Adaptation of the Engineering Curriculum in the Age of Industry 4.0

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ABSTRACT

With the rapid proliferation of Industry 4.0 across the globe there is an immediate need for institutes of higher learning to adapt their curriculums, especially in the fields of engineering and IT, in order to ensure relevance to both industry and society. Industry 4.0 is synonymous with cyber-physical systems, AI and the internet of things and requires a knowledgeable workforce that are both inter- and multi-disciplinary skilled. This paper proposes a framework for a three- or four-year electronic engineering degree that aligns itself with the needs of Industry 4.0. The framework is comprised of three core pillars and provides a roadmap for the adaptations required in the curriculum, practical work and competency components of the qualification. In addition to knowledge attributes we also discuss the notion of graduate attributes as well the assessment of these outcomes. A three-year bachelor’s degree in electronic engineering that applies this framework is currently being offered at the Durban University of Technology, South Africa.

Keywords: Industry 4.0, Industrie 4.0, Fourth Industrial Revolution, Engineering Education, Education 4.0

INTRODUCTION

The first industrial revolution began with the mechanisation of mass labour-intensive manufacturing processes. Subsequently, and arguably the more important leap, was the automation of one or more of the manual mechanisms that made up those machines; this was primarily owing to the invention and use of the steam engine. The second industrial revolution involved the improvement and upscaling or massification of manufacturing and production methods; this coincided with the invention of the combustion engine and electric generator. Contemporarily, industry and society were being transformed through a deeper understanding of the relationship between and use for electricity and magnetism. The third industrial revolution involved the integration of digital systems across all aspects of the manufacturing process; this was owing, in the main, to the invention of the transistor, integrated circuit and microprocessor as well as the subsequent proliferation of digital communication systems and computers. The integration of digital electronic and communication systems with automated mechanical systems is termed mechatronics. Mechatronic systems may be highly precise in their operation but are nevertheless methodical and non-decisive in nature. The fourth industrial revolution (4IR) refers to the ‘independence’ of the digitally automated manufacturing processes using cyber-physical systems (CPS). CPS may be described as systems that have integrated feedback sensors with intelligent decision-making capabilities; this may be considered as the transition from mechatronic to robotic. Incidentally, the term “fourth industrial revolution” was previously associated with the development of nanotechnology (Hung, Wang, & Chang, 2012); however, in recent times it has become associated with CPS and more synonymously with the terms “industrie 4.0”, industry 4.0 (I4.0 or I4) and industrial internet of things (IIoT).
With the proliferation of I4.0 across the globe there is an immediate need for institutes of higher learning to swiftly adapt and implement the methodology and elements of these rapidly changing trends and evolving demands of the industry into their current syllabu

s (Kozák, Ružický, Štefanovič, & Schindler, 2018). The consequence of not doing so will result in cohorts of graduates finding themselves as part of the redundant workforce where their acquired knowledge might quickly become obsolete (Wermann, Kliesing, Walter, & Moraes, 2015).

With the changing landscape of I4.0 it is predicted that jobs, such as those in parts assembly, could be eradicated; however, there may be new jobs in R&D and engineering, such as 3-D printer designers, that could be invented (Lorenz, Rüßmann, Strack, Lueth, & Bolle, 2015). Similarly, according to a 2016 World Economic Forum white paper it is estimated that by 2030 anywhere from 2 million to 2 billion jobs will be in jeopardy because of these digital disruptor technologies associated with the machine age; however, it is estimated that 6 million new jobs will potentially be created by 2025 (Accenture, WEF-SC, & WEF-WG, 2016). Currently, there are jobs (and even words and descriptors for jobs) that didn’t exist 10-years ago; these include mobile application designer and developer, Uber and Taxify driver, blogger and vlogger, big data analyst, tech ethicist, drone expert, 3D printer and printing designer, and driverless car engineer. These new type of jobs will primarily benefit those people in the fields of electronic and process engineering, information technology, mathematics and computer science (Benešová & Tupa, 2017). In Germany, for example, it is projected that there will be a shortfall of around 120,000 university graduates with degrees in computer engineering and IT by 2025 (Lorenz et al., 2015). Consequently, there is an immediate need for universities to adapt to these industrial and societal changes, especially in the fields of engineering and IT.

Figure 1: STEM Education and Industry 4.0 (Idin, 2018)

Although science, technology, engineering and mathematics (STEM) would appear to be related to I4.0 there is no coherent link between knowledge, skills and attributes of the higher education graduate and the associated requirements of industry in the machine age (Idin, 2018). Universities therefore are required to proactively adapt the curricula of their STEM qualifications in order to create this relationship. Figure 1 provides a model that shows the relationship between STEM, 21st century skills, aims and I4.0.

Both social as well as global economic development are intertwined with engineering education (Lucena & Schneider, 2008); consequently, in addition to knowledge of the engineering sciences, it is necessary for engineering students to have robust skills in human relations as well as
practical experiences in real contexts (Baena, Guarin, Mora, Sauza, & Retat, 2017; Litzinger, Latucca, Hadgraft, & Newtetter, 2011; Male, Bush, & Chapman, 2010). The purpose of engineering cultivation at an institute of higher learning is to provide students with theoretical knowledge and enhanced practical ability to promote innovative thinking in order to meet the needs of society and industry while ensuring their employability (Jun & Jing, 2017). However, higher education, like industry, is just as susceptible to disruptions brought about by digital transformation; consequently, traditional education methods are no longer adequate in providing a foundation for employability (Ciolauc, Svasta, Berg, & Popp, 2017).

According to the European Commission (2016), 4.0 will require a greater focus on practical education and practical skills in order to develop, maintain and operate systems in smart factory environments where humans and machines will be working in collaboration. With the development of complex equipment there is a shift towards merging deep theoretical knowledge with practical emphasis and real world skills; this will undoubtedly put pressure on universities (Madsen, Bilberg, & Hansen, 2016). The curriculum must be industry-relevant, particularly in institutes that have a high emphasis on practical skills; students should be taught with stimulating learning experiences that promote the development of skills demanded by industrial markets (Hashim, Abdullah, Herman, Taib, & Alias, 2014; Ramirez-Mendoza, Morales-Menendez, Iqbal, & Parra-Saldivar, 2018).

The aim of this paper is to present a curriculum that incorporates a significant amount of the requirements of 4.0 for a three-year undergraduate bachelor’s degree, and a subsequent one-year postgraduate Honours degree, in electronic engineering. Complementary to the curriculum, the integration of the practical work components and competency outcomes of the programmes are also discussed. The bachelor’s degree discussed in this paper has been on offer at the Durban University of Technology, in South Africa, since January 2018.

METHODS

Figure 2: Industry 4.0-based Curriculum Framework for Electronic Engineering
The core objective of higher education is to arguably prepare graduates for work and life whereby content mastery, deeper learning, teamwork, communication skills, creative problem solving, higher order thinking and increased critical thinking abilities are integrated (Jeganathan, Khan, Raju, & Narayanasamy, 2018). Other attributes may also include practical ingenuity, business and management, creativity, strong analytical skills, global awareness, leadership, dynamism, ethical values, and social consciousness.

Since the technologies associated with I4.0 will have to be controlled by employees that are highly educated and qualified, basic engineering is seen as a tool that avoids obsolescence (Benešová & Tupa, 2017). A sensible point therefore in designing a new curriculum will be to find a balance between a strong scientific foundation, broad education and specialisation. In developing countries, such as South Africa, where there are often only limited job opportunities in all specialities, the graduate must be able to adapt to what is available (Venturino, Alberto, & Godfrid, 2007).

In this part, a framework for an electronic engineering qualification that incorporates the requirements of I4.0 is presented. As aforementioned, the qualification is currently being offered at our institute, the Durban University of Technology (DUT), and is referred to as the Bachelor of Engineering Technology in Electronic Engineering (BEngTech:EE). The framework, which is illustrated in Figure 2, comprises three overarching core pillars that are interrelated and interdependent on each other; these include curriculum, practical work and competency. Curriculum refers to the modules, theoretical content, flow and structure of the course or qualification. Practical work implies the observation, practice, manipulation and/or application of the theory in various environments such as laboratories, industry, natural surroundings, homes and classrooms. Competency, according to the late former United Nations General Secretary, Kofi Annan, may be defined as the combination of skills, attributes and behaviours that are directly related to successful performance on the job (Irigoin, Whitacre, Faulkner, & Coe, 2002). The measure of the competency is achieved through the assessment of the relevant knowledge profile (theoretical and practical work) underpinning the skills as well as attributes associated with a qualification. Attributes in this context refers to the wholistic quality, attitude and disposition of the graduate; this commonly referred as graduate attributes (GAs).

Curriculum

In this sub-section we will discuss the curriculum framework that was developed for the BEngTech:EE at DUT. Engineering education finds itself in a quandary whereby graduates must be prepared for jobs that haven’t been created, using technologies that haven’t been invented, and solve problems that haven’t become problems yet. It is therefore unrealistic to devise a curriculum that accounts for all real-time problems that currently exist and may exist in the future. Engineers are expected to be life-long learners and therefore be able to provide solutions to a myriad of realistic problems. The curriculum needs to be resilient, agile and dynamic that include technical, soft-skill and social components (Jeganathan et al., 2018). Although specialisation is important it is also necessary for engineering students to have a solid general foundation in the physical, mathematical and engineering sciences as well as multidisciplinary know-how and inter-disciplinary exposure (Kozák et al., 2018; Wermann et al., 2015). Albert Einstein’s own pedagogical viewpoint was that the development of general ability for independent thinking and judgement should always be placed foremost, not the acquisition of special knowledge.

Moreover, with industrial processes becoming ever more complex, the creation of intelligent automated systems require elements of many different aspects of engineering, knowledge and skills across a variety of disciplines and an understanding of topics not related to one’s area of
expertise (Jeganathan et al., 2018; Ramirez-Mendoza et al., 2018). Figure 3 provides an illustration of a multidisciplinary system design (Kozák et al., 2018).

**Figure 3: Multidisciplinary professional areas of education for Industry 4.0**

The International Engineering Alliance (IEA) is an organisation that establishes and enforces internationally bench-marked standards for engineering education; it represents 27 countries, including South Africa, which are signatories to the Washington, Sydney and Dublin accords. The IEA refer to engineering content areas as a knowledge profile; this includes mathematical sciences, natural sciences, engineering sciences, engineering design and synthesis, computing and IT, and complementary studies (IEA, 2013).

Although at first glance there may not appear to be much flexibility within the IEA knowledge profile, however, both engineering sciences and complementary studies allow for the incorporation of inter-disciplinary, multi-disciplinary and humanities components.

Another factor that needs to be considered is the educational level at which the content is being presented and evaluated. In South Africa, the different levels of education from Grade 9 up to Doctorate are classified according to a national qualification framework (NQF), whereby Grade 9 to Grade 12 (matric or exit-level for high/vocational school) are defined as NQF levels 1 to 4, one-year post-matric vocational certificates are NQF level 5 (emphasis on remembering, understanding, applying and analysing content), two-year post-matric diplomas or advanced certificates are NQF level 6 (emphasis on evaluation of content), three-year post-matric degrees or advanced diplomas are NQF level 7 (emphasis on creation and application of content), four-year post-matric degrees or post-graduate diplomas are NQF level 8 (emphasis on research), Master’s degrees are NQF level 9, and Doctoral degrees are NQF level 10.

The BEngTech:EE is a three-year (NQF level 7) 210 ECTS-credits bachelor’s degree and the Honours is a further one-year (NQF level 8) 70 ECTS-credits degree. The fundamental difference between the BEngTech:EE and the Honours degrees, besides the different NQF levels, is that the former deals with the notion of broadly defined engineering problems while the latter involves the notion of complex engineering problems.

A graphical overview of the knowledge and content areas incorporated into the BEngTech:EE and Honours degrees as well as the associated NQF levels are provided in Figure 2. At the foundational level the core fundamentals of the mathematical and physical sciences, analogue, digital and power electronics, as well as general literacy, computing and IT skills are introduced and developed. Subsequently, the students are broadly exposed to four interdisciplinary electronic engineering subject areas; these include (i) telecommunications, (ii) instrumentation and control systems, (iii) embedded and intelligent systems, and (iv) renewable energy. These four subject areas are developed and assessed from the intermediate to the exit level. In addition, a fifth complementary core stream, which includes the principles and applications of engineering design, is incorporated. Finally, multidisciplinary topics such as data and statistical analytics, machine
learning, economics, project management, innovation, entrepreneurship and ethics complete the knowledge profile. All modules in the BEngTech:EE are compulsory.

At the Honours level the gravitas of the knowledge profile will be further enhanced through a deeper understanding of the interdisciplinary and multidisciplinary subject areas together with their application to complex engineering problems as well as engineering research. At that stage, the broad subject areas covered in the BEngTech:EE will be amalgamated into some of the core topics associated with I4.0; these include, among others, cyber physical and AI systems, automation and mechatronics, embedded telecommunications as well as IoT and cybersecurity. It is proposed that a significant portion of the modules in the Honours programme be compulsory; however, a selection of elective modules will be provided for students desiring a modicum of sub-specialisation.

For a detailed breakdown of the BEngTech:EE curriculum, including modules, content and handbooks, refer to the department of electronic and computer engineering webpage at www.dut.ac.za.

**Practical Work**

In this sub-section we discuss the role and integration of practical work into the curriculum of the BEngTech:EE degree at DUT. Practical learning may be defined as the process whereby knowledge is created through the transformation of experience (Kolb, 1984). Kolb’s experiential learning cycle is arguably the most frequently referenced model of practical, reflective learning (Ramsey, 2006); this is illustrated in Figure 4. Briefly, a *concrete experience* may be described as a sequence of events or some situation; *reflection* is the answering of the ‘how’ and ‘why’ did something occur; *generalisation* may be considered as the abstract conceptualism of how the experience may apply to other situations; and *action* is seen as the application of the learnt experience. At least one other institute is applying Kolb’s model to the laboratory components of the curriculum in regard to I4.0 engineering education (Coşkun, Kayikci, & Gençay, 2019).

![Figure 4: Kolb’s Experiential Learning Cycle](image)

Reflective learning, simply put, is the idea of reflecting upon what you have done and thinking about how you could do better next time (Ramsey, 2006). This is not about ‘just trying harder’ when faced with difficult problems, since real world experiences, unlike mathematical algorithms, are not repetitively identical. An apt comparison may be made with Churchill’s (1948) paraphrased quote of Santayana: “Those who fail to learn from history are doomed to repeat it.” Here the word “learn” may prudently imply reflective learning. Students must understand that for a different result there needs to be a different approach.

Ramsey (2006) proposes an amalgamation and minor expansion of Kolb’s experiential learning model. In this case, experiential learning is understood to happen when you firstly, generate and evaluate new ideas from an experience or content; secondly, when you reflect on the experience by considering what has happened and what can be learnt from it; and thirdly, by considering your
past experiences as well as feedback and the experiences learnt from others. An important component of learning is not just self-reflection but also reflection based on feedback or experiences of others; this factor is not explicitly considered in Kolb’s model.

A common misconception, especially in relation to practical work, is that the ability to do and the ability to know why one is doing something are the same; however, these actually represent two different outcomes (Millar, Tiberghien, & Le Maréchal, 2002); this is illustrated in Figure 5. Practical work should not be designed like a ‘recipe’ since the result may be successfully achieved (effectiveness at level 1), however, the reason behind the result being achieved is not understood (effectiveness at level 2) (Millar, 2004). For example, if a modified version of the original ‘recipe’ is provided, however, with an incorrect ‘ingredient’ (step or component), then an error in the result may either not be realised nor understood. In the BEngTech:EE programme the practical work has been developed by considering an adaptation of Kolb’s model, where external feedback is also considered, as well as taking into account both levels of effectiveness whereby students not only focus on the observables but also have to think about the explanatory ideas involved. The assessment of practical work is discussed in the next sub-section.

![Figure 5: The process of developing and implementing a practical task](image)

**Figure 5: The process of developing and implementing a practical task**

**Competency**

In this sub-section we discuss the outcomes and assessments of the curriculum of the BEngTech:EE degree at DUT. In addition to the knowledge profile, the IEA also emphasises the graduate attributes (GAs) of the student (IEA, 2013). According to the IEA, *GAs form a set of individually assessable outcomes that are the components indicative of the graduate's potential to acquire competence to practise at the appropriate level; these include engineering knowledge, problem analysis, design/development of solutions, investigation, modern tool usage, the engineer and society, environment and sustainability, ethics, individual and teamwork, communication, project management and finance, and lifelong learning.*
The theory, practical work as well as the GAs must be assessed across the curriculum and throughout the qualification. In modules with practical work, we set a benchmark of 40% of the assessments to be based on these components; although not prescriptive, this is however in keeping with the ethos of I4.0 engineering education. Both the theory and practical work are continuously assessed throughout the semester in a series of formative and summative assessments. Formative assessments allow for students to get feedback from the lecturer and are intended to provide an opportunity to reflect on their results and/or shortfalls. The summative assessments are usually developed as a form of re-assessment, where the students are given the opportunity to improve on their previous shortfalls and/or solidify their knowledge and application of the content (effectiveness levels 1 and 2, as discussed in the previous sub-section).

In the BEngTech:EE, GAs are developed during the first two years and subsequently assessed at the third year exit level. In Honours, the GAs are only expected to be assessed. For the assessment of the GAs it is necessary to be innovative since these measurements are not as clearly defined as those for the theory and practical work components; for example, how does one assess ethics or even lifelong learning? It is not as simple as just providing a module on, for example, morals and ethics since effectiveness level 1 may be achievable in this manner, however, it doesn’t automatically address effectiveness level 2; in these cases, reflective learning is imperative, as discussed in the previous sub-section.

In South Africa, post-graduate degrees generally refer to Master’s and Doctorate degrees, while Honours degrees are associated with professional qualifications. At present the BEngTech:EE at DUT will allow for registration as a candidate professional engineering technologist. The international accreditation of the programme is dependent on both the requirements of the knowledge profile being adhered to as well as the graduate attributes being achieved.

**CONCLUSIONS**

In this work we proposed a generic framework for a three- or four-year electronic engineering degree which incorporates several factors associated with the demands of the burgeoning Industry 4.0. The framework consists of three overarching components viz. curriculum, practical work and competency. In the curriculum component, we incorporated inter-disciplinary, multi-disciplinary and humanities components into the recommended IEA knowledge profile. In the practical work component, we incorporated an adaptation of Kolb’s experiential learning model, where external feedback is also considered, and students not only focus on the observables but also must think about the explanatory ideas involved. In the competency component, we assess not only the theory and practical work aspects but also the graduate attributes. The practical work components of the modules represent 40% of the total assessment; this is in keeping with the ethos of Industry 4.0 engineering education. Finally, the recommended IEA graduate attributes are also developed and assessed throughout the curriculum. This framework is applied to a three-year bachelor’s degree in electronic engineering currently being offered at the Durban University of Technology, South Africa.

Although universities are urged to adapt their engineering curriculums to address the needs of Industry 4.0, there are two immediate factors that hinder this conceptual shift. The first is that there is no clear direction with regards to Industry 4.0 and the rapid changes in the requirements of the labour market (Lambrechts & Sinha, 2018). The second is that educators are having difficulties in being able to acquire new knowledge relating to these current trends and subsequently applying these principles to the teaching of their students (Chan, Chen, & Chou, 2006). These are not small concerns, however, in the coming years it is imperative that institutes of higher learning remain relevant and evolve with the rapidly changing needs of industry and society or they themselves might also become obsolescent.
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