to industry and society.

With global competition and new technologies reshaping the markets, there is a fast-growing demand for research and innovation. Universities and enterprises are becoming more interested in education and professional training where students and novice engineers learn certain innovation skills, like framing problems and opportunities, developing feasible, creative solutions, prototyping, and creating, sustaining and growing business. No other profession unleashes a greater spirit of innovation than engineering. As a result of the horizontalisation of organisational structures there is a clear trend for innovation to become more inclusive, incremental and “liberalised” from the traditional centralised model. A company’s entire workforce is expected to make suggestions for improvements and innovations. This is why all engineering students need to develop basic innovation skills that will allow them to adapt to changing circumstances and be open to new ideas, enabling them to engage with, and respond to, innovation. The mastery of innovation skills will become paramount for a successful career in many industry sectors and academia.

Technological innovation is a major driver behind an ever-changing demand for professional skills. What do our students need to learn to be prepared for a world where artificial intelligence is going to change the knowledge landscape as well as the practice of design and engineering? How can we teach them to bridge scientific discovery and practical applications, create and exploit knowledge for product and process innovation, and translate knowledge into innovative, competitive systems, products and processes? How important will deep specialist disciplinary knowledge be in 15 years, when information and knowledge are at our fingertips and engineers will be supported by intelligent systems that may even outperform the engineer of flesh and blood? Students not only have to learn to design things right, but also to design the right things, i.e. to learn how to generate ideas by using their creativity. Rational problem solving that focuses on convergent thinking is no longer enough. Due to the increasing complexity of the technological world, engineers need framing and complex problem solving skills, whilst bearing in mind the human factor and the bigger picture, all with an entrepreneurial mind-set, whilst coping with and exploiting diversity. Both convergent and divergent thinking are necessary, but not everybody will be able to master both types of thinking. It will therefore be important to collaborate in diversified teams that include both types of thinkers. Future innovation will be increasingly distributed or “open”, meaning that it no longer takes place in isolated research labs, but collaboratively through co-creation with business partners and end-users. Engineers will work in a world where conceptual thinking is increasingly linked to the client and the end-user, meaning prototypes will be developed together with experts, designers, business managers and customers in proto spaces, while the specifications are still being written.

Innovations are increasingly crossing disciplinary boundaries: new materials developed by the textile industry have potential for aircraft construction, medical equipment or submarine communications cables. This technological fusion blends technical improvements and innovations from separate fields of technology to create new systems, products or processes. Since most, if not all engineers will be involved in innovation work, they need to be familiar with more than one disciplinary domain of knowledge and have skills in multi- and interdisciplinary thinking. With technological fusion and cooperation between enterprises on a global scale, innovations will increasingly cross industry, technological and national boundaries. Tomorrow's engineers, specialists and scientists will therefore need broader, less specialised skills, involving system level thinking, cross-cultural communication and deep working knowledge of multiple disciplines.

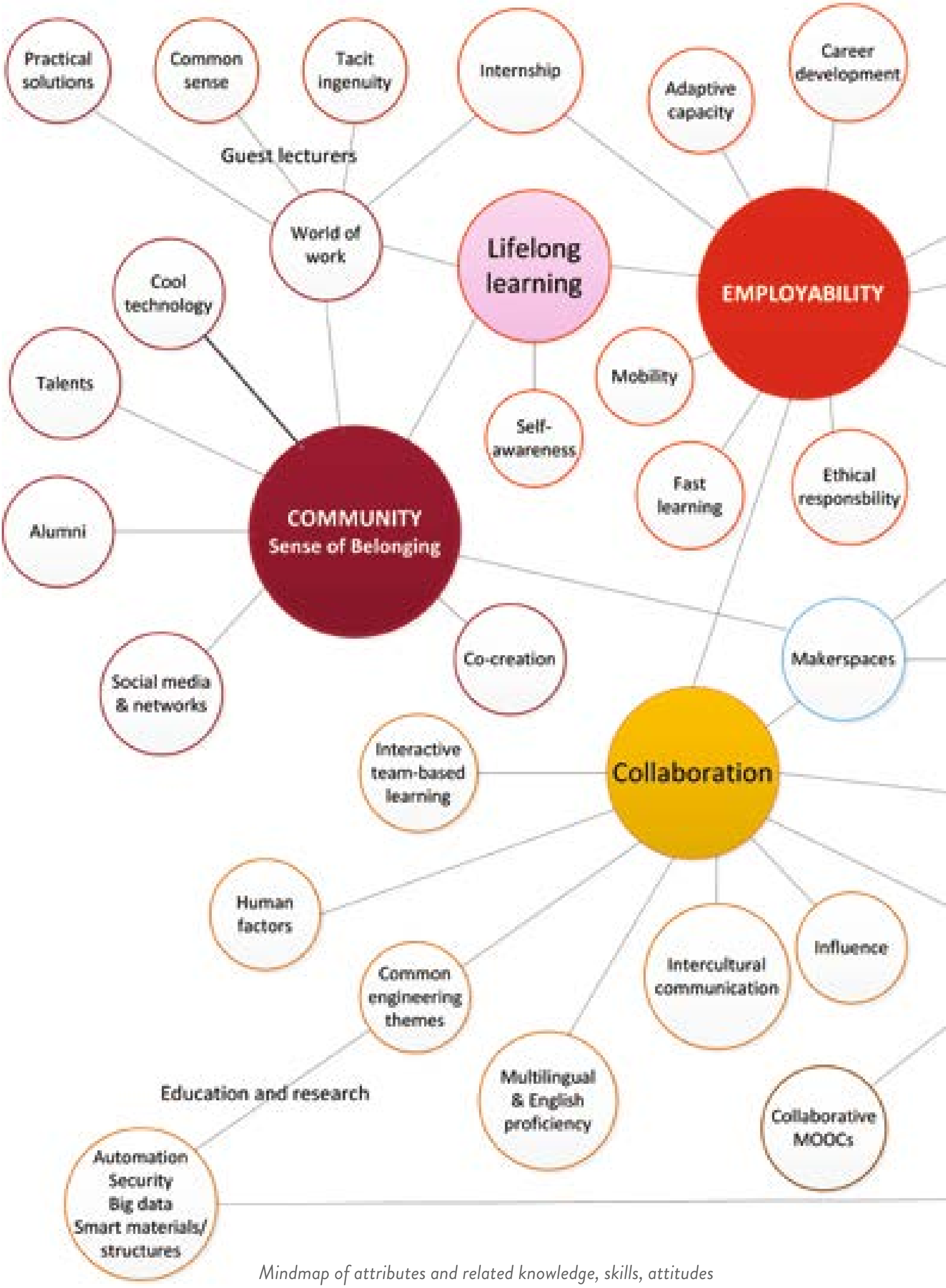
Employability

Employability is the second cornerstone of future-proof engineering programmes. Although the role of research-intensive universities in building and developing employability as part of their curriculum has been a subject of debate for as long as universities have existed, employability is a prime concern for students, universities and employers. Young people see a job as something that provides purpose and self-pride, and unemployment is their number one worry.

Employability is the ability to find employment and remain employed. It is an important argument for students in choosing a university, with an institution's engineering expertise often a second priority. For company recruiters a university's alumni employability success rate is an important criterion when evaluating the employability of a young graduate. Recruiters increasingly favour a university based on past experience with graduates. The shift of the employer's focus away from academic achievements ("what do you know" and "what can you do") is an emerging trend. The emphasis more often lies on "what have you done" and "what are you like". Personal attributes like autonomy, organisational sensitivity and empathy become more important during the selection process. With employability as a cornerstone, lifelong learning, engineering ethics, professional and career development and adaptability need to become important elements in curricula, to optimally prepare graduates for the future job market.

Community

The more open and interconnected the world is, and the larger the student body, the stronger the need for a trusted community becomes. The sense of belonging to a community develops into an important argument for students to join a specific university or programme. A sense of belonging is very important for students of the Millennial Generation because it strongly influences their motivation to function and perform well in different learning environments. They want to be emotionally and behaviourally connected to a university or programme that has a mission and a purpose, where they will gain knowledge and develop skills, join a profession and find a job. Acquiring knowledge alone is no longer



Mindmap of attributes and related knowledge, skills, attitudes and know-how in the context of engineering education.


Emotional intelligence
Societal relevance
Value creation
Freedom & Autonomy
Virtual labs
Physical Labs
Experiment ation
Complex Problem Solving
Creativity
Designing the right thing
Systems view
Logical analysis
Algorithmic thinking
Digital literacy
Idea generation
Deep disciplinary knowledge
Rational Problem Solving
Enterprise Systems Engineering
INNOVATION
Designing it right
Rapid proto-typing
Idea conversion
Divergent thinking
Failure as key for learning
Entrepreneurial thinking
Convergent thinking
Customer thinking
Diversity in thought
Business acumen
Global trends in engineering
International partnerships
Study abroad
Communication & pitching
Joint Summer Schools
Customised programmes
Inter-disciplinary thinking

the main driver for millennial students to attend university. Their motivation is to explore, co-create and develop their purpose in life. They want to feel a part of the university and have a sense of ownership.

Engineering programmes will have to help students cultivate a sense of belonging and feel part of a committed academic community. For campus universities it will be increasingly important to shift the focus from student satisfaction to student well-being. If campus-based universities like TU Delft do not emphasize the added value of campus education, they will lose students to so-called e-universities. Students expect to find a real world context in their university training, with cool technologies such as smart materials and structures with revolutionary properties, but also innovative properties of additive manufacturing, miniaturization, energy transition, big data, the Internet of Things, open standards and open sources, man-machine hybrids with increasing intelligence and more autonomous functions, safety and security. Exploring these subjects in curricula helps build a sense of belonging. It is equally important to engage students socially during their studies and after graduation through excursions to industrial companies, guest lectures, extracurricular experiences, the co-creation of education by supporting teaching assistantships, and the availability of inspiring collaborative learning spaces, makerspaces, labs and cafeteria. Engineering curricula can foster community engagement through design projects in teamwork and cross-cultural collaboration opportunities on campus, or by study-abroad programmes and industrial internships. Failure to provide the level of flexibility required by the modern student can easily damage this sense of community.

Building a sense of belonging calls for an identity and a dominant culture, the “couleur locale”. The university, department or study programme needs to be a beacon of sorts, one which can attract ambitious engineering students. It is risky to let go of the dominant culture by, say, an uncontrolled intake of foreign students and staff in favour of growth, internationalisation or greater diversity, or a massive move from face-to-face education to online education in order to reduce effort and cost. Such changes will distort the existing culture and the sense of belonging of the home students and staff. It is important to secure a dominant culture in which students are engaged and can develop into engineers with solid reputations and unique selling points.

If you take only one thing away from this

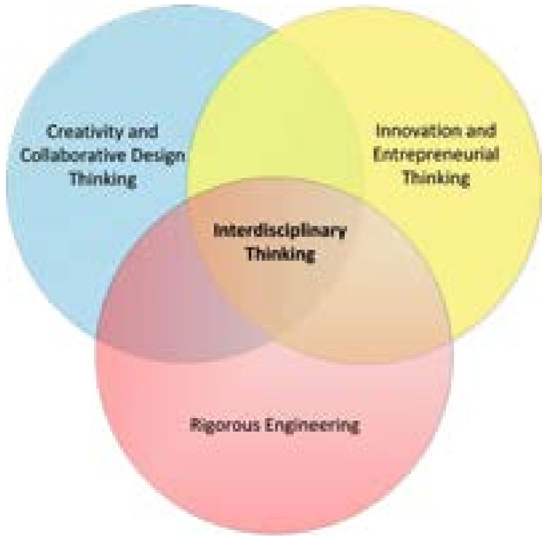
Over the past two decades, the world around us has changed at a dizzying pace through globalisation and digitalisation, the horizontalisation of the socio-economic world, and the blending of technical and economical and societal cultures. The way we communicate, work, travel, play and do business has changed dramatically, and is expected to change at an even faster rate in the coming decades. The world is being disrupted by new technologies, education cannot keep up with the rapid pace of change, and student populations no longer look the same. The Western European Millennial Generation and those born after 2010 have different values from the Baby Boomers or Generation X. Future generations of graduates will embark on solving unforeseen challenges, communicating in undreamed-of ways, innovating and working globally.

The world of higher engineering education has, up to now, been a very conservative one. In many cases it still stresses skills that are no longer critical in the new world and seems to ignore those that are gaining prominence. Many educational programmes, conceived and constructed in the 70s and 80s, in which ambitious students are trained to become capable engineers with an academic degree by empha-

> *"The OECD is signaling that higher engineering education is losing the race with the pace of innovation in technology and in the skills-demand of 21st century economies and the many social changes of contemporary globalised societies. At the same time significant reform is often difficult."*
>
> *OECD Centre for Educational Research and Innovation (October 2014)*

sising the theory of engineering sciences, will no longer be adequate to equip future generations of graduates with the knowledge, know-how and professional skills they need for a successful career in the 21st century. The Knowledge Society (know what you know, know what you can do with what you know) is in a state of transition to a Global Learning Society (know what you need, know how you can acquire it, know how you can use and apply what you have acquired). It is not the creation and dissemination, but the acquisition, sharing and combining of knowledge that will become the key factors of success. The new world of work also calls for a more holistic approach to engineering education. The new breed of bright technical minds needs to understand how to help solve the societal and engineering challenges of the 21st century through creative workable solutions, the performance and function of which not only depend on technology, but also on human factors and engineering business smarts. Engineering education will only be future-proof if it not only leads to an excellent preparedness in technical rigour, but also in operational skills for creative thinking, leadership and decision making which are required to lead successfully and solve complex projects.

What are the most important skills our engineering graduates need in their future careers? This is a universal question for universities and companies contemplating the next generation of academically educated engineers. And it has become a cliché to argue that future engineering curricula have to shift focus from "knowledge" to "skills". If we want to produce self-motivated and responsible engineers who have the ability to help solve 21st century societal and engineering challenges through creative workable solutions (the Mission Statement I formulated in the first chapter of this report), then the key skills to be developed are a broad and deep working knowledge of the fundamental engineering sciences, systems thinking, interdisciplinary thinking that encompasses engineering domains as well as human factors and business acumen, creative thinking, cross-cultural communication and collaboration, and a global mind-set. These attributes are not new, but their relative importance is shifting and will shift further in the coming decades. There is a strong consensus that a positive attitude towards lifelong learning is the most important skill an engineering graduate should have. In the 20th century, it has become common practice for engineers to learn everything they need on the job, mostly from experienced people. The rapid changes in technology also require them to keep up with new developments through continuous learning. In the new world of work it is no longer what an engineer knows, but how he learns and is able to apply what he learns that will make his career successful. Engineering students and educators have to adopt an approach to learning as an on-going experience and not as an end goal. An attitude of lifelong learning therefore seems the most important skill for successful future employability. Extensive experience as a design and systems engineer and many discussions with researchers in institutes, expert engineers in industry and young



The scene for innovative engineering curricula (adapted from Murray, 2014).

entrepreneurs have taught me that lifelong learning can only be successful if an engineer has a deep academic and working knowledge of the fundamentals of science, technology, engineering and mathematics, an analytical mind, as well as a good grasp of systems thinking and algorithmic thinking. These were the attributes that academics, industrial leaders and young entrepreneurs labelled as a top priority in the many discussions I have had.

"Lifelong learning will be the most important attribute for engineers in the future, but only if they have a deep academic and working knowledge of the fundamentals of science, technology, engineering and mathematics, an analytical mind and a good mastery of both systems and algorithmic thinking."

Rapid developments in teaching and learning methods (mobile learning, knowledge sharing, virtual reality, predictive learning analytics, and many more), combined with a deep interconnectedness, the free availability of large amounts of high quality (online) education with its "any time, any place"-availability, the increasing diversity in student population, and the increasing Do It Yourself mentality of a new generation of students, require an opening up of our educational programmes and a putting aside of control-freak tendencies. Students are seeking a greater degree of flexibility in their study programme and a more personalised learning journey, in which they can set their own learning agenda that reflects their prospective career, personal ambition and lifelong learning goals. It seems inevitable that our educational programmes will transition from established, clear models to new and uncertain ones, of coalitions of best-practice elements that are produced by partner universities and harmonised around joint didactic concepts. These programmes have to be built on the cornerstones of Innovation, Employability, and Community. Innovation and Employability are the two main reference points for future curricular structures and subject matter associated with the technical, professional, personal, interpersonal and cross-cultural needs of the future job market. Community is the third cornerstone for tomorrow's programmes. People devote more time and effort to their study or work when they share common values with the organisation they work for. In coming decades, engineering universities will transition from institutes of knowledge to institutes of connections. The more open and interconnected the world is, the stronger the need for a sense of belonging and a trusted community becomes. The younger generation wants to co-create and feel connected. A sense of belonging is developing into a key component for student motivation and success.

Programme change will not be driven by technology but by university strategy, the changing nature of the student body and the decisions of individual faculty members. Quite a number of programmes show a dangerous sense of complacency, where people deny or are insufficiently aware of the growing mismatch between job market needs and the narrow focus on technical knowledge in our current curricula. We have entered an era where higher engineering education is in the throes of a major shift. Making fundamental changes is inevitable. It is the only way to reap the benefits of pedagogical and technological innovations, and better prepare graduates for the increasing and very different demands of the new world of work. It is better to envision these changes and make choices on how to adapt education now, than to wait for time to pass and then try to respond.

> *"Prepare for change before it happens."*

The future may arrive long before we have been able to make the necessary changes.

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Appendix: Initiating change

At universities change can come awfully slow sometimes. Initiating change is therefore a real challenge. In this Appendix I describe three types of workshops and panel sessions I have used to create awareness about the need for change in engineering education in the coming decades.

Deadly Dilemmas

Objective

To provoke thought and discussion about necessary changes in the future of engineering education.

Format

In an interactive presentation, the audience and a panel of four to five different stakeholders in engineering education are forced to leave their comfort zone and make a choice between some pretty strange, sometimes absurd dilemmas on the theme of Transforming Engineering Education. What do they choose and why? Below you will find the eight dilemmas I constructed for a panel session about the Transformation of Engineering Education at the Hanover Fair 2016 which led to inspirational debates.

Dilemma 1

I am aiming for a successful career in engineering. Which option should I choose?
A university where I can only obtain a deep working knowledge of engineering OR a university where I can only develop personal and professional skills?

Dilemma 2

Intelligent machines will be capable to complete more and more non-routine cognitive tasks and develop abilities that used to be exclusively human. They will replace most of the current work of an engineer. Creativity, common sense and the human factor will be the only areas in which the engineer of flesh and blood can excel. What should I do to have the best chance of getting employed as an engineer in the future?
Complete a study in Arts and Humanities? OR complete a study in Social Sciences?

Dilemma 3

I know what type of engineer I want to become. All the skills and knowledge I need to develop has been made available on the web by the best professors of renowned institutes at a fraction of the cost of a campus education. What should I do to have the best chance of being employed?
I follow my Do-It-Yourself approach and shape my own education by taking online courses to build an excellent CV, OR I enrol at a campus university with an excellent reputation where I am taught the fundamentals in engineering sciences?

Dilemma 4

Engineering knowledge is developing rapidly and specialist knowledge is highly volatile. All up-to-date knowledge and information is available anywhere anytime. I have a choice to make:
I only learn the fundamentals of science and engineering, OR I only learn how to acquire new knowledge and how to apply it with the engineering tools available?

Dilemma 5

As a student, the only opportunity I have in my career for in-depth, specialized learning is during my academic years. At the same time, the more specialists are educated, the more integrators are needed by industries. I want the best chance of employability. What should I choose?
An education that only trains my systems thinking and develops me into a system integrator, OR an education where I only learn how to specialise deeply and advance knowledge by research?

Dilemma 6

Engineering universities are traditionally organised in monodisciplinary stove pipes. As a student I want to learn how to innovate. What should I do?
Do my thesis project at the university department where I am supervised by monodisciplinary experts who assure the academic level, but lack an interdisciplinary mind-set or innovation skills, OR do my thesis at the innovation department of an industry where I am supervised by engineers

who have a multidisciplinary mind-set and are focused on value creation, but have no clue on an academic level?

Dilemma 7

I am a lecturer and will be teaching a course on innovation in an engineering programme. Which of the two messages will I convey to my students?

Be competitive in innovation, specialisation is what is needed, OR successful innovation requires a multidisciplinary and entrepreneurial mind-set?

Dilemma 8

The university community is involved in many exciting educational innovations. These innovations are mostly based on personal experiences in the academic classroom. If we want to improve the quality of our education and make it future proof, each academic staff member:

Has to professionalize in educational research, OR has to professionalise in engineering practice by a regular placement in industry?

Shifting Attributes

Objective

Creating awareness about the changing needs of society and the industry.

Format

Categorising cards that list current and new attributes of an academic engineer and visualising the choices made by sticking the cards in the chosen field on the flipchart.

It is not the result but the discussion during the prioritisation process that counts. Below you will find the attributes and flipchart lay-out I constructed for an engaging workshop with about 40 enthusiastic participants at the CDIO Fall Meeting in Belfast November 2015.

Materials used

About 40 sticky notes, each one listing an attribute, and a flipchart with the following lay-out.

KNOWLEDGE
knowledge of engineering science fundamentals
knowledge of multiple engineering disciplines
deep disciplinary knowledge
up-to-date expert knowledge

WAYS OF THINKING
creative thinking
critical thinking
customer thinking
logical reasoning
interdisciplinary thinking
common sense
systems thinking
vertical thinking
complex problem solving
formulating problems
algorithmic thinking

LIFE AND CAREER
agility
autonomy
career development
ethical responsibility
personal leadership
lifelong learning
self-reflection
mobility

GLOBAL AWARENESS
environmental literacy
intercultural awareness
understanding non-engineering disciplines
business economics
sustainability
entrepreneurship

WAYS OF WORKING
communication, pitching
work in teams
work under pressure
networking
risk taking

TOOLS FOR WORKING
digital literacy
data analytics (big data)
programming
project management
systems engineering
research methodology
design and manufacturing processes

Source: The categories Knowledge, Global awareness, Ways of Thinking, Ways of Working, Tools for Working, Life and Career are based on the four categories of knowledge, skills, attitudes and values in the Assessment & Teaching of 21st Century Skills Project (www.atc21s.org).

'Free Spirits' Think Tank

Objective

- Look ahead to the year 2030 and revaluate what students' capacities should be, without losing their current core strengths.
- Creating awareness and support for change by a wide representation of the academic community (on a university or department level).

Format

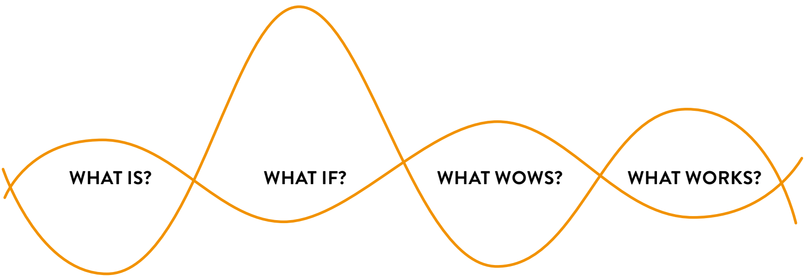
Five dedicated workshops of five hours each, including time for socialising at lunch or dinner, with typically 15 full, associate and assistant professors, senior lecturers, programme directors, members of the valorisation centre, student bodies, and educational experts.

Exploration of a set of challenging questions via the method of Design Thinking. Exploration of trends in engineering and society. Developing ideas based on possible future worlds and building concepts that address the "What" question. The workshops may be supported by survey data on trends in science, student interviews on campus pavements, and social media like Twitter or Facebook on which progress can be shared with the academic community and feedback can be obtained. Below you will find the Think Tank activity flow and questions we developed for the "Free Spirits" Think Tank at TU Delft in the spring of 2015. Details have been presented at the CDIO Annual Conference 2016 (Kamp, Klaassen, 2016).

Examples of challenging key questions:

- What type of students do we want to educate?
- What are the major changes our students will face in 2030?
- What is the added value my university can deliver in terms of educational content?
- Which learning processes help to sustain the preparation of the future engineer?

Design Thinking process (source: Kamp, Klaassen 2016).



What is?	**What if?**	**What wows?**	**What works?**
Critical Questioning Journey Map Insight questions Dilemmas and SWOT Survey response on trends in engineering, sciences and education Design Challenge Mind Mapping	Building world scenarios Profiles and added value Pockets of knowledge LEGO exploration	Common languages Roles and profiles Hubs	Pilot testing Validating stakeholders Discussing policy

What is: Exploring present trends and innovations in engineering, engineering sciences and engineering education, defining the problems and reframing the questions.
What if: Generating new concepts for on-campus engineering education.
What wows: Identifying the best opportunity.
What works/manifests: Defining rapid-prototyping options; creating a Manifest- Results of previous sessions and the way it will be disseminated.

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 15 years of academic experience in teaching and educational management have given him a good overview in the academic and professional capabilities that engineers will need to obtain for a successful career in the future world of engineering, science and technology.

In his 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 programmes. He has taught Bachelor and Master courses on Space Engineering & Technology, History of Spaceflight, and Space Instrumentation Engineering. He is a member of the Council of the CDIO Initiative, the global innovative educational framework for producing the next generation of engineers, and the TU Delft Leader of the Dutch 4TU Centre of Engineering Education (4TU.CEE), which facilitates innovations in higher engineering education within and outside the Netherlands. He is also involved in the Educational Leadership Course produced by the Erasmus University Rotterdam, TU Delft and University Leiden as a board member and trainer of the module “Curricular Change is not Rocket Science”.

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