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Chapter 11

Essential Contextual Knowledge for Agricultural and Biosystems Engineering Education in Low-income Countries

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James P Trevelyan and Andrew L. Guzzomi

Introduction

Since pre-history, people who we would call engineers today have provided artefacts, such as infrastructure and tools, enabling people to be more productive, to do more with less effort, time, energy and material resources. Irrigation systems, roads, vehicles, and communication systems are common examples. Starting with the industrial revolutions of the 18th century, rising agricultural productivity in high-income countries (HICs) has reduced the number of people needed for agricultural production from over 60% of the working population to around 1% today in Europe and the USA (Senzanje, 2003). At the same time, in many HICs, agricultural production not only meets domestic requirements but also provides large surpluses for export. This transformation has also completely restructured societies from small rural communities to large and diverse urban communities with high quality education, social welfare, and healthcare services. Large productivity increases, not only in agriculture, enabled HICs to invest in education, infrastructure, and technological advances, facilitating further productivity improvements.

Agricultural and biosystems engineers played a significant role in this productivity transformation, providing labour-saving machinery such as irrigation, tillage machines, mechanical harvesters, tractors, instruments, electronic ID tags for animals, and post-harvest processing and storage solutions for farmers. In common with food processing, biological, and biomedical engineers, they design for the intrinsic variability of living organisms where large differences in morphology and properties are normal (Opara, 2004). Engineers also created factories to process agricultural products into higher-value packaged food with much longer shelf life than the raw products from farms. Farming itself has become a far more finance- and knowledge-intensive occupation for which post-secondary education is at least highly desirable if not essential. Huge farming enterprises run by corporations have gained easier access to the investment capital to acquire complex modern farming machinery.

In many densely populated low-income countries (LICs), this social, economic, and technical transformation is still in progress. Half the world's food is produced by 1.5 billion small-scale farmers in non-industrialised countries with 80% of food produced by small-scale farmers (Bragdon & Smith, 2015). Data from the World Bank shows agricultural employment ranging from 35 to 45% in LICs like India, Pakistan, Nigeria, and Sudan, accompanied by increasing urbanisation.[1] Agricultural transformations in HICs relied on easily processed mineral deposits, many in colonised countries, and low-cost fossil-fuelled energy that generated pollution and greenhouse emissions. Most LICs with large populations desire a similar transformation but have to work with higher costs and environmental constraints, so different approaches will be needed. Therefore, the future challenge for agricultural and biosystems engineers, particularly in LICs, is to enable large productivity improvements without relying on unsustainable mineral extraction, costly chemicals to control pests, and fossil-fuelled energy. They will need to minimise the need for refrigerated storage and transport while minimising waste in challenging climates and long farm to market transport systems. Engineering schools will need to reshape agricultural engineering curricula to enable graduates to meet these challenges (Opara, 2004). Also, many might question the wisdom of practically eliminating the agricultural labour force as in HICs. Instead, they argue, increasing the value of agricultural products, moving up the 'value chain', might create sufficient resources to meet the need for high quality social welfare, education and health services for large rural populations.

Today, agricultural engineering is a minority engineering discipline in many HICs and agriculture typically forms a smaller part of their economies. However, in LICs, there is still the potential for large productivity gains and possibly greater opportunities for agricultural engineers than in HICs where most agricultural engineers find work today. Frey and Osborne (2017) indicate that, within the US HIC context, some agricultural engineering tasks may be susceptible to job automation with advances in information technology. Significant improvements in global agricultural productivity could be achieved if the majority of the world's food producers who operate small scale farms in LICs were the beneficiaries of agricultural engineering R&D (Moss, Nichols, Foster, Ryan, & Guzzomi, 2021) and this will require considerable human ingenuity. For that reason we have chosen to focus on LICs in this chapter.

Senzanje (2003) has reported that agricultural engineers in LICs today face many challenges gaining relevant employment

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in their field with reasonable remuneration. This is a common issue in many engineering disciplines in LICs and arises partly because current engineering school teaching programmes do not enable graduates to meet the needs of local firms (Blom & Saeki, 2011; Tilak & Choudhury, 2021). As Domal (2010) and Trevelyan (2013, 2020, 2022) have observed in India, many engineering graduates today find themselves almost completely unprepared for work, especially in smaller firms and government enterprises. The first author's research interviews in South Asia demonstrated that many engineering graduates find higher paid work as programmers with a couple of months training than as engineers provides additional evidence that four or years of engineering education has not prepared them well enough for local engineering workplaces. Senzanje's (2003) observations help to demonstrate that the Indian experience can be generalised to Africa as well.

Further evidence of education shortcomings comes from observations over several decades showing that engineers see much of their work as 'not real engineering'. This phrase captures the frustrations experienced by many engineers who yearn for more technically challenging tasks in their work (Bailyn & Lynch, 1983; Perlow & Bailyn, 1997) and who perceive socio-technical interactions as "interruptions" (Perlow, 1999). Many educators mistakenly shape the expectations of students by describing engineering in terms of design and technical problem-solving, activities that constitute a very small proportion of the working life for most engineers, especially in LICs (Sheppard, Colby, Macatangay, & Sullivan, 2006).

In this chapter, we draw on new insights from engineering practice research that offer explanations for these difficulties. It should be possible to improve engineering education, enabling graduates to better meet the needs of local firms, thereby improving engineering graduate employment outcomes in LICs (see Figure 11.1).

Today, most engineering educators, referred to in this chapter as 'faculty', have limited if any practice knowledge having been recruited mainly for their research abilities. This is a global issue: Cameron, Reidsema, and Hadgraft (2011) have presented data for Australia, and a similar situation exists in other countries.

It is not unreasonable, therefore, to ask "how can faculty properly educate students without understanding how novice engineers are expected to perform in local workplaces?" For the last two decades at least, most engineering education programmes have adopted professional engineering competency definitions such as those published by the International Engineering Alliance (2021), ABET and others. The assumption implicit in these definitions is that students who demonstrate sufficient competency can practice effectively as engineering novices, anywhere. Although there is still very limited evidence from LICs, there is sufficient to seriously question this assumption.

However, there are several obstacles that prevent faculty from acquiring practice knowledge. Most agricultural engineers gain employment in places far from engineering schools, making it difficult for faculty to experience engineering work practices while teaching. The lack of practice knowledge among faculty also makes it expensive for firms to help faculty acquire work experience though limited term secondments because they would require close supervision and instruction by experienced engineers.

However, we think it is possible for faculty to acquire improved knowledge about engineering practice that could help them provide a more authentic context for students building their knowledge of mathematics and engineering science.

Some faculty would argue that students can gain awareness of engineering practice by working on industry projects and through internship experiences. However, students start with limited notions of engineering practice because their coursework focuses on technical problem-solving and analysis. As a result, most graduates do not see socio-technical interactions as "real engineering", a perception that is strongly reinforced by the professional engineers they meet. This preconceived mental framework hinders their learning about socio-technical interactions with other people that dominate professional practice as explained in section 2.

FIGURE 11.1 Residential construction in Melbourne and Islamabad in November 2022. There are obvious differences in practices.

So far, there have been no detailed ethnographic research studies of agricultural and biosystems engineering practice. Therefore, in this chapter we will draw on published research studies of engineers in other disciplines and draw on our personal agricultural engineering work experiences to provide some insights into agricultural engineering work.

This knowledge can help faculty in several ways. First, it may help faculty understand that engineering work, especially in LICs, is very different from notions of design and technical problem-solving advanced by many engineering schools today. Second, this knowledge may help faculty more appropriately shape the expectations and cultural awareness of students. Third, this knowledge can help faculty design more authentic education experiences that would enable students to understand the context in which they will use technical analysis and design methods learnt in their coursework and improve students' motivation to learn. Fourth, we hope it will stimulate some faculty to research practice in local firms to further build knowledge and understanding about agricultural and biosystems engineering work.

With a focus on LICs, there is inevitably some overlap between agricultural and biosystems engineering and humanitarian engineering that focuses on capacity-building in predominantly rural low-income communities (Gupta, Singh, Sharma, Chatterjee, & Saha, 2019). One distinction between the two is that agricultural and biosystems engineering initiatives, other than research, require economic justification whereas humanitarian engineering tends to be motivated by altruism. That said, it is important to note that altruism can be linked with economic benefits as Paul Polak (2008) showed in his work at the Stanford D-School.

What We Know from Engineering Practice Research

Most of the research on engineering work has come from social scientists in HICs with some contributions from engineering education researchers. Until the 1980s, most researchers were interested in engineers as a social class in HICs and also the dynamics of professions such as engineering (e.g. Bailyn & Lynch, 1983; Layton, 1986; Meiksins & Smith, 1996; Noble, 1979; Perrucci, 1971; Smith & Meiksins, 1995). The rise of Japan's economic power in the 1980s stimulated comparative studies to understand how engineers contributed to that success (Bailyn & Lynch, 1983; Bratton, 1991; Button & Sharrock, 1994; Kilduff, Funk, & Mehra, 1997; Lam, 1997; Lynn, Piehler, & Kieler, 1993). As Japan's economic success receded in the 1990s, research interest shifted to workplace studies on individual technicians and engineers, partly inspired by Zussman's and Bucciarelli's seminal works studying the activities of engineers (Bucciarelli, 1994; Zussman, 1985). In comparison with engineers, many aspects of technicians' work are relatively easy to observe, though it can be hard to identify the cognitive skills that contribute to their performances (Bechky, 2003; Flesher, 1993; Orr, 1996). Many studies were motivated by an interest in understanding engineering design and the thinking behind it, then thought by many to represent the essence of engineering work (Dym, Agogino, Eris, Frey, & Leifer, 2005; Eckert et al., 2004; Ewenstein & Whyte, 2007; Henderson, 1999; Moritz, 1996; Wong & Radcliffe, 2000). Dominique Vinck and his collaborators studied engineers in a wider range of industrial settings with the longer term aim of understanding practice and systematic influences on workplace behaviour (Vinck, 2003). Even so, Barley (2005) concluded that very little was known about the social organisation of engineering work at that time, and called for grounded interpretive studies of engineers at work.

Several researchers have since responded to Barley's call. Even so, engineering practice research, empirical investigations on what engineers actually do in their work, is still in its infancy. A few hundred publications since 2005 make up a small collection alongside technical engineering literature. However, the results already pose significant challenges for engineering faculty. Not the least of these is the finding that engineers spend relatively little time on solitary technical analysis and calculations for which much of their formal education has prepared them, supported by a vast body technical literature. The greater part of engineers' work consists of social interactions with other people (Williams, Figueiredo, & Trevelyan, 2013).

Models of Engineering Work

Following occupational classifications outlined by Howell and Wolf (1991), we can identify three groups of engineering work activities.

Group 1: ***interactions with physical objects***, often referred to as 'hands-on' activity, requiring manual dexterity, perception-motor coordination, and tacit knowledge accumulated from many years of experience.

Group 2: ***cognitive interaction with abstract objects***, requiring substantial periods of solitary work, often with computers serving as intermediary communication devices. As for group 1 activities, tacit knowledge accumulated through years of experience enables high levels of performance.

Group 1 and group 2 activities also involve collaboration when the artefacts are large or complex and beyond the capacity of one person to perform the required work.

Group 3: ***socio-technical interactions with other people*** enable engineers to plan, organise, collaborate in, and coordinate physical (group 1) and cognitive (group 2) activities by other people. Many of these interactions are synchronous (e.g. face to face dialogues, conferences or meetings, either physically present or by phone or video calling or teleconferencing), relying substantially on oral and written communications supplemented by non-verbal cues and gestures. They may be in formal meetings or informal workplace settings, or socialising outside the office or workplace. Engineers also interact asynchronously through email correspondence, text messages, with boundary objects (Star & Griesemer,

> 1989; Whyte, Lindkvist, & Jaradat, 2016) such as images, two- and three-dimensional drawings, digital data using workflow and project management systems, customer relationship management systems, word processors, and many other forms of computer-mediated communication. Computer systems have enabled people to work with artefacts so elaborate that the details exceed the memory capacity of people to recall accurately (e.g. Whyte et al., 2016).

It would be a mistake to presume that these interactive performances are non-technical. Trevelyan (2014,Ch7-12), Jesiek, Buswell et al. (2019), Blandin (2012) and others have identified socio-technical performances required for technical collaboration in which technical expertise is a prominent if not pre-eminent factor. Engineering firms have evolved highly structured ways to manage interactive performances as exemplified in project management processes, including the critical element of technical specifications (Trevelyan, 2014,Ch10). Such performances demand high-quality relationships (Korte, 2009; Lutz & Paretti, 2021) with high levels of trust and engagement as most interactions tend to rely more on informal leadership and referent power rather than organisational authority. These workplace performances are not distinct nor exclusive, but rather overlap with and reinforce each other.

Numerous research reports confirm that professional engineering work predominantly consists of Group 3 activity, with varying but less significant involvement in Group 2 activity (Jesiek et al., 2019; Trevelyan, 2014). Few professional engineers participate directly in Group 1 activities (e.g. Korte, 2009; Korte, Brunhaver, & Sheppard, 2015; Lutz & Paretti, 2021; Trevelyan & Tilli, 2008). Figure 11.2 illustrates this finding.

Magarian and Seering (2021) identified responsibilities that distinguish professional engineers and reviewed earlier discussions on what is considered professional engineering work. They argued that the primary distinguishing aspect of professional engineering work is responsibility for the efficacy and safety of products, services, processes, and systems through governance of design. Furthermore, professional engineers often hold responsibility for the financial success of a project along with managing other people involved. Extensive group 3 activities frequently stem from these responsibilities.

Technicians' work mainly requires group 1 activities, with a steadily increasing component of group 2 activities as more tools require programming skills. As supervisors, group 3 performances may also become a significant component of their work.

Technologists mainly include programmers and drafters interacting with computer systems, along with plant and system engineers interacting with power grids, chemical process plants, ships, aircraft, telecommunications networks, and other complex artefacts. They will typically adjust settings in the intermediary computer systems. While their work primarily involves group 2 activities, supplemented with some experiences of group 1, collaborative work also requires group 3 activity.

Where professional engineering predominantly requires Group 3 activity, engineering education typically emphasises solitary Group 2 activity and, in doing so, leaves a significant

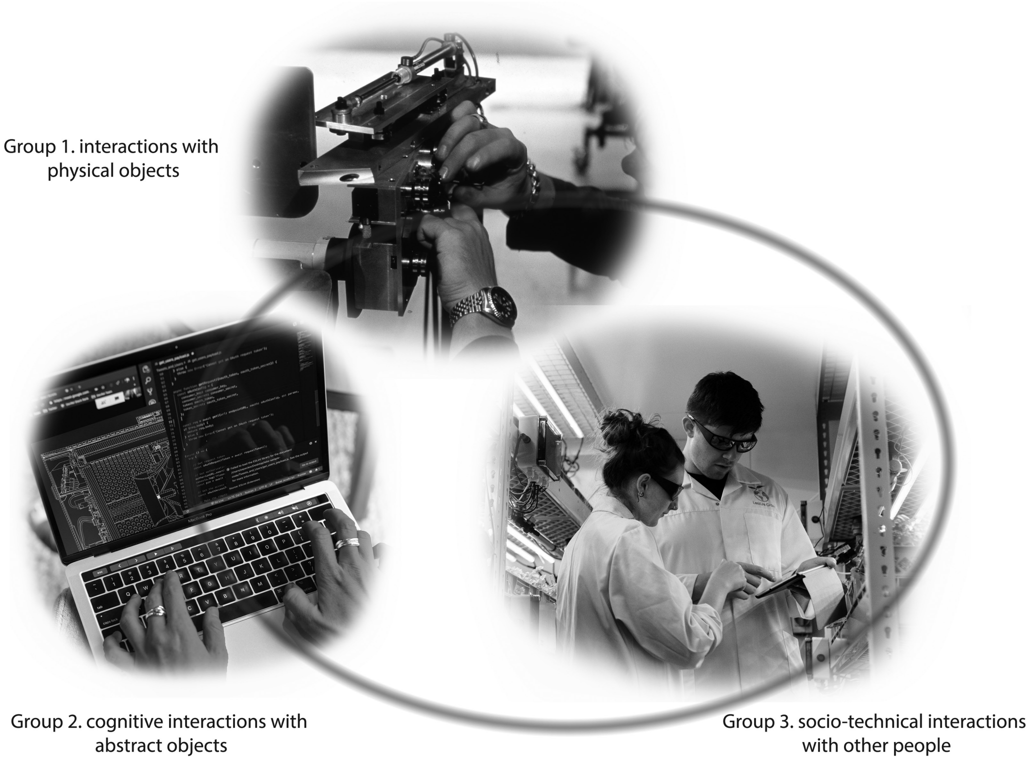

FIGURE 11.2 Research demonstrates that occupational work activities for professional engineers mostly requires group 3 activity, socio-technical interactions with other people, with some hands-on work and some cognitive interactions with abstract objects.

gap between education and workplace practices. Students learn little if anything about Group 3 activity, collaboration methods, and the organisational contexts in which engineering work takes place.

Trevelyan (2014, Ch3) presented a model of professional engineering practice showing project-related activities, reproduced as Figure 11.3. Activities in the upper row result in a detailed technical and commercial case to support the final investment decision. Engineers start by identifying possible engineering solutions that address clients' needs. In the next activity, they conceive solution details, either by drawing on similar solutions developed before, or by designing new solutions. Then, they analyse the likely performance of one or more solutions to determine technical and commercial feasibility. Preparing the solution and investment case represents around 10% of the total expenditure. The main activity in the lower row is delivering the chosen solution, as far as possible within time and resource constraints.

Few if any engineering education programmes address the grey shaded areas of the diagram. Therefore, this representation provides a different view of the education–workplace gap in terms of solution delivery activities that are not addressed to a significant extent in engineering education. As in the earlier model, these activities comprise substantial collaborative work requiring frequent socio-technical interactions with other people.

Research studies provide insights that explain why Group 3 socio-technical interactions require so much time. Most engineers need to rely on expertise beyond their personal knowledge, often arranging for others with the required expertise to contribute skilled collaborative performances (Anderson, Courter, McGlamery, Nathans-Kelly, & Nicometo, 2010; Blandin, 2012; Itabashi-Campbell & Gluesing, 2013; Trevelyan, 2007, 2010). Engineers also need to advocate for resources and particular interpretations of requirements (Mukerji, 2009; Sandberg, 2000).

As explained later, agricultural engineering practice requires a broad range of expertise beyond that capacity of students to learn in a four- or five-year agricultural engineering curriculum. Agricultural engineers, therefore, need to draw on the expertise of people from many other specialist disciplines. This activity has been described as boundary-crossing work (Asplund & Flening, 2021; Jesiek, Mazzurco, Buswell, & Thompson, 2018; Jesiek, Trellinger, & Mazzurco, 2016; Jesiek, Trellinger, & Nittala, 2017). Wilde and Guile (2021) describe "conversations, debates, deliberations and recollections of previous experiences that may occur face-to-face or be facilitated by computer-mediated communication, which inspire professionals with the same or different specialisms to think imaginatively about how to tackle project problems". They refer to this as 'immaterial activity', socio-technical interactions that generate ideas that, at some point in time, emerge as solutions even though they are never explicitly mentioned or costed in project work plans.

As the Figure 11.3 caption explains, engineering education programmes mainly address analysis and performance prediction capabilities and hardly mention the processes needed to deliver working solutions: construction, manufacture, assembly, testing, and commissioning. In many if not most instances, solution delivery activities are performed by different teams. However, relying entirely on document packages passing from one team to another is seldom sufficient for the original technical intentions to be realised faithfully. Design and performance evaluation engineers, therefore, also spend much of their time monitoring implementation activities (Trevelyan, 2014, Ch 9, 10). In particular, they evaluate technical interpretations that mutate in the minds of implementation teams as they work around regulatory, environmental, safety, expertise, logistical, and financial constraints. The effects of these constraints may be unfamiliar for the engineers who conceived the original technical intentions. For example, it is not uncommon for a contractor or technician to re-work many design details to make construction easier and cheaper.

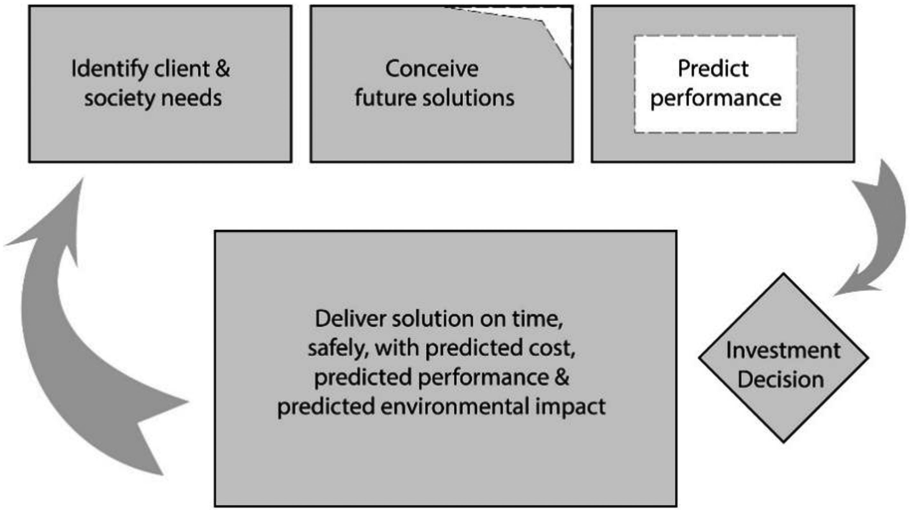

FIGURE 11.3 A sequence of professional engineering activity related to projects, starting with identifying client and society needs (Trevelyan, 2020). The lighter shaded sections with dashed outlines indicate aspects addressed in engineering education programmes. Most aspects are unfamiliar for engineering graduates.

We can see this pattern of re-interpretation in detailed published accounts of events leading up to the collapse of walkways in the atrium of the Kansas City Hyatt Regency hotel in 1978 (Gillum, 2000; Luth, 2000; Moncarz & Taylor, 2000; Pfatteicher, 2000). 114 people died and the small city endured decades of trauma afterwards. Many faculty use this event to illustrate an engineering ethics failure.

However, the detailed published accounts also tell us much about engineering practices. They reveal how the original design was re-interpreted by the construction contractor such that forces in the walkway supports were far higher than in the original design. As a result of mis-communication between the supervising engineers and the construction contractor's drafting team, this mistake remained undetected. Contributing factors included adopting a fast-tracked project plan in which many design details were only considered after construction had started, several other critical issues arising during construction, and a decision by the steel fabrication contractor to outsource completion of design drawings to a subcontractor because they won another large contract. Therefore, the engineers who should have been able to use their technical expertise to identify where interpretations diverged too far from the original intentions were under extreme pressure to complete their work quickly. They did not allow sufficient time to identify the force overload and decide whether to advocate for corrective actions. In among the countless socio-technical interactions every day, in meetings, by email, text messages, phone calls, reports, and other information systems, engineers are called upon to make rapid, consequential technical decisions, often based on imprecise information.

The Hyatt Regency investigations provided a detailed account of structural and construction engineering work practices. Normally, engineers record few details of their complex, interdependent socio-technical activities. It is only because the Hyatt collapse was extensively investigated and studied to prevent a recurrence of a similar disaster that we have such extensive records in this instance. Each of the four cited papers includes different aspects of the events leading to the disaster and, as a collection, provide insightful reading for any engineer.

These accounts also help to explain why tacit knowledge plays a such a significant role in these decisions. Goold and Devitt (2013) provided supporting evidence for this finding, showing that engineers tend to apply their mathematics and science knowledge in rapid technical assessments more as tacit knowledge than by applying slower methods learned in classrooms. Kahneman explained similar ideas in his book, *Thinking Fast and Slow* (2011). Tacit knowledge is, by definition, knowledge of which one is unaware (Polanyi, 1966), and this helps to explain frequent comments by engineers that they hardly apply any of the science and mathematics they learned in engineering schools. They do apply the knowledge, but without necessarily realising it.

Technicians – fabricators and machinists working on the development of agricultural implements and machines – also reinterpret instructions and designs represented by drawings and conversations with agricultural engineers. Here are some examples from personal observations.

- A technician re-interprets welding details specified by the engineer, e.g., making stitch welds instead of fully welding components. The technician may not notice or fully understand welding symbols on the drawing, or may use their own contextual knowledge to select an appropriate welding technique.
- A technician produces parts with dimensions significantly different from those shown on the sketch/drawing, using their contextual knowledge to reinterpret the engineer's requirements.

Experienced engineers have learned technical coordination techniques (Trevelyan, 2007), particularly the need to discuss critical technical requirements with technicians and technologists before work starts, and to regularly monitor work for unacceptable reinterpretations.

These examples reflect contextual knowledge, or experience, suggesting that agricultural implements do not require precision. This may be acceptable for low cost machinery. However, increased agricultural system performance requirements demand more attention to detail in design and fabrication. In HICs, farms require higher performance machines with advanced capabilities and can afford the additional cost. Furthermore, farmers expect higher quality and precision associated with that higher capital cost. Agricultural engineers can add significant value by recognising market drivers that influence machinery designs for better adoption by end users across diverse markets (Cavallo, Ferrari, Bollani, & Coccia, 2014). Some engineers, particularly in HICs, still see agricultural engineering as 'crude' engineering as reflected by phrases such as 'it's a bit agricultural', a derogatory term to incorrectly imply lower standards in agricultural engineering. Recent work by Moss et al. (2021) draws attention to high quality and attention to detail demonstrated by on-farm developed prototype devices, particularly considering limited resources requiring considerable design ingenuity. Other instances demonstrating how increased agricultural performance requirements lead to new technology, including tractor manufacturers developing structural engine gearboxes and dry-sump technology often incorrectly attributed to formula 1 race car developers.

Drawing on these examples, faculty can readily devise education experiences that enable students to develop contextual knowledge based on observations of practice.

Social Culture Influences on Engineering Practices

Uniform accreditation criteria applied in many countries under agreements such as the Washington Accord (International Engineering Alliance, 2021) rely on an implicit assumption that engineering practice is similar everywhere. While Figure 11.1 shows obvious physical differences, there are also significant cultural differences that influence the socio-technical interactions that dominate professional engineering practice.

The term 'social culture' represents habitual ways in which people interact with each other, denoted by *habitus,* the word used by Bourdieu (Nash, 2003). These patterns reproduce themselves in a society through child-rearing, education, and day-to-day social interactions through which people engage with each other in family and public spaces.

Since Group 3 socio-technical interactions with other people form the largest component of professional engineering work, it is to be expected that the social culture of the society hosting an engineering enterprise influences practices that depend on social interactions. Of course, one is so immersed in the social culture of one's home country or region that it is almost impossible to notice how it influences day-to-day life. Temporary immersion in a different culture can make the influences of one's own culture more obvious. Many people experience this when they start working in a new company or institution even within their home country. Similarly, engineers may be exposed to aspects of this when dealing with international companies, suppliers, or manufacturers. Each company or institution will develop a culture that reflects both the host society and the organisation's influences. Work or an extended stay in another country can also make cultural differences more obvious.

In contrast to most HICs, LIC societies in the 'Global South' are often characterised by complex patterns of social behaviour where perceived reputation, socio-economic status, caste, tribal identity, and language strongly mediate power structures and hence collaborative performances (e.g. Waris & Kokab, 2017).

Several studies in LICs have described cultural influences on engineering practice. Coelho (2004) studied water supply engineers in Chennai, a city that recently completely ran out of drinking water supplies for several months ("How Chennai, one of the world's wettest major cities, ran out of water", 2021). Matemba (2020), while researching engineering education in East Africa, also observed significant cultural influences on engineering practice as part of her fieldwork. Kusimo and Sheppard (2019) studied engineering work in a Nigerian factory (2019) where higher skilled workers tended to see lower skilled workers as lazy and lacking an appropriate working attitude. Trevelyan (2022) showed how high-performing engineers create a sub-culture in their own work group to counteract the influence of the host society culture that inhibited knowledge sharing essential to enact distributed expertise (Trevelyan, 2010). The first author's research evidence base includes 7 years working first-hand with engineers in Pakistan, ethnographic interviews, field studies, and extensive visits to India and Pakistan over 25 years (For details, see online appendices, Trevelyan, 2014)

The following excerpt from Trevelyan (2022) illustrates how inhibitions on knowledge sharing arise from social *habitus*.

> A junior South Asian engineer acting as a production supervisor is considered to have high social status relative to production workers. He listens to his manager and later briefs workers on what has to be done. No questions are asked either by the junior engineer or the production workers because that can imply an unwillingness to listen properly. Without being able to ask clarifying questions, the listeners are acutely aware of their own unresolved uncertainties. Workers patiently wait for directions, and expensive machinery lies idle in the meantime. The engineer runs from one worker to the next explaining every small action to each of them in turn. While a casual observer might see this as laziness or 'lack of appropriate work attitude', it may be wiser for the worker to wait for a supervisor or engineer to be present to issue directions and therefore take the blame if an action turns out to be incorrect. Work stops in the absence of visible supervision. Inaction inevitably contributes to low productivity. When his manager asks for a progress report the next day, the junior engineer remains silent instead of reporting production shortfalls.

Domal (2010) and Trevelyan (2013) observed several other factors that contribute to the high costs of engineered services in the LICs they studied. For example, engineering firms lacked the systems and procedures that strengthen technical collaboration in engineering firms in HICs. While engineers in HICs also missed the significance of indirect labour costs (e.g. supervision, training, insurance, transport, accommodation, rest breaks, protective equipment), the proportion of indirect costs in a low-income country is much higher, and can dominate labour costs (Trevelyan, 2014, Ch13). Engineers in LICs missed the significance of productivity and so these two factors combined to create a misperception that labour is much cheaper in a low-income country when, if anything, the reverse is true once indirect costs and productivity are taken into account. Sales engineers representing specialist engineering suppliers are relatively rare in LICs so most novice engineers miss out on the extensive workplace training provided by sales engineers in HICs (Darr, 2000). Few engineers in LICs are entrusted with detailed financial information about their employer or project so it is difficult for engineers to exercise the level of financial accountability that would be normal in a wealthy country, limiting their ability to generate economic value for their employers (Trevelyan & Williams, 2018). Company owners commonly maintain different and contradictory accounts. Taxation accounts tend to understate income. Accounts created to support borrowing tend to overestimate income. It is not uncommon for cash transactions to form a significant proportion of turnover and expenses, often with limited if any documentation.

Local language barriers also play a part. Skilled hands-on production workers often speak a different local language or dialect from the engineers. The engineers are likely to have been educated in a language inherited from European colonial powers, mixing that with the national language and their own mother tongue in casual conversations. They may not be fully proficient and literate in any language. Production supervisors translate engineers' instructions into local dialects for production workers, often losing much in translation, magnifying apparent uncertainties. In the presence of so much apparent uncertainty, a rational response for production workers is to choose inaction unless someone more senior is present to provide guidance and take the blame for misunderstandings.

Engineered service cost differences are startling. For example, the real economic cost of safe drinking water across most of South Asia is 10–50 times the cost in Australia, mostly because one has to carry water rather than rely on pipe networks

(Trevelyan, 2014, Ch 1, 13). Similar data came from a study in Uganda in 1990, with a different cost base (Whittington, Mu, & Roche, 1990). Electricity on demand is typically five times as expensive because of the need for alternative supplies from batteries or generators. Even construction at identical quality standards is 50–60% more expensive than New York. In the absence of understanding how cultural constraints affecting engineers' performances contribute to these costs, many people attribute the differences to corruption, a questionable hypothesis (Trevelyan, 2014, Ch 13).

These studies help us understand the difficulties experienced by engineers seeking employment in LICs (Senzanje, 2003) where the social culture presents significant barriers for the engineering collaboration making it more difficult than in HICs. Engineers require cultural awareness to overcome these barriers and practice effectively, particularly in LICs.

Mapping Agriculture and Biosystems Expertise

Many agricultural engineers face challenges well beyond the intrinsic variability in morphology and properties of biological materials. Animals, as sentient organisms, not only exhibit individual behaviour traits but also require culturally-specific handling by people because of differences in the ways that people consider animals in relation to themselves (e.g. Singer, 1989).

Therefore, in addition to the fundamental mathematics, physical, and biological sciences that support relevant engineering topics, agricultural and biosystem engineers need access to expertise in a far wider range of topics than can feasibly be addressed adequately in a four- or five-year engineering curriculum. Therefore, students need to learn how to access expertise beyond their prescribed studies and work experience, an activity referred to as 'boundary-spanning' (Asplund & Flening, 2021; Jesiek et al., 2018).

Trevelyan (1992) described the development of robots for shearing sheep in Australia between 1974 and 1992, an ambitious and successful agricultural engineering undertaking performed by a team of mechanical, mechatronics, and electronic engineers. The team worked with professional shearers and drew on expertise from many others including animal physiologists, animal behaviour specialists, agricultural economists, occupational health and safety experts, ultrasonic radar specialists, specialist agricultural engineers, shearing contractors, wool marketing experts, wool classers, farmers, sheep breeding experts and many others. In addition, the team's engineers had to work with animal welfare organisations and appear before special commissions to address political concerns arising from the animal-rights movement. Boundary-spanning work was an integral part of the team's daily experiences, both within the team and with outsiders.

One of the most challenging boundary-spanning aspects was translating human shearing skills into explicit software code and electro-mechanical components (Figure 11.4). Team members acquired elementary manual shearing skills early in the project. However, they sought advice from professional

FIGURE 11.4 Robotic sheep shearing, 1989. The team tapped the expertise of human shearers to improve the robot's performance. Video of the robot operating is available at: https://www.youtube.com/watch?reload=9&v=6ZAh2zv7TMM

shearers and later a professional shearing instructor joined the team as a full-time member to help improve the shearing actions of the robot. It was difficult to perceive the shearer's actions because the wool-cutting tool is almost entirely hidden by wool for much of the time. Furthermore, it was not possible to measure the forces applied by the shearer because the cutter's mechanical oscillation motion imparts large periodic forces. However, when team members programmed the robot and prepared the shearing comb and cutter in accordance with the shearer's instructions, the results did not match expectations. Gradually, it became clear that the shearer was instinctively translating his skilled actions to ones that *he thought* were appropriate for the robot. He had prepared a shearing comb with more rounded tips than he used for himself, thinking that this would make it less likely that the robot would cut the skin. This affected the response of the sensing circuit that detected skin contact. The more rounded comb tips required a *larger* force from the robot to penetrate the densely packed wool fibres close to the skin and make electrical contact with the skin. This *increased* skin friction forces, gave rise to wrinkles ahead of the comb tips, making skin cuts more likely. Later, the team prepared comb tips with sharper points and the shearing performance improved to a level similar to a human shearer, with much fewer skin cuts than a normal human shearer.

We can see in this interaction how boundary-spanning work can be challenging, especially when there are different thinking styles and knowledge types. Translating *tacit* sensory-motor knowledge acquired by the shearer over decades of experience into explicit software code and precisely defined shapes for the shearing comb tips was not easy and required many seemingly 'immaterial' conversations, debates, discussions, and humour (Wilde & Guile, 2021), causing considerable concern for project managers insisting on a tight development schedule.

The multidisciplinary nature and boundary spanning aspects typical of agricultural engineering endeavours are also reflected in recent development of alternative site-specific weed control technologies. Low weed density in cropping fields coupled with advances in optical sensing technology is driving demand for site-specific weed control technologies that remove the need for wasteful whole-field herbicide treatments (Walsh et al., 2020). This led to the development of the first broadacre site specific spot tillage device – the Weed Chipper[2] – compatible with conservation cropping systems. Whilst tillage and site-specific weed control is not a novel concept, the team aimed to mechanise the process by developing a rapid response tyne triggered by commercial optical sensing technology (Figure 11.5).

As outlined by Walsh *et al.*, the concept was conceived during meetings in 2012 of leading Western Australian farmer-innovators and with farmers in Queensland and New South Wales experiencing significant herbicide resistant weed growth. With support from the Grains Research Development Corporation (GRDC), the project team of weed scientists, agricultural engineers, machinery manufacturers, and farmer-innovators was formed to develop the targeted tillage system. The team prioritised rapid development and wide user acceptance, and all the stakeholders contributed to the design. Therefore, the engineers, led by the second author, based their design on widely recognised tyne systems to maximise farmer acceptance in terms of familiarity, serviceability, and technology awareness. They modified the commercial hydraulic breakout tyne system on a Shearer Trashworker[3] triggered with WeedIt camera technology.

FIGURE 11.5 The Weed Chipper in operation in a fallow field in NSW. The tynes which are held in a stand-by position above ground are triggered by cameras to chip out weeds.

In work conducted at the Centre for Engineering Innovation: Agriculture & Ecological Restoration, Moss et al. (2021) showed how farmers can often contribute significant innovations. Their research on harvesting technology for subterranean clover (a legume which buries its seeds in pods under the ground) showed how close collaboration between farmers and agricultural engineers can result in commercially useful innovations, even in relatively small industries. A key contextual factor that drove innovation in the industry was the relative isolation of the farmer-inventors. Both team diversity and farmer skill versatility increased inventive outcomes (Singh & Fleming, 2010): isolated farmers have to operate as skilled mechanics, farmers, and business owners (Moss et al., 2021). However, most farmers cannot afford significant research and development (R&D) activity, especially as they are now increasingly affected by climate variability.

Australian farmers have long contributed to research through industry levies, amplified with government funding, helping to ensure that research priorities align with the interests of farmers who can benefit directly from research outcomes (Moss et al., 2021). Mobile telecommunications technology could help with similar initiatives in LICs where government support is often weak or non-existent.

Reliable mobile telecommunications and high-integrity information systems have the potential to transform farming (Opara, 2004; Sigrimis, Hashimoto, Munack, & De Baerdemaeker, 1999), and access to capital (Asongu & Boateng, 2018; Kendall & Voorhies, 2014). Traditionally, farmers in many LICs have relied on finance from powerful actors such as landlords and produce-buyers for seed, fertiliser, fuel, and machinery investments. Mobile phone systems are transforming finance because they provide trustworthy means for financial transfers, a service that formerly relied on banks that served a small minority who could meet their creditworthiness requirements. As a result, a far larger proportion of the population in low-income countries can access electronic banking and access to credit, bypassing traditional ‘gatekeepers’ such as landlords and corporations. This change also enables farmers to bypass traditional supply chains that favour bulk commodities while providing the credit that farmers needed.

Mobile phone technology might enable even small farmers, in sufficient numbers, to contribute significant finance through producer levies to support industry-specific agricultural and biosystems research and development in LICs. It is also essential for engineers to develop social networks with farmers to encourage them to feel safe enough to share their own innovative ideas so that commercially useful inventions can emerge through collaboration.

Implications for Agricultural and Biosystems Engineering Faculty

Particularly in LICs, faculty work long hours for low pay under time pressure and have to make up for the limitations of local school education. There are limited if any opportunities for research, and very limited access to research literature. Competency statements (International Engineering Alliance, 2021) now frame the educational objectives of most engineering education programmes, even in countries that have not ratified the Washington Accord, emphasising what graduates *can do* rather than what they *know.* Accreditation agencies such as ABET (2021), Engineers Australia (Engineers Australia, 2011) and others issue similar lists of competencies.

Competency Statements Have Limitations

Unfortunately, competency statements are brief and require contextual knowledge for understanding and, in its absence, can cause misunderstandings and inappropriate learning by students (Hager, 2004).

For example the competency “ability to cut a cake” relies on common contextual knowledge that tells us that the cutting instrument is a long enough knife to reach from the centre of the cake to the edge. However contextual knowledge relevant for cutting a cake comprises implicit and tacit knowledge (knowledge that the user is unaware of), and therefore is unwritten. In the absence of contextual knowledge, competencies can easily be misinterpreted by faculty and students alike. As Conrad (2017) recently reported, student writing emulates attributes valued by faculty: long and complex sentences with numerous reference citations. This style of writing is likely to cause confusion in typical engineering workplaces that value short, concise statements with simple sentence structures and clear standardised drawings (which can be hand drawn) where possible. Gonczi (2013), citing Hager’s influence, concludes that competencies need to be assessed, at least in part, by experienced practitioners who have relevant contextual knowledge.

Suggestions for Faculty

The aim of this chapter has been to provide agriculture and biosystems engineering faculty with some insights into engineering as *practice researchers* have reported from field studies. We conclude with a series of suggestions that faculty could readily implement within existing curriculum frameworks, enabling students to develop more appropriate knowledge, skills and expectations.

Naturally, there are many on-going improvements in agriculture engineering education that have broad applicability. An emphasis on creativity combined with an appreciation for the economics of small-scale agriculture, including the value of unpaid labour (Whittington et al., 1990), can help graduates identify problems worth solving. A strong focus on freehand sketching to build visual perception skills followed by instruction on manual drafting and then CAD can help designers develop solution ideas that “make sense” as outlined in Guzzomi et al. (2012). Students need to learn that design is an iterative process in which, more often than not, the designer does not have all the necessary information and must start with assumptions or guesses, and that there is no perfect solution with so many unknowns.

The specific suggestions we have described below are particularly aimed at addressing issues that affect graduates in LICs, and which can easily be implemented by individual faculty without significant curriculum changes.

Students graduating from any engineering school enter a wide range of occupations, many in different countries and many embark on non-engineering careers. This reality can lead one to argue that engineering faculty should focus on the science and maths capabilities common to all careers in a particular engineering discipline. Graduates from many LICs obtain employment in HICs. Therefore, education programmes need to address issues that are relevant across diverse employment locales. However, in this paper, we argue that understanding how culture influences engineering practices is likely to empower graduates in any career, particularly agriculture and biosystems engineering careers in LICs.

1. We suggest the most important research finding that faculty can pass on to students is that it is possible to earn a salary in low-income countries (LICs) that is at least as high as in high-income countries (HICs). Typical engineering salaries in LICs are one fifth to one third of salaries in HICs, motivating many LIC engineers to migrate to HICs. Our research exposed engineers who attracted much higher remuneration, as high or higher than for an equivalent position in HICs, largely by their ability to foster effective collaboration, and also an ability to create significant value for their firms (Trevelyan & Williams, 2018). There is no need to migrate to a wealthy country to gain a high salary and income security.

   The first author located networks of LIC engineers earning high salaries by starting with specialist engineering suppliers distributing relatively high-cost components and materials. These companies compete with other distributors selling similar products at much lower prices. The high-cost supplies can be justified by the superior value they provide to the user, for example by providing high quality and reliability, helping to ensure that high-value assets operate reliably without costly breakdowns or frequent unplanned maintenance. In many LIC firms, purchasing departments insist on procurement processes that select the lowest cost components. However, high-cost components often provide much greater value. Engineers who can successfully influence purchasing departments to focus on value rather than purchase cost are likely to be among those earning much higher salaries. These engineers can serve as role models for students to demonstrate how an understanding of value generation can lead to higher remuneration and job satisfaction.

2. Students who learn early on that socio-technical interactions will take most of their time will be less likely to experience a mismatch between expectations and the reality of engineering work as engineers, and also that these interactions are essential for success. Trevelyan (2020) provides guidance to help students rapidly acquire socio-technical workplace skills.

   Faculty can also point out that classroom interactions are socio-technical. Education, after all, is a socio-technical process in which students learn as much from each other as from faculty, and much of the learning occurs through complex social interactions in and out of class.

   This is not an easy task for faculty or students. There are strong beliefs in most engineering communities that social interactions and most collaborative engineering activities such as technical coordination (Trevelyan, 2007) and project management are ‘not real engineering’. Students and engineers identify real engineering as the Group 2 mathematical and science-based activities learned in engineering schools. Changing this perception is difficult and will require frequent repetition.

   Collaborative learning methods can provide a setting in which students can appreciate the significance of socio-technical interactions (Smith, Sheppard, Johnson, & Johnson, 2005). Traditional group projects may not satisfy the requirement for collaborative learning because students tend to subdivide the work between them and work separately on each part (Leonardi, Jackson, & Diwan, 2009; Sheppard, Macatangay, Colby, & Sullivan, 2009; Tonso, 2006). Jigsaw puzzle learning is one truly collaborative method that, in many ways, mirrors the kinds of distributed expertise encountered in engineering workplaces (Brown et al., 1993; Trevelyan, 2010). In the first phase, groups of students each learn distinctly different technical topics. Next, after being allocated to teams in which each student acts as a subject-matter expert, they create solutions for problems that can only be solved by students contributing their respective expertise and collaborating together. An important feature of collaborative learning is that more able group members need to help teach the less able members as any of them will be called upon to present the group’s work.

3. Faculty can explain the notion of productivity to students, helping them understand why economic development is so challenging in LICs. Many people in LICs imagine that their countries remain poor because of corruption by elites and economic mismanagement by incompetent rulers. While these factors cannot be eliminated from any analysis of productivity, the significant role of engineers in providing the means by which people can be more productive is very often ignored. Indeed, engineers are barely mentioned in UN documents related to the Sustainable Development Goals (e.g. United Nations, 2017a, 2017b; United Nations Development Programme (UNDP), 2017; United Nations Development Programme (UNDP), 2019) and the potential for engineers with regard to the UN’s Decade of Ecological Restoration not clearly apparent (Masarei, Erickson, Merritt, Hobbs, & Guzzomi, 2021). To help faculty and students in making this connection, we have advanced a succinct new

definition of engineering, based on our research observations of engineers at work:

> Engineers are people with specialized technical knowledge who conceive, deliver, operate and sustain artificial objects, systems and processes that enable people to do more with less effort, time, materials, energy, uncertainty, health risk, and environmental disturbances. (Trevelyan, 2019, 2020)

4. Faculty can help students learn that the cost of engineering activity in LICs is likely to be higher than in HICs, for similar product quality, reliability, and fitness for purpose. This will seem counter-intuitive for many, even most faculty. Data on the cost of safe drinking water provided in this paper, easily verified, can help students understand this. This is the result of low productivity. This is also an opportunity: engineers who can reduce costs to levels comparable with HICs will be well rewarded by their firms.
5. At the same time, faculty can draw on published material to explain why labour costs are higher in LICs once productivity is factored in. Even in China, where the overall productivity is about 3–4 times lower than in HICs, the intrinsic cost of manufacturing products is higher than in the USA, Europe, and Japan. China manages to provide cheaper products than these countries by a combination of subsidies to manufacturing companies and, in some instances, offering cheaper products with lower levels of quality and performance (Trevelyan, 2020). Chinese firms accept profit margins and investment returns much lower than typical HIC firms. China can also achieve economies of scale with production volume unattainable in most countries.[4]
6. Faculty can encourage students to ask questions to clarify lecture presentations, something that can conflict with local culture. One way to overcome cultural resistance is to ask them to work in groups of two or three students adjacent to each other in the lecture hall. Each group has 3–5 minutes to come up with a question written on a piece of paper which is placed on a pile at the front of the class. The instructor then draws questions at random and has no way to know which student asked the question.
7. Faculty can provide an authentic context for engineering science textbook practice problems to help students appreciate the context in which they will apply the relevant methods. For example, faculty can provide worked solutions to textbook problems, simulating design calculations by engineers, but with authentic features such as missing or extra details, some incorrect assumptions, and mistakes in some of the workings (sparingly applied). Students would have to apply textbook methods to verify the results independently and detect mistakes. Such approaches have been shown to be useful in related contexts (Hesterman, Guzzomi, & Stone, 2007). They would need to find data from reputable sources to substitute for missing information. Some data should be provided with large uncertainty limits so that students learn to identify worst case and likely case scenarios and perform appropriate calculations. At least for some of the time, students could be required to work under very tight time constraints to simulate the realities of practice not only to provide the solutions whether numerical answers or design but also the limitations/caveats associated with the constrained information, time to work on the solution, etc. Asking students to prepare a short presentation on how engineers use mathematical and scientific methods has been demonstrated to be a powerful motivator, significantly improving student learning (Goold, 2015).
8. Faculty can encourage students to perform detailed ethnographic observations on practicing engineers by shadowing an engineer or small-scale farmer for a week, spending about half of each day observing and taking notes, and the other half of each day writing a detailed account of their observations earlier in the day. These observations can then provide case study material to help provide authentic contextual framing for textbook problems in class exercises.
9. Faculty can draw students' attention to the influence of culture on engineering practice by reflecting on student and instructor behaviour in the education setting. For example, the instructor can encourage students to discuss how comfortable they feel in posing questions to other faculty in the presence of their peers. The instructor could prompt a discussion on how comfortable students would feel having a drink with or eating with their faculty, such as a senior professor. Faculty could prompt students to observe how people behave in situations with large power differences, for example a servant speaking with the owner of a house. They could then compare these interactions with their own behaviours with their parents, and behaviours when with their peers. The aim would be to sensitise students to become more observant with respect to social interactions and how people behave with each other in different social situations.
10. Faculty can alert students to interpretation differences. For example, when students perform classroom exercises, their grades often reflect interpretations of the exercise that differed from those of the instructor rather than lack of knowledge or willingness to work hard at studies. Students should be made aware that interpretation differences are a fundamental attribute of human beings. Everyone will have a different interpretation of the same words and drawings or diagrams. Some differences will be minor, but some can be very significant and in engineering these differences can have catastrophic consequences. As engineers, students will encounter

similar interpretation differences. A class exercise to explore interpretation differences could take the following general format.

Stage 1) Students construct a simple model from readily available materials such as wire, cardboard, adhesive tape, etc. It does not have to be a functional model.

Stage 2) Students create drawings of their models and, if necessary, a written set of instructions or a specification. The written materials and drawings are placed in envelopes.

Stage 3) Students draw envelopes at random (excluding their own, of course) and use the drawings and instructions to replicate the original model without being able to see the original model.

Stage 4) Students compare their constructed replica with the original model. Most of the replicas will be different from the original models in some respects because inexperienced students neglect to specify important features and dimensions. The results are often amusing and sometimes surprising. Students can reflect on the interpretation differences to distinguish deviations resulting from inadequate specifications and drawings from those resulting from differences in interpreting text and drawings.

11. Faculty can encourage students to participate in extra-curricular activities, particularly part-time work, and reflect on the social interactions that they take part in to help them become more observant of human behaviour. Students working as volunteers can learn collaboration and coordination techniques that they will find helpful in engineering workplaces. Service learning of this type has been shown to facilitate student learning in the US and has now begun to be implemented in some Indian engineering schools (Dustker, Reddy, Kandakatla, Joshi, & Oakes, 2021).

There are many instructional techniques known to improve the quality of student learning in higher education (Schneider & Preckel, 2017; van Alten, Phielix, Janssen, & Kester, 2019). Many of these methods can be implemented to improve student learning about engineering practices.

One cannot be sure that improving engineering education will influence what happens in engineering workplaces where organisational culture can overwhelm earlier behavioural influences (Buch, 2016). However, by researching engineering practice over time, and observing how education influences workplace practices, it should be possible to improve employment outcomes for agricultural and biosystems engineers in low income countries and significantly increase the wellbeing of rural communities.

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NOTES

1. Data from the World Bank at https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS data obtained 8 December 2022.
2. Video available at https://www.youtube.com/watch?v=9cKo5MWZseI
3. https://johnshearer.com.au/
4. The first author's substantial recent experience working first-hand with engineers in Chinese appliance manufacturing factories has provided these insights, also frequently referred to in business commentary on Chinese manufacturing.

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