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Preparing Chemical Engineers for Industry 4.0: An Interactive Education Approach

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ABSTRACT

CONTEXT

With the emergence of predictive data analytics and advanced technologies such as digital twins and artificial intelligence, the potential exists to transform the chemical industries over the next two decades. In this pivotal time, it is crucial to equip future engineers with such skillsets to address the current need of the industry. However, the core of industry 4.0 mainly concerns computer science and IT disciplines, and as such, these concepts have hardly been addressed in chemical engineering education.

PURPOSE

While it is expected that in the coming years, incremental changes apply to the engineering curriculum by including digitisation, it is important to design courses to prepare the chemical engineering graduates for the transition of chemical industries from 3.0 to 4.0. To this end, we designed a master-level course, which is also an elective for 4th-year undergraduate learners. This unit of study aims at developing an understanding of the available means (e.g., advanced sensors, industrial internet of thing (IIoT), digital twin, and deep learning algorithms using Python) and their implementation within chemical processes. It is expected that the designed projects and hands-on activities in this educational package provide a valid basis for the current transitioning phase of industries from 3.0 to 4.0 while allowing practising and developing transferable professional skills.

APPROACH

The learning and teaching activities presented in this article were spanning across multiple components of industry 4.0 as well as learners' creativity in the enhancement of chemical processes. To transfer the Industry 4.0 topics to the learners within the framework of chemical engineering, we benefited from various teaching practices, including recent industrial case studies and hands-on activities (e.g., making a neural network predictive temperature control system with Arduino microcontroller and wireframing a mobile app for a chemical process unit). Three capstone projects were designed: 1) to propose a solution for the digital transformation of a chemical process using the concepts of industry 4.0, 2) to apply deep learning for big data analysis of a chemical process using Python, and 3) building a digital twin for neural network predictive control of a DC heater/fan system using Arduino microcontroller.

ANTICIPATED OUTCOMES

The activities are designed to provide opportunities for students to understand advanced digital technologies and apply them in real-world engineering scenarios. It is expected that students develop skills in big-data analytics and real-time data processing using sophisticated data-driven approaches, including deep learning. Students gain hands-on experience working with Arduino lab kits in wiring up a heater/fan system and applying process control theory into practice by programming a neural network predictive controller in Matlab/Simulink for real-time temperature control. Such practical skills in real-time data acquisition and processing are identified as critical attributes for engineering graduates, according to experts from the industry.

SUMMARY

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A novel teaching and learning package including hands-on activities was designed to prepare chemical engineering learners for the digital transition to industry 4.0. The importance of hands-on activities and engineering laboratories are not hidden to the engineering educators. Thus, there are numerous opportunities in transforming the conventional chemical engineering laboratories to their 4.0 versions. The students' feedback has been positive, suggesting engagement and overall satisfaction with the course. However, a comprehensive pedagogical survey will be carried out in the future to gain more insight into the educational offer of different components of this unit of study.
KEYWORDS

Industry 4.0, Chemical Engineering Education, Arduino microcontroller, Big-data analytics.

Introduction

With the success of the digital revolution, and the rise of technological developments on cybernetics, distributed physical devices with built-in computing and communication capabilities, new sensor technology, sophisticated IT infrastructures (e.g., cloud storage and computing), the industries are evolving rapidly – creating what is referred as smart industry and smart manufacturing. The industrial plant (physical world) synergistically combined with the cyber world in a way that they can communicate and affect each other has been labelled as industry 4.0. Whether industry 4.0 is merely an "old wine in new bottles" (Köbsell, 2015), or a completely shaped landscape (Pfeiffer, 2017), it is axiomatic that it is the biggest paradigm change that the industry is currently experiencing.

In a survey performed by PWC from 222 chemical company executives in 26 countries (PWC, 2016), it was inferred that while most companies were expecting to strengthen their digital offering either by using big data analytics or by digitising their existing products and processes; they believe lack of digital culture and training is the biggest challenge facing them. Hence, it is most appropriate that the educational organisations respond to the knowledge gap of their graduates for addressing the new technological and training challenges.

Most elements of industry 4.0, such as digital twin, advanced sensors, internet of things, augmented reality (AR), virtual reality (VR), big data analytics and machine learning, are originated from computer science, information technology (IT) and to some extent electrical engineering. Hence, they are fundamentally new to other engineering disciplines, particularly chemical engineers. Many educators have recently emphasised on creating graduate programs or updating the whole curriculum of undergraduate programs to include industry 4.0 topics. Hernandez-de-Menedez et al. recently reviewed the established programs in engineering education for industry 4.0 (Hernandez-de-Menendez et al., 2020). Despite building momentum in updating the chemical engineering curriculum, adopting industry 4.0 in courses is still challenging – mainly due to the lack of knowledge of the use and implementation of industry 4.0 components within chemical processes (Kakkar et al., 2021).

Teaching students the unusual topics to their background whilst keeping them engaged to the topic is of most importance. Interactive methods of training such as case study (Shallcross, 2013a), peer feedback (Rodgers, 2019), project-based learning (Ballesteros et al., 2019), game-based learning (Ghadi et al., 2020), storytelling (Smyrnaiou et al., 2020), and basket and action learning methods (Guimarães et al., 2021; Yakovleva et al., 2014) have been successfully used for students engagement in contemporary higher education of chemical engineering. It should be noted that some interactive methods have proven to be more successful and well-received by students in certain areas of chemical engineering. For instance, case studies could be very effective in educating process safety, risks assessment, and cybersecurity (Shallcross, 2013a, 2013b; Wu et al., 2018). The inclusion of real-world cyberattacks to chemical processes presumably enhance the course relevance and subsequently encourage the students to be more proactive in the course. However, Wu et al. reported that, based on their experience, technical writing as well as generating solutions to

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“open problems” were challenging to the students while doing cyberattack case studies in their process control course (Wu et al., 2018).

Industry 4.0 can provide opportunities in process system engineering. For instance, deep neural networks have been used to predict the adsorption equilibrium using Artificial Neural Network (ANN) and MATLAB in a bioprocess engineering course in the last year of undergraduate level (Kakkar et al., 2021). The lecturers provided the MATLAB codes to the students in the classroom and encouraged them to modify them (Kakkar et al., 2021). While Kakkar et al. received positive feedback from the students, they cautioned that their approach could potentially make the students take neural networks as purely “black box” modelling, thus, hindered students’ ability in understanding the mathematical aspects of neural networks (Kakkar et al., 2021).

On another note, there have been recent discussions arguing if the chemical engineering students possess the “programming skills” required to answer the new problems, particularly those problems that were defined in the framework of digitisation of the chemical industries (Pfeiffer, 2017). In a survey from students performed by Cano del las Heras et al., students stated that the presence of programming content with the whole curriculum is insufficient, and they favoured Python over other programming languages (de las Heras et al., 2021).

It should be highlighted that the ratio between demonstrations and hands-on activities must be well-balanced to answer the goal of the learning industry 4.0. A great initiative that recently applied is using digital twins for the education of engineering sciences, particularly within laboratory experiments (Zacher, 2020). The main advantage of such method is adaptability and expandability depending on the training need. However, building such medium-to-high fidelity digital twin still involves high costs. Recently, innovative microcontrollers for process dynamics and control have been developed using Arduino and Raspberry Pi (Park et al., 2020; Škraba et al., 2020). The engineering students appreciate the low cost of prototyping devices such as Arduino, Raspberry Pi, and BeagleBone Black and become motivated by their own creativity using such devices (Jamieson et al., 2015).

Building on the literature, we propose a combination of interactive methods for introducing different components of industry 4.0 to chemical engineering students within one unit of study. This article summarises the development of a lecture resource package for preparing the learners for industry 4.0 in the final year of an undergraduate chemical engineering program. The work contributes to a new course designed and delivered in 2020 and 2021 at the School of Chemical and Biomolecular Engineering, The University of Sydney, Australia. The learning and teaching activities presented in this work incorporate a combination of different elements of interactive teaching and are a framework for sharpening students’ soft skills such as thinking and creating in industry 4.0, understanding and applying predictive data analysis using deep learning and ultimately building a digital twin using an Arduino kit and predictive control. We hypothesise that using multiple interactive approaches tailored to the industry 4.0 components not only prepare the students for their future career in an emerging digitised industry but also engage them effectively throughout the course.

Context of the course

In designing the course contents, the following three main areas were targeted: (i) safety of chemical processes (e.g., HAZOP review, and cybersecurity), (ii) training of new personnel (including safe operator experimentation, process unit start-up and shutdown), and (iii) process system engineering (PSE). At the beginning of the course, major components of industry 4.0 (e.g., augmented reality, digital twin, sensors, IoT and cybersecurity) within the framework of chemical and biochemical engineering were introduced and discussed through examples and case studies from industry. Students were encouraged to reflect on the demonstrated examples in groups and then apply similar concepts to new processes. Group members brainstormed and presented their ideas to the rest of the class and received feedback from their peers and the teaching staff. This provided students with the opportunity to exercise idea generation and innovation within the context of industry 4.0 transformation while practising teamwork, giving/receiving critics and engaging with risk-free and open-ended scenarios. To further consolidate the acquired knowledge and skills, a capstone project was designed for the students to write a proposal for updating a chemical process from industry 3.0 to 4.0. To carry out the design activity, students followed "design thinking" principles, including (1) research, (2) empathise, (3) define the problem, (4) ideate, (5) prototype, and (6) test (Dym et al., 2005; Santos et al., 2017). Students conducted research on a chemical process to identify the areas that they could improve the process using digitisation. They were also encouraged to empathise with the client by considering the client's needs when including the components of digitisation (e.g., AR, digital twin, sensors and IoT). They were also asked to provide a general discussion identifying the overall recommendation for implementing their proposal as well the risks associated with their plan. The overall goal of this capstone project was to encourage students in (i) understanding the process and the role of digitisation, (ii) ideation by designing innovative solutions to enhance the overall performance of the process, (iii) empathising with the client, (iv) avoiding the digitisation-hype, (v) planning for risk mitigation, and (vi) practising professional writing. Feedback was provided to the students based on meeting the aforementioned items.

As stated above, the application of industry 4.0 topics (e.g., cybersecurity, AR/VR, machine learning, sensors, IoT and digital twin) within the context of safety, training personnel, and PSE were taught with different interactive teaching methods as depicted in Figure 1.

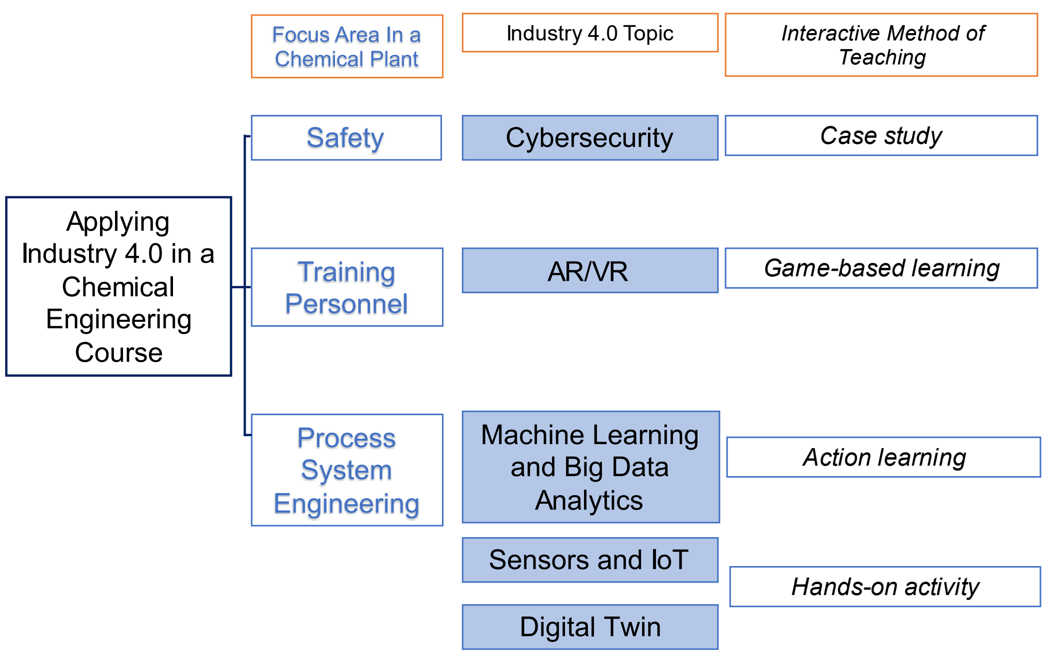

Figure 1: Teaching industry 4.0 topics via interactive teaching methods in a chemical engineering unit

Cybersecurity via a case study

A list of cyber incidents cases in chemical processes and control systems was adapted (INL, 2018) and provided to the groups of students to choose from prior to the session. Students had the chance to review the list and be exposed to multiple scenarios. A worksheet (Table 1), similar to what was presented by Wu et al. (2018), was designed and provided to the groups. Each group was asked to fill the worksheet while brainstorming and discussing various sections of the worksheet, including "knowing", "investigating", "engineering", and "designing".

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Afterwards, each group presented their completed worksheet to the rest of the class and received feedback from their peers as well as the lecturer.

Table 1: Cybersecurity case study worksheet

Section	Questions (point allocated)
Knowing	Briefly describe the process that was targeted
Investigating	Describe in technical terms how the cyber-attack happened.
Engineering	If you were the engineer responsible for this plant, a) What would you do to promptly detect if your process/control system was under attack? b) What actions would you take to stop the adverse effects of this security bridge?
Designing	Design a system to protect your plant from a similar attack in future. Explain how your proposed plan would protect this chemical plant.

Augmented Reality (AR) via game-based learning

Game-based learning was applied to educate the learners on the concept of augmented reality (AR) and its application in training personnel. For this activity, groups of 3-4 students were asked to wireframe a mobile app to (i) navigate the trainee to the bubble column unit in the laboratory in our school via university map; (ii) provide step-by-step safe operational training and navigation to the trainee using augmented reality with arrows popped up on the screen upon turning on the camera; (iii) build features in the app to access the manual and submit the report at the end. The activity was performed in a hackathon manner using a game-based learning approach as an effective pedagogy in boosting creativity, motivation, engagement, and retention of the subject matter (Cojocariu et al., 2014; Heininger, Prifti, et al., 2017; Heininger, Seifert, et al., 2017).

The bubble-column operational manual was provided to the students. Several photos taken from different parts and different angles of the bubble column were also provided. Students were familiar with this educational laboratory equipment as they operated this unit in the past. Interestingly, many students were inspired by PokemonGo mobile game and IKEA app interfaces – common mobile apps using AR. A score was awarded for a reasonable app design where all the required questions were addressed reasonably and relevantly within the allocated time frame. Scores varied according to the compliance with design objectives while avoiding overdesign of the application, i.e. including other laboratories map or other units in the same lab within the app design. In the next stage, they started prototyping by wireframing their mobile app based on augmented reality. Students then presented their completed wireframe to the rest of the class. The lecturer promoted discussions among groups and made notes of each group's interesting design points on the screen.

Artificial intelligence (AI) and machine learning via hybrid action learning

Perhaps one of the most applicable components of digitisation is artificial intelligence. As discussed earlier, educators commented on how students took the pre-existing computing packages as a "black box", in which the math behind these algorithms, e.g., Artificial Neural Network (ANN), was a great challenge to them (Kakkar et al., 2021; Samek et al., 2017). We avoided this issue by first covering the fundamental mathematics behind the neural network algorithms and, hence demystifying them. Several exercises were defined, and students were asked to use hand-calculation to solve a simple perceptron model. Next, Python codes (in Numpy and Panda) were provided to the students. Students inserted each line while the lecturer explained them. It should be noted that pre-existing black box packages for the neural network, such as TensorFlow and Keras were not introduced to the students at this stage.

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Students were encouraged to code and to fix the errors. The aim of this step was to introduce Python as well as avoiding the “black box” perception of deep learning in Python.

In the next step, we applied action learning which is a favourable approach to operate within the context of a real and complex project (Stappenbelt, 2010). The groups of students received a big data set that included physicochemical properties of red and white wine (Cortez et al., 2009). The students were asked to develop an ANN model to predict the wine quality, which is often assessed by sensory testing based on the physicochemical properties. Since students developed a good understanding of the math and fundamental coding for neural networks by this stage, the Keras package was provided to the students with descriptions. However, the codes regarding optimising functions were excluded. Students were then asked to run the code and check the accuracy of their predicted model. Through this process, the learners were encouraged to reflect on the math that they learned in the first step and suggest improvement in their models. Almost all students asked how they could include modifications such as various optimisers in their codes. Through the process of running the code, checking the accuracy, reflecting on the change, and planning the next modification (a classic do-check-act-plan cycle), the groups of students built a robust ANN model. They have then drafted a professional report and discuss their outcomes and submitted their work for assessment.

Heater/fan set-up using Arduino microcontroller for predictive temperature control

Students participated in a hands-on activity in which they wired up and programmed a 12V heater/fan system using an Arduino microcontroller, thermocouple sensor, and electronic parts. Figure 2 presents a photograph and schematic diagram of the heater/fan set-up. Students were exposed to the working concept of MOSFET transistors, resistors, diodes, analogue/digital input/output, and pulse-width modulation (PWM) to build circuits on a breadboard to control the electrical loads of the heating element and the fan.

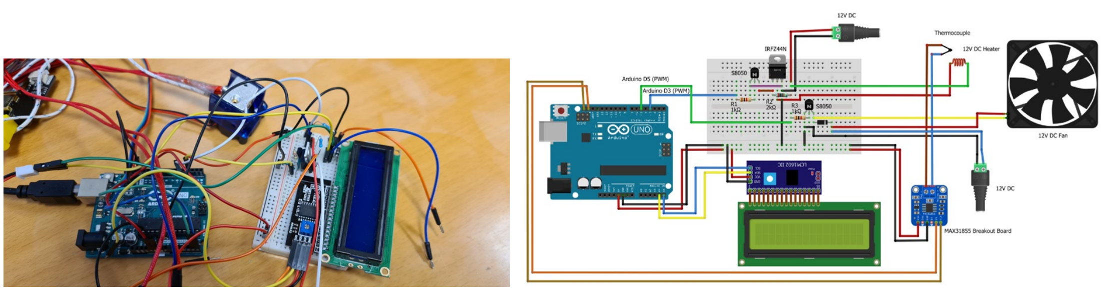

Figure 2: Photograph and schematic diagram of the Arduino heater/fan set-up

The Arduino set-up provided the context and practical motivation to consolidate their learnings about industry 4.0 and machine learning and to exercise programming using Arduino software, Python, and MATLAB/Simulink. Students used libraries such as “pyfirmata” in Arduino and “serial” in Python to control the PWM outputs of digital pins 3 and 5 corresponding to the heater and fan outputs, respectively, and read/plot the temperature measured by the thermocouple. Students also took advantage of the MATLAB Support Package for Arduino Hardware to write PWM signals and read the temperature sensor using I2C communication protocol through the Arduino board. The “in-house” built Arduino set-up was used as a “physical asset” for real-time data processing and to exercise neural network predictive temperature control along with its “digital twin” programmed in Matlab/Simulink. Figure 3 shows the block diagram of the feedback control system developed in Simulink to control the Arduino microcontroller using a Neural Network predictive controller. Through this design-and-build activity, students gained practical experience in predictive control via data-driven techniques such as model predictive control (MPC) using ANN-based models, which is the current trend in process system engineering.

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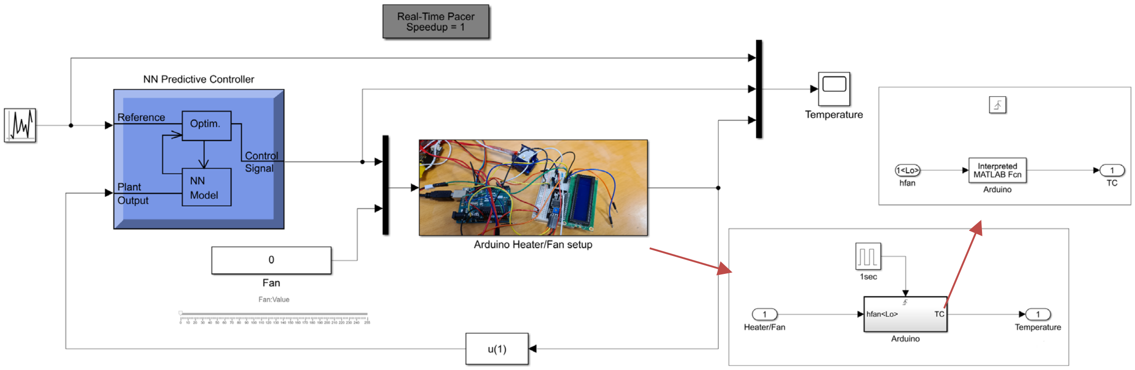

Figure 3: The feedback control system block diagram used to control the Arduino microcontroller using Neural Network predictive controller in Simulink. An Interpreted Matlab function was written to control the PWM pins outputs. I2C communication protocol is used to transmit the measured thermocouple output back to the computer.

Students' feedback

In anecdotal conversations throughout the semester, students expressed their views of the individual activities and their overall experience with the course. There were many positive comments about the course being challenging, innovative and intellectually rewarding. Students commended the authenticity of the learning experience and how they can see the acquired skills are applied in the evolving industry. They appreciated the interdisciplinary nature of the course introducing them to digital technologies, Data Science, programming, and basic electronic concepts and how they can interface with the emerging Chemical Engineering discipline. The hands-on experience of working with Arduino and programming with Python was also suggested to be fun, engaging, and informative. Nevertheless, they suggested they needed more time to work on the Arduino and understanding the concepts behind the electrical circuits, which will be taken into consideration in the future.

Conclusion

An educational initiative in transforming the chemical engineering curriculum in response to the new training needs regarding digitisation and industry 4.0 has been presented. The learning and teaching activities aim to develop an understanding of the role of various components of Industry 4.0 in chemical industries as well as applied skills in programming (e.g., Python and Matlab), data-driven modelling, digital twins, predictive data analytics, data wrangling, artificial intelligence, and deep learning. Various teaching methods, including game-based learning applying design thinking approach, action learning, and hands-on learning (Arduino set-up and wireframing activities), have been successfully implemented to address the diverse nature of the industry 4.0 components and maintain high students' engagement. Anecdotal feedback from students and observations from the teaching staff suggested high students' engagement and satisfaction with this unit of study. The successful implementation of this initiative has inspired us to explore opportunities in transforming some of our conventional chemical engineering laboratories to their 4.0 versions as potential hands-on activities for the next academic year. The effectiveness of this educational intervention in achieving the intended learning outcomes will be assessed through a combination of targeted survey questions, student reflections, feedback from academics, and unit of study evaluation responses.

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