New Challenges in Manufacturing Engineering Education

Asbjørn Rolstadås and Jim Browne

Abstract Industry 4.0, additive manufacturing, digitalization and the emergence of the circular economy are changing the face of manufacturing. New pedagogical approaches, including web-based delivery, are changing the face of teaching and learning. This paper considers these issues and offers a framework for developing a new manufacturing engineering curriculum based on a T shaped structure with five knowledge areas, and using Kolb's learning model and the CDIO (Conceive-Design-Implement-Operate) or "teaching factory" approach.

Keywords Education · Manufacturing · Engineering

1 Introduction

Manufacturing is a key industrial sector. It is an important engine of growth for the global economy [1]. Over the last 200 years plus, manufacturing industry has undergone a number of significant changes. This is clearly demonstrated in the concept of Industry 4.0. Through the maturing and convergence of digital technologies together with the development of 5G communications systems and additive manufacturing technologies, Industry 4.0 represents a step change in terms of the digitalization of manufacturing systems and total integration across the value chain. We are thinking of developments in what might be called ubiquitous telecomputing including cloud computing, 5G, artificial intelligence, and the Internet of Things. Industry 4.0 represents *disruptive change*; it is a consequence of and an enabler of *servitization* and through the development of additive manufacturing opens the possibility of distributed and localized manufacturing, efficient small batch production and indeed one-of-a -kind products. Converging technologies are changing and

A. Rolstadås (✉)
Norwegian University of Science and Technology, Trondheim, Norway
e-mail: asbjorn.rolstadas@ntnu.no

J. Browne
National University of Ireland, Galway, Ireland

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will continue to change the nature of business models, products, delivery of services and work.

We believe that there are four major future industry development trends that will influence future manufacturing engineering curricula: (a) circular economy and the decarbonized society, (b) digitalization and the emergence of multiple technologies which are maturing, interconnecting, and converging, (c) new manufacturing technology (in particular additive manufacturing), and (d) the shift from owning a product to buying services (servitization).

1.1 Circular Economy

Dealing with climate change, and the challenge of developing a circular economy as the 4th industrial revolution rolls out will require enormous structural change in our business models and our economy. Ultimately products will have to be redesigned with reuse and recovery in mind. Products will also have to be designed to be smart or intelligent: that is, they have to carry with them a profile of their design, constituent parts, history of use, service etc. which can then be made available to support repair, upgrading, reuse, recovery at end of life. This is all technically possible using RFID technology and embedded sensor and memory devices. The emerging Internet of Things, nano-technologies and micro sensors allow us to embed memory chips, computing and communications devices in consumer and capital good products which, combined with design for reuse, disassembly and recycling, facilitate the development of a circular economy.

The challenge is to migrate over time from a "*Design—Manufacture—Distribute—Consume—Discard*" industrial system, to a "*Design—Manufacture—Distribute—Consume—Return—Disassemble—Reuse/Recycle/Reclaim*" system. This transition requires a paradigm shift in public policy, human behaviour, economic thinking and analysis, engineering design etc. and of course the development of new industrial systems to support circularity.

1.2 Digitalization

Digitalization enables the development of *"Smart Products"* which comprise embedded technology giving them the capability to identify themselves and describe their properties, status and history. They are capable of executing computations, storing data, interacting with the environment and communicating with external devices. While early implementation was based on RFID technology, they now incorporate full sensing, computing and communicating capability. This gives them the ability to support service, maintenance and, particularly important from a circular economy perspective, *end of life* product dispositioning.

Digitalization also facilitates the development of true cyber-physical systems and the creation of *digital twins* of both products and production systems, which in turn enables the direct translation of design data into process instructions which are in turn passed directly to the production equipment. In effect the engineer can test the design of a complex component on a simulated manufacturing system before ever going to the physical production system.

Artificial Intelligence and Data Analytics systems have a wide range of applications in Industry 4.0; they facilitate the personalization of products and mass customization and facilitate smart production and circular manufacturing. They are in many cases based on statistical analysis and pattern recognition in large data bases and provide the ability to “learn” statistically from annotated “training” data, using machine learning and neural networks technologies.

At the operational level, these systems are frequently embedded in manufacturing execution systems to collect data from smart sensors on the manufacturing shop floor, diagnose or predict problems and prescribe actions in areas such as inspection and associated decisions, guiding industrial robots, managing industrial processes through component recognition systems, and real time scheduling and process selection and control, using optical character recognition, image processing, checking presence/absence of parts, feature recognition etc.

1.3 Additive Manufacturing

In recent years a new group of manufacturing technologies known as *additive manufacturing* [2] have emerged. Digital 3D design data is used to build up a component in layers by depositing material. Originally, these technologies were used to build prototypes of complex geometry components; they have now morphed into a set of production techniques capable of producing sophisticated high specification plastic and metal parts.

Additive manufacturing is now becoming established in the aerospace and med tech industries to produce small batches of very complex products efficiently and economically. Its impact can be seen in two areas; from a process point of view, it provides for “tooling free” manufacturing which considerably simplifies the supply chain, allows for the fast development of prototypes as the design emerges and reduces the lead time for production. From a production point of view, it facilitates the manufacture of parts with complex geometry in a single pass. Taking a longer-term perspective, it is likely that additive manufacturing will facilitate the greater distribution of manufacturing as locally based additive manufacturing facilities will be in a position to download part programmes over the internet and manufacture components close to market.

1.4 Servitization

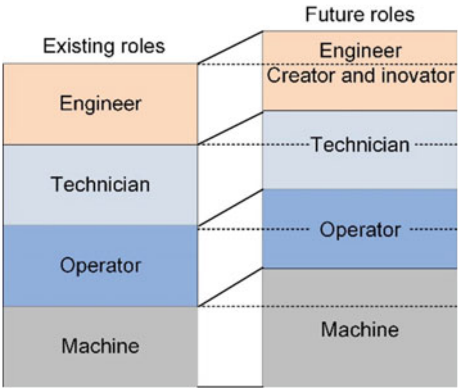
Today for many products the customer has moved from being an *owner* to a *user* of the product; effectively the customer is paying for access to the service that the product offers. We are moving towards a *sharing economy* for products as diverse as entertainment including music and films, books, the news media, personal transport through shared bicycles and ultimately cars etc. In the business world, we see the move toward software as a service, businesses paying for the service rather than buying printers, scanners and photocopiers; hospitals paying per use for laboratory and advanced medical equipment installed in the hospital by the supplier, rather than buying the equipment. Effectively *the product has become the platform to deliver a service,* in a process known as *servitization.* The business model has been upended, the manufacturer has become a service provider, and all of this enabled by the Internet of Things, sensor technology, cloud computing, 5G and artificial intelligence working in tandem.

2 Changed Role of Manufacturing Engineers in Industry 4.0

Apart from the developments in circular manufacturing, digitalization and servitization, technology has already significantly changed the respective roles played by machines, operators, technicians and engineers. Consider what has happened in the traditional machine shop. In the past, skilled machinists, having served a long apprenticeship, operated the machines; technicians maintained the machines; production engineers planned the process steps, determined the tooling and machining parameters and worked with technicians to design and build any jigs and fixtures necessary to machine the part.

Today the same part is machined on a CNC machine or in a flexible manufacturing cell. The control of the machining process has passed from the operator to the CNC controller which the operator now programmes. The machine has taken over some of the tasks previously undertaken by the machinist and the machinist has upskilled to become the part programmer. Furthermore, the technician role is upgraded to undertake tasks in jig, tool and process design previously undertaken by the engineer. The engineer in turn is freed up to undertake more challenging tasks in the design of the overall process and system; tasks which require **increased creativity**, an **understanding of the products and the business** and an ability **to work in cross functional teams**. This incremental change in the respective roles of machinists, technicians and engineers illustrated in Fig. 1, has consequences for the education and training of all three.

Fig. 1 Change in job roles



3 Manufacturing Engineering Education

Manufacturing engineering education follows a structure of Bachelor–Master–Doctorate (Ph.D.). Traditional manufacturing engineering curricula focus on building a solid theoretical platform so that students are well prepared to solve applications problems in industry. Graduates are trained to solve complex problems in manufacturing systems and manufacturing technologies per se, using non-routine methods.

A recent study by MIT [3] argues for socially relevant and outward-facing engineering curricula which emphasize student choice, multidisciplinary learning and societal impact, coupled with a breadth of student experience outside the classroom. "The future of education and skills 2030" [4] suggests that future-ready students need to exercise agency and a sense of responsibility to participate in the world and, in so doing, to influence people, events and circumstances for the better. The team at MIT have developed a learning framework for 2030 focusing on competences, understood as knowledge, skills, attitudes and values.

Innovation and management are as important in the curriculum as technology. Van Brussel [5] states that innovation requires creativity and multi- and transdisciplinary thinking. He sees a shift in the manufacturing engineer's role, moving from routine tasks to solving unstructured problems. According to Moravec's paradox manual and cognitive routine tasks are "easy" to automate while tasks requiring manipulative skills and creative thinking are much more difficult to automate.

Many employers and the professional engineering bodies emphasize the requirement for today's young professional engineers to have deep disciplinary knowledge and broad capabilities to work across various professional, disciplinary, social and cultural boundaries. Broad skills of problem solving, creativity, team working, innovation, leadership etc. are required in order to function effectively as a design or manufacturing engineer in an Industry 4.0 environment. *Deep disciplinary skills, which were emphasized strongly in the past, are necessary but not sufficient*.

So called “T-shape” graduate professional engineers are in demand; the horizontal line of the “T” represents broad generic skills while the vertical represents deep disciplinary knowledge.

4 New Learning Environment

The classic model for engineering education sets the teacher to the fore imparting and transferring knowledge to students. This passive learning is far from efficient. To enhance learning outcomes, we must move to a more involved learning mode. The need for enhanced learning models arises because Industry 4.0 presents large and complex challenges (*wicked problems*) and frequent technology driven changes; manufacturing engineers must be *change agents* who seek to shape the future, understand others’ intentions, actions and feelings, and anticipate the short and long-term consequences of what they do.

This points in the direction of more *experimental learning*. Experiential learning is the process of learning through experience. Kolb [6] is one of the main contributors to the modern theory of experiential learning; see Fig. 2. During the first stage the learner is exposed to a *new experience* which at the next stage is subject to *reflective observation.* Then follows *abstract conceptualization* where the learner develops new ideas from the reflections. At the final stage ideas, effectively proposed solutions are tested through *active experimentation* in the real world.

Challenge-based learning is a similar approach. It is a framework for learning by working with real-life problems. It is organized into three phases [7]: *engage—investigate—act.* A concept using the principles of challenge-based learning is the teaching factory [8]. It aims to align manufacturing teaching and training to the needs of modern industrial practice and is based on the knowledge triangle (*research—innovation—education*). It is a two-way knowledge transfer channel as illustrated in Fig. 3. The teaching factory can also be facilitated through virtual visits for students to review manufacturing equipment and operations.

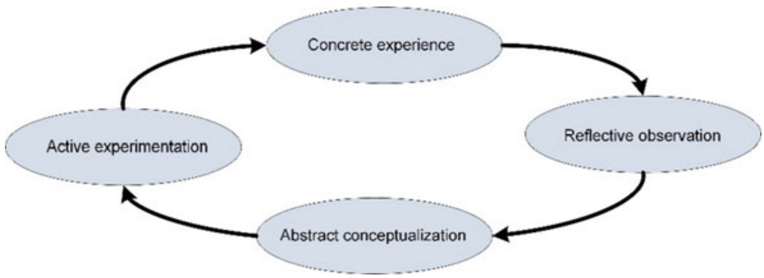


Fig. 2 Kolb’s experimental learning model

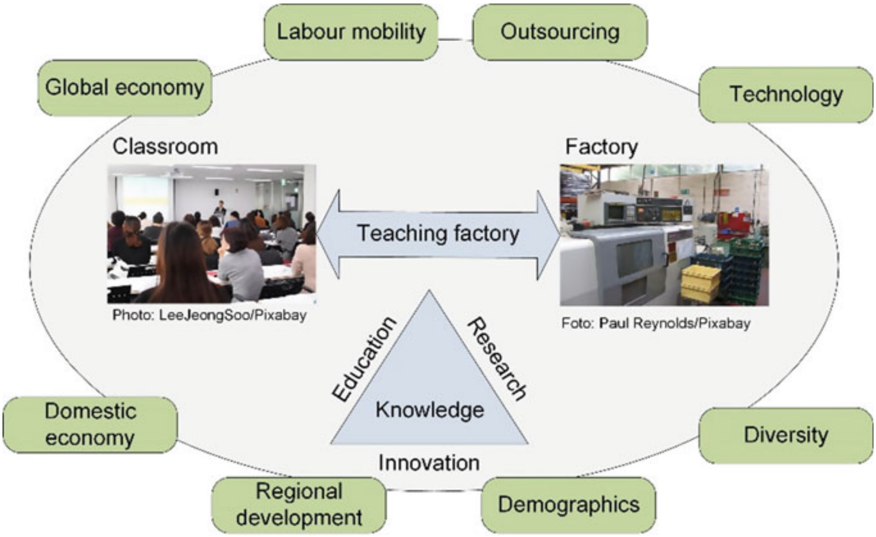


Fig. 3 The teaching factory concept

Computer games are commonly used for entertainment. Their origin however was to train people for tasks in particular roles through the development of simulated environments; well established examples include the training of pilots on simulators. By exploiting advanced simulation and visualization technology, well designed games can contextualize the learner's experience in a realistic and challenging environment [9].

Such games add a new dimension to learning. They train the learner in decision making, but in a virtual environment where there are no consequences of a poor decision. Serious games may thus also be used in a setting with *digital twins* of the manufacturing system and the products to be manufactured.

A framework for engineering education allowing experimental learning has been launched as the CDIO initiative [10]. The framework provides the learner with an education stressing engineering fundamentals in a context of *Conceive—Design—Implement—Operate (CDIO)* real-world systems and products. The authors claim that the learners must be technically expert, socially responsible, and inclined to innovate.

In conclusion, the learning environment is rapidly changing. The future solution is based on an active learning model using experimental learning. It takes advantage of digital technology and thus creates more flexibility in the learning process with respect to time, place and progress.

5 Towards a New Manufacturing Engineering Education

We believe it is necessary to rethink manufacturing engineering education. In the following we will outline some thoughts on how manufacturing engineering education should be positioned in the global education system, some guiding principles for delivery of manufacturing engineering education and a framework for the design of the manufacturing engineering curriculum.

In terms of the global engineering education system, graduate engineers should be trained to the level set out in the requirements of the Washington Accord (www.ieagreements.org), that is to masters degree level as set out in the European Higher Education Area.

From a delivery perspective a number of principles should be followed. The programme should be delivered using the approach set out in Kolb's learning model, and therefore include significant action and project-based learning; be delivered in a research-led teaching environment; and include significant access to practice, which should include "virtual visits" to industrial sites. The programme should be delivered in a blended learning format with appropriate use of conventional "face to face" teaching and laboratory exposure and virtual learning. Given the reality of continuous change and innovation, the curriculum should be delivered in a manner which ensures that the graduate has acquired a deep knowledge of the underlying principles of manufacturing processes and systems and a capacity to continually upgrade and update his/her knowledge as technology and business processes change and develop.

Today manufacturing covers a tremendous variety of products and associated processes: from biomedical devices to biopharmaceuticals, silicon fabrication foundries to fast moving consumer goods; from aerospace and automotive to electronics and nanotechnology-based sensors; etc. Individual programmes and curricula will have to concentrate on a particular manufacturing sector, and this might reflect the industrial sector(s) which are well developed in their region, thus providing the necessary access to practice to ensure a high quality graduate.

The design of a curriculum should be based on a set of learning objectives or learning outcomes. The student should achieve competence making him or her able to:

- L1. Demonstrate fundamental knowledge of generic and enabling technologies.
- L2. Demonstrate solid knowledge in the field of product development, manufacturing processes, manufacturing systems, product and systems maintenance and operations management.
- L3. Apply relevant tools and techniques to critically analyze and solve industrial problems and develop sustainable solutions.
- L4. Effectively work in teams and in projects.
- L5. Engage in the public discussion on the impact of technology on society and environment and demonstrate a high ethical standard.
- L6. Continuously learn in a life-long learning perspective.

These learning objectives can be met by designing a curriculum using the T-shape structure discussed in Sect. 3. The "T" comprises both a breadth of knowledge and a depth of experience, and rests on a competence foundation.

The competence foundation contains subjects such as mathematics, basic natural sciences, economy, humanities and social sciences. The purpose is to serve as a basis for deeper and more specialized technological knowledge. As we define competence as a combination of knowledge, skills and attitudes, the foundation also provides the student with the necessary background to develop a positive attitude and place the technological learning in a scientific, social, and societal perspective. It contributes to learning objectives L5 and L6 above.

In the "breadth of knowledge" part of the "T", there are basic technological subjects such as:

- Information and communication technology (ICT)
- Materials science
- Systems engineering
- Circular economy and industrial ecology
- Reliability, availability, maintainability and safety (RAMS)
- Project management.

In these fields, the candidate should develop both knowledge and skills. It contributes to learning objectives L1, L3 and L4.

The "depth of experience" part of the "T" contains the manufacturing engineering specific subjects. It falls beyond the scope of this paper to define a specific curriculum. We will provide a framework defining types of subjects to be included. We will refer to those as *knowledge areas* (KA). A knowledge area defines a number of processes with tools and techniques where the candidate should have both knowledge and skills. Following the trends of industrial and societal development discussed in the preceding, we underline the need to rethink such knowledge areas from the classic thinking towards today's needs for sustainability and a green shift. Thus, our framework suggests the following manufacturing engineering knowledge areas:

KA1. Servitization and new product development
KA2. Business operation and competitive strategy
KA3. Intelligent manufacturing processes
KA4. Intelligent manufacturing systems and supply chains
KA5. End-of-life engineering and management.

These knowledge areas correspond to learning objectives L2 and L3.

In conclusion we believe that this framework provides the basis for creating a detailed manufacturing engineering curriculum.

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