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Investigation of technical competencies for Quality 4.0 in Australian manufacturing curriculum

Venkata Sudha Manjusha Vanarla, Zach Quince and Steven Goh
University of Southern Queensland, School of Engineering
Corresponding Author Email: Zach.quince@unisq.edu.au

ABSTRACT

CONTEXT

Quality 4.0 is a topic that is in the limelight for the application of technological advancements of Industry 4.0. Quality 4.0 is defined by concepts like Internet of things, data analytics and cybersecurity. Despite the criticality of Quality 4.0 and Industry 4.0 in the future, quality professional engineers do not possess the necessary technical competencies required to adapt to Quality 4.0. While Quality 4.0 is an integral part of all business units, it is crucial for the mechanical and manufacturing disciplines.

PURPOSE

The purpose of this research project is the exploration of manufacturing engineering curriculum in Australian higher education providers and map the current programmes of study to a newly developed framework of the competencies required under Quality 4.0. The main objective of this research is to identify the potential gaps in current manufacturing degrees and provide a way forward to future proofing pedagogical direction.

APPROACH

The research mapped the current manufacturing curriculum to a newly derived framework of technical competencies under Quality 4.0. The course learning outcomes, program learning outcomes and course synopsis of engineering manufacturing programs of Australian higher education was mapped to the framework to identify gaps.

OUTCOMES

The work herein identifies the gaps in the manufacturing engineering curriculum, alongside recommendations concerning the current pedagogical direction required to up-skill engineering students for a career under Quality 4.0. Results of this work will enable universities and industry partners to identify similar mapping in other engineering disciplines and define opportunities for improvement.

CONCLUSIONS

This paper provides an overview of the key competencies for the application of Quality 4.0 for quality engineering graduates in manufacturing. This paper also serves as the first mapping study under the new framework that enables essential technical competencies.

KEYWORDS

Curriculum, mapping, industry, graduates, skills, outcomes

Introduction

'Industry 4.0' (I4.0) or the 'Smart Industry" is the fourth industrial revolution based on digitalisation and data (Rico et al., 2024). It enables flexibility and adaptability to the changing needs of market based on emerging technologies like cyber-physical systems, the Internet of Things (IoT), cloud computing, additive manufacturing, Artificial Intelligence (AI), big data, virtual and augmented reality, drones and blockchain (Rico et al., 2024). It also aids in other benefits like resource utilisation, horizontal integration, and value creation (Mason et al., 2022). Aligning to this industrial revolution, is the advancements in quality management known as Quality 4.0 (Q4.0). Q4.0 spotlights on integrating people, process and technology while improving decision making, quality, trust, and traceability (AlKhader et al., 2023).

Implementing Q4.0 means applying a closed quality loop system with features like inspection activities, digitalisation of results and integration of results with the entire manufacturing system (Sader et al., 2022). It minimises human error during measurement and analysis of inspection results by utilising sensors and IoT devices consequential in huge data (Sader et al., 2022). Additionally, predictive analysis of this mass data provides insights about the expected defects eventually helping in avoiding defects from occurring (Sader et al., 2022). Other important technologies in this closed loop system include: AI, Big Data, Blockchain, Deep Learning Machine Learning, data sciences and enabling technologies like sensors, actuators, RFID etc. These enable experts to explore identified and hidden factors affecting quality (Sader et al., 2022). Whilst there has been significant work on defining sub-topics of quality 4.0, there is still much work to be done on combining these topics and bringing them into a singular framework.

As a result of this, Q4.0 has impacts in industries like manufacturing, R&D, service and after sales, procurement, logistics and sales (Küpper et al., 2019). Our focus which is manufacturing, is the seventh largest employer, sixth largest for output, and with highest expenditure on research and development is a critical component of Australian economy (Tortorella et al., 2021). Enactment of Q4. 0 principles in this domain involve notions like integration of systems, computer aided design & manufacturing, robots, computer vision, data, man machine interface, smart machinery for production, overall digitalisation etc (Javaid et al., 2021). In addition, the other major factor aimed at this effective adaptation is employees (Ejsmont, 2021) and their competencies (Maisiri & Dyk, 2020).

Furthermore, competencies are categorized as technical, which are particular of a discipline or professional, which help acquire the disciplinary skills (Ramirez-Mendoza et al., 2018). Whilst Q4.0 incorporates both the technical and non-technical skills, this work will only focus of the technical competencies of Q4.0. There exists limited work on developing a comprehensive framework of the technical skills required under Q4.0 for engineering graduates. As such, previous work by Vanarla et al), developed a comprehensive framework that encompasses the critical technical skills for engineering graduates under Q4.0.

The current paper investigates the fundamental factors necessary to the transition into a future quality graduate in the era of Q4.0 using the developed framework. Whilst there is currently a heavy emphasis on professional skills in Australian engineering education as depicted by (Hernandez-de-Menendez et al., 2020), the focus of this research will remain in the technical domain. As such, there are two aims of this research.

1. Through the utilisation of the framework, determine if current engineering manufacturing programs in Australia are meeting the required competencies under Q4.0.
2. Provide a review of the developed framework to assess if there are any improvements that would be made.

Evolution of Quality Skills

Current quality technical skills are implemented by tools and strategies including 5S, six sigma, ISO 9001:2015, and lean manufacturing (Hamid et al., 2019) which is focused on people alongside networks focus. Quality management is now evolving into smart focus which ensures quality in people in the smart environment (Hamid et al., 2019) which is the current industry emphasis. For effective transition, we need to understand what the current and required quality skills are. Based on literature review, we present the current skills for quality management which are referred to as traditional tools (Table 1) (Klementev, 2015; Oliveira et al., 2024; Psarommatis et al., 2022) and Q4.0 competencies (Santos et al., 2021).

Table 1: List of Traditional tools and Quality 4.0 technical competencies

Traditional tools	Quality 4.0 competencies
Total Quality Management (TT1)	Artificial Intelligence (QT1)
Six Sigma (TT2)	Machine Learning (QT2)
Lean Manufacturing (TT3)	Intelligent Process Automation (QT3)
Continuous Process Improvement (TT4)	Connected Devices (QT4)
5S (TT5)	5G Technology (QT5)
ISO 9001:2015 (TT6)	Big Data Analytics (QT6)
Statistical Process Control (TT7)	Cloud Computing (QT7)
Zero Defect Management (TT8)	Cybersecurity (QT8)
	Block Chain (QT9)
	Internet Of Things (QT10)
	Cyber Physical Systems (QT11)

This paper evaluates the technical competencies required for Q4.0 transition for an engineer through a thorough review of the current literature. A core list of topics that encompass this technical move revealed 11 required skills by engineering graduates. This list of topics was developed into a framework for the technical skills required by Q.40.

Methodology

As previously discussed, to validate the framework, an investigation into undergraduate programs offering manufacturing engineering alone in Australia were assessed. In total, five universities offer 4-year manufacturing engineering as a major in both mechanical and manufacturing graduates were found. The system used mapping of course profile form these five universities to the identified technical competencies in the proposed framework. Literature review was conducted to arrive at this framework. The current paper for the first time identified competencies that are both industry needs and universities outcomes by mapping. The competencies were investigated in the six elements of all the coursework for these five degrees.

1. Program (degree) synopsis
2. Program (degree) learning outcomes
3. Course or subject synopsis
4. Course or subject learning outcomes
5. Course or subject topics
6. Course or subject assessments

The coursework and programs that were investigated were found via a web search for manufacturing engineering at undergraduate level. A total of five programs of 4-year study were found.

Table 2: Universities and coursework investigated

Western Sydney University (WSU)	Advanced manufacturing
University of New South Wales (UNSW)	Mechanical and manufacturing engineering
Flinders University (FU)	Advanced manufacturing and digital design
RMIT University (RMIT)	Advanced manufacturing and mechatronics
University of South Australia (UniSA)	Mechanical and advanced manufacturing

In the following sections, the universities and courses will be deidentified as this work is not aimed to single out any specific institution but look at Australian curriculum as a whole. The quality of the outputs is based on the quality and quantity of information provided by the course entries in the websites of respective universities. This relationship means that any misalignment between the course entries and what is taught in the subject will affect the final map produced. This misalignment can occur when Q4.0 concepts are taught in a subject but not included in the handbook. It can also happen when subjects claim to teach Q4.0 but do not address the concepts in the curriculum. Efforts have been made to limit the impact of mis-claimed Q4.0 inclusion and are discussed below. However, the detection of mis-claimed Q4.0 inclusion is outside the scope of this paper further require analysis of teaching and assessment materials which serves as a limitation of this work. This investigation was conducted by thorough search for keywords of both 11 Q4.0 skills and 8 traditional skills as it is in the above mentioned six elements. Robotics and sensors were considered part of connected devices during this search whereas smart control, smart factory were considered part of cyber physical systems. Quality control, Quality management, Quality assurance keywords are attributed to Total Quality Management. Also, Industrial internet of things considered as IoT. The below definitions of the 11 Q.40 were used to map the topics to the programs.

Artificial Intelligence: A subfield of computer science that deals with the development of intelligent agents, or autonomous reasoning, learning and acting systems is called Artificial Intelligence (Ettalibi et al., 2024). **Machine Learning:** A study of learning algorithms wherein a computer program call model self develops with experience is called Machine Learning (Hoffmann & Reich, 2023). ML enables computers to learn and make predictions or decisions with computational algorithms and statistical techniques (Hoffmann & Reich, 2023). **Intelligent Process Automation:** “IPA is a combination of process enhancements and next generation tools with an aim to reduce or eliminate repetitive as well as regular tasks where it imitates human behaviour and learn from it with an aim to increase the efficiency in each iteration” (Kholiya et al., 2021). **Connected devices:** According to a paper by (Lenz et al., 2023) connected devices are “physical and information-based representations of an item which possesses a unique identification, is capable of communicating effectively with its environment, can retain or store data about itself, deploys a language to display its features, production requirements, etc., and is capable of participating in or making decisions relevant to its destiny”. **Cloud Computing:** Cloud computing was first coined in the year 2007 and is defined as “a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction (Bhatt et al.)”. **Cybersecurity:** While Industry 4.0 is driving innovation in the manufacturing sector, companies are vulnerable to cyber-attacks. A lack of investment in cybersecurity has led to losing of $240 billion in revenue in the manufacturing sector in the U.S. (Wu et al., 2018). The WannaCry malware has forced Honda’ Tokyo based automotive production plant to go offline (Mahesh et al., 2021) showcasing the importance of cybersecurity in manufacturing. **Blockchain:** Blockchain is a decentralized database technology for autonomous decision making in data operations and validation through consensus algorithms (Bankoff et al., 2023). Blockchain transactions form a cryptographically secure and append only chain of blocks offering decentralization, security, immutability and transactional trust (AlKhader et al., 2023). **Internet of Things (IoT):** An extension of internet is called Internet of Things (IoT) (Bi et al., 2014) which enables networked interconnection of objects to be constantly connected into the internet space often equipped with ubiquitous intelligence (Caputo et al., 2016). IoT plays a crucial role in the manufacturing sector by allowing objects to be connected remotely across existing network infrastructure, creating opportunities for more direct integration of the physical world into computer-based systems. **Cyber Physical systems:** Cyber-physical systems (CPS) is the collaboration of the cyber and physical systems whose operations are monitored, controlled, coordinated and integrated by a computing and communicating core (Monostori et al., 2016). **5G Technology:** Connectivity plays a main role in the current transformation of smart manufacturing. 5G is predicted as an integral part of an end-to-end networking infrastructure supporting smart manufacturing operation (Godor et al., 2020). 5G or the fifth-generation communication technology enables the “ubiquitous communication” needed to achieve interconnection of all production equipment, materials, tools workers and production process (Cheng et al., 2022). **Big Data Analytics:** Big data possesses datasets whose size exceed the abilities of typical database software tools to capture, store, manage and analyse and have volume, variety, velocity, and veracity. Big data analytics is the ability to acquire information from data by applying statistics, mathematics, econometrics, simulations, optimizations, or other techniques to support decision making (Belhadi et al., 2019).

Results and discussion

Quality 4.0 Competencies

The investigation is visually presented as mapping between the tools against six elements in two different tables for each university to meet the scope of the research questions discussed in the introduction.

Table 3 Summary of Quality 4.0 competencies against universities

	QT1	QT2	QT3	QT4	QT5	QT6	QT7	QT8	QT9	QT10	QT11
U1	X		X	X		X	X			X	X
U2	X		X	X		X		X		X	X
U3			X	X				X			X
U4	X		X	X							
U5			X	X							

X= Seen in at least one of the 6 elements over the 4 year degree

As summarized in table 3, QT3 and QT4 are present in all universities illustrating the emphasis on robotics and automation by all universities. Further breaking down, the competencies QT2, QT5 and QT9 are not found in any universities reflecting how the coursework still has scope for development towards Q4.0. U1 in its undergraduate level manufacturing early year intake offers courses like Automated manufacturing in Year 2 of Spring session. Automation and robotics are present in course synopsis and outcomes of Automated manufacturing coursework. Digital manufacturing and IIoT is a coursework itself in Year 3. Data analyst is in course synopsis of Digital manufacturing and IIoT whereas Big Data, Clouding Computing and Advanced Data Analysis, Smart Control of Manufacturing Process, smart machinery and smart factory is in course content. Mobile robotics is a coursework with sensors in course synopsis and learning outcomes. AI is present in Robotics course synopsis. Advanced sensors which is part of connected devices, automation is present in program synopsis of Advanced manufacturing major.

Table 4: U1 Quality 4.0 competencies

U1	QT1	QT2	QT3	QT4	QT5	QT6	QT7	QT8	QT9	QT10	QT11
Program synopsis			X	X		X				X	X
Program learning outcomes											
Course synopsis			X	X		X				X	
Course learning outcomes			X								
Course or subject topics	X		X	X		X	X			X	X
Course or subject assessments											

U2 offers Bachelor of Engineering in Manufacturing Engineering with robotics, automation in program synopsis. Learning outcomes of program has automation, data analysis, AI, IoT. Process Technology and Automation is a year 3 course with robotics and automation in course synopsis. Year 4 has Design of Intelligent Manufacturing systems with smart factories, cyber physical production systems, robotics, IoT in course overview while cybersecurity, IoT, big data analytics is in learning outcomes.

Table 5: U2 Quality 4.0 competencies

U2	QT1	QT2	QT3	QT4	QT5	QT6	QT7	QT8	QT9	QT10	QT11
Program synopsis			X	X							
Program learning outcomes	X		X			X				X	
Course synopsis				X						X	X
Course learning outcomes								X		X	
Course or subject topics											
Course or subject assessments											

Bachelor of Engineering Technology (Advanced manufacturing)of U3 has cyber physical systems, robotics, automation, cybersecurity in its program overview. Industry 4.0 is a coursework at year 1 itself with automation in subject aims. Also, sensors is seen in course overview of Electronics in year 1 itself. Cyber physical systems, robotics and automation and Networks and cybersecurity are year 2 coursework. Advanced manufacturing (robotics) is a major given in year 4.

Table 6: U3 Quality 4.0 competencies

U3	QT1	QT2	QT3	QT4	QT5	QT6	QT7	QT8	QT9	QT10	QT11
Program synopsis			X	X				X			X
Program learning outcomes											
Course synopsis			X	X				X			X
Course learning outcomes				X							
Course or subject topics											
Course or subject assessments											

Keywords of robotics and automatic are present in program synopsis of Bachelor of Engineering Advanced manufacturing at U4. Keywords like Automation and AI are not seen until Year 3 coursework of Mechatronic design, Design for Assembly and Automation and Automatic control Systems. Also, advanced robotics is a year 3 elective.

Table 7: U4 Quality 4.0 competencies

U4	QT1	QT2	QT3	QT4	QT5	QT6	QT7	QT8	QT9	QT10	QT11
Program synopsis				X							
Program learning outcomes											
Course synopsis	X		X	X							
Course learning outcomes											
Course or subject topics											
Course or subject assessments											

Automated machinery is present in snapshot of program Bachelor of Engineering (Honours) (Mechanical and Advanced Manufacturing): U5 along with quality assurance. Robotics and Automation is a year 3 coursework. Year 4 of coursework also has Integrated industrial actuation and automation subject. It offers Intelligent Production Systems coursework in Year 3 with automation in course synopsis.

Table 8: U5 Quality 4.0 competencies

U5	QT1	QT2	QT3	QT4	QT5	QT6	QT7	QT8	QT9	QT10	QT11
Program synopsis			X								
Program learning outcomes											
Course synopsis			X	X							
Course learning outcomes											
Course or subject topics											
Course or subject assessments											

Traditional tools

To illustrate the traditional competencies, we mapped these to the six elements of the five universities. Below Table 9 illustrate that while seven of the Q4.0 skills are identified for U1, the traditional competencies remain empty. So, findings from this study indicate that U1 in its undergraduate level manufacturing course is inclined towards Quality 4.0 competencies. While looking for traditional tools at U2, Reliability and maintenance engineering course in year 4 has SPC, 6-sigma, quality assurance methods in course overview. Engineering management of year 4 has lean manufacturing, SPC, quality management in course aims. Seven of the Quality 4.0 tools are noted while four of the traditional tools are also identified in the U2 program. Table 5 and Table 9 depict this equal emphasis of U2. While investigating the same at U3, ISO standards and quality assurance is present in course overview of Design for Sustainable manufacture which is a Year 2 coursework. Production engineering in year 3 has Lean, quality and automation in course overview. Table 6 and 9 illustrate that 4 competencies of Quality 4.0 are identified while only 3 traditional competencies are noted at U3. At U4, Quality management is also a year 3 elective with SPC, quality assurance, six sigma, international quality standards in course description and learning outcomes. The electives are repeated for year 4. Table 7 and 9 provide this visual summary of competencies both traditional and Quality 4.0 to be 3 and 4 in number at U4. Total Quality Management is a year 4 coursework at U5 with traditional tools like 6 sigma, SPC, process improvement, total quality in course content. Table 8 and 9 provide a breakdown of the type of competencies present in the program of U5 which are 2 and 4 at traditional and Quality 4.0 competencies respectively.

Table 9: Traditional tools analysed against universities

	TT1	TT2	TT3	TT4	TT5	TT6	TT7	TT8
U1								
U2	X	X	X				X	
U3	X		X			X		
U4	X	X				X	X	
U5	X	X		X			X	

Firstly, U1 and U2 have highest competencies emphasising Quality 4.0. Secondly, U4 and U5 have highest focus on traditional tools. It is worth noting that U2 coursework has equal emphasis on traditional tools too.

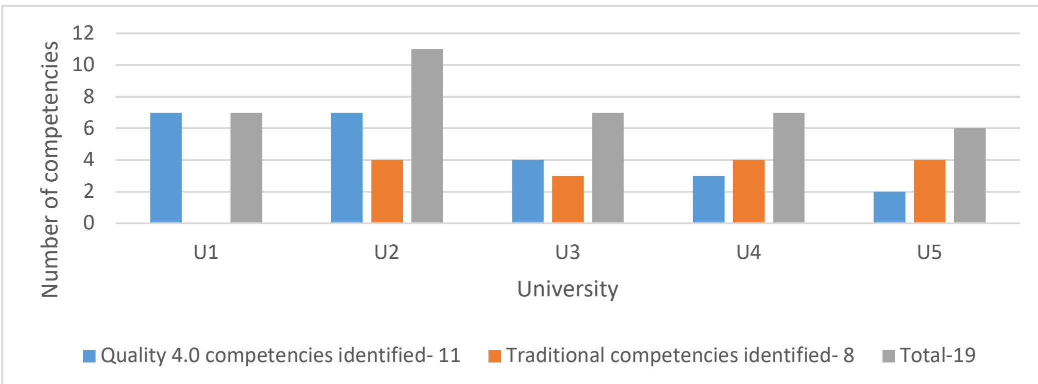

Figure 1: frequency of appearance of keywords in the five universities

The frequency of appearance of keywords for all universities combined as shown below depicts that the emphasis on the traditional tools increases over the four-year course while Q4.0 skills peaks at Year 3.

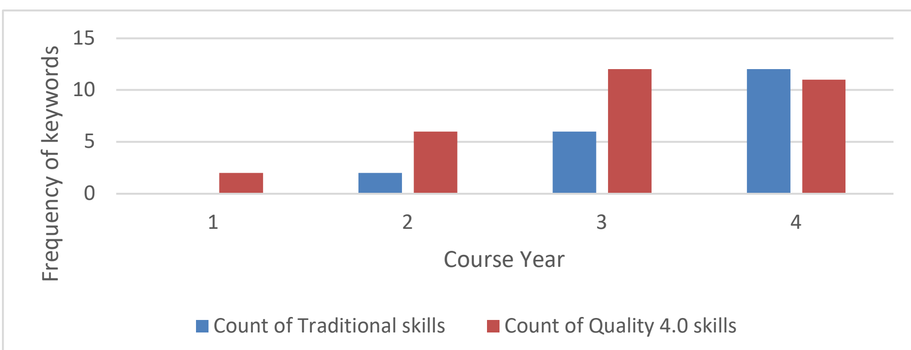

Figure 2*:* **Frequency of Appearance of Keywords in the six elements over four-year degree of all universities**

It was observed that U1 and U2 which have high focus on Quality 4.0 competencies teach these skills over 4 and 2 courses respectively. U3 emphasises on these skills with teaching them over six courses while U4 and U5 with limited focus on Quality 4.0 competencies teach them over 4 and 3 courses respectively. Observing traditional tools, U1 has no coursework in this regard. U2 program has two coursework with focus on traditional tools. U3 also has two coursework whilst U4 and U5 which have heavy focus on traditional tools teach these competencies over one course alone.

Mapping and framework

Understanding graduate outcomes is important in the manufacturing curriculum, as the industry is shifting from traditional tools to Q4.0. The curriculum mapping to the technical skills of framework provide a simple but effective picture of graduate outcomes of this in Q4.0 context. The mapping seeks to capture how the competencies are reflected in the curriculum of manufacturing engineering in Australia which is rapidly developing towards Q4.0. Within this rapidly changing curriculum, the framework provides a snapshot and a map of the current competencies that need to be incorporated in Australian manufacturing curriculum. While not all competencies taught match framework, the mapping shows that the universities are already shifting their prominence towards Q4.0 competencies. The second advantage is that the traditional tools were mapped alongside the Q4.0 competencies. Building the mapping has also discussed the limitations of mis-claimed competencies.

Conclusions

In this paper we have investigated different competencies of Quality in manufacturing engineering coursework by surveying six elements at universities offering it at undergraduate level. Secondly a framework for hard skills in Quality 4.0 adaptation that will better equip undergraduates for their Quality engineer role is provided. Engineering programmes need to ensure that they transition to Q4.0 and able to provide the expertise necessary for local and global work, and to exert a positive influence in the world. The mapping provides to achieve this vision by exploring the current curriculum and identifying gaps of improvement. Future analysis will also explore industry practises to facilitate the implementation of this framework.

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