Smart Manufacturing Course: Proposed and Executed Curriculum Integrating Modern Digital Tools into Chemical Engineering Education

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ABSTRACT

The paradigm shift into an era of Industry 4.0, also referred to as the fourth Industrial Revolution, has emphasized the need for intelligent networking between process equipment and industrial processes themselves. This has brought on an age of research and framework development for smart manufacturing in the name of Industry 4.0 [1]. While the physical and digital advancements towards smart manufacturing integration are substantial the inclusion of engineers themselves amongst this shift is often less considered [2]. There are educational efforts in Europe to create and implement smart manufacturing curriculum for non-traditional or adult learners already integrated in the workforce, but attention is also needed on a next generation smart manufacturing curriculum for pre-career students [3]. We, the teaching team of CHE 554: Smart Manufacturing at Purdue University, developed and implemented a curriculum geared towards the training of undergraduate, graduate, and non-traditional students in methods of smart manufacturing as they apply directly to industrial scenarios. Through this elective course, taught primarily through the context of chemical engineering but enrolling students from other disciplines, we introduce concepts not covered in its entirety by the core engineering curriculum. Our course includes but is not limited to material on data reconciliation, machine learning, chemometrics, data-driven fault detection, digital twin development, and process optimization. Further, these concepts are executed through the context of open-source Python packages, enabling the accessible and practical application of smart manufacturing in the form of assignments and in the context of professional application in the future [4,5]. The integration of modern tools and Python libraries connects academic solutions to industrial challenges with industrial practice becoming evident for students who would otherwise be unaware of these resources. With the creation and implementation of the Purdue University Smart Manufacturing elective course, we help develop a uniquely prepared and technologically educated generation of engineering students capable of bringing Smart Manufacturing capabilities to industry. This helps catalyze smart manufacturing knowledge transfer where all enrolled students are given the tools to apply their knowledge mastery to their specific engineering discipline and industrial application.

Keywords: Industry 4.0, Fault Detection, Artificial Intelligence, Interdisciplinary, Model Predictive Control, Digital Twin, Process Optimization

INTRODUCTION

Industrial revolutions have consistently marked transformative eras of technological advancement, shaping the modern world. Industry 4.0, also known as the Fourth Industrial Revolution, is no exception [1]. This era has witnessed an unprecedented integration of novel technologies into manufacturing, aimed at making processes more sustainable, robust, customizable, and profitable. However, despite the transformative potential of these technologies, their adoption is not always met with universal success. Even in companies that

enthusiastically embrace Industry 4.0, a critical gap often arises. Students entering the workforce frequently lack exposure to the technologies and concepts foundational to Industry 4.0. This unawareness highlights the opportunity for academic institutions to prepare graduates with concepts that allow them to immediately contribute to industrial engineering and manufacturing.

Purdue University has long been recognized as a leader in fostering experiential learning through co-ops, internships, and other opportunities for industrial engagement. However, sending graduates into the chemical manufacturing workforce during an era defined by Industry 4.0 necessitates equipping them with relevant skills for evolving industrial landscapes. To equip students properly, universities must critically evaluate their core curricula and integrate data-centric and digitally focused material alongside traditional engineering education, transitioning academic programs into the realm of Education 4.0 [7]. Recognizing this need, Purdue's Davidson School of Chemical Engineering leveraged its strong process systems engineering community to develop an innovative elective course: Smart Manufacturing. This course is designed with several features that enhance accessibility across physical, generational, computational, and disciplinary boundaries. By welcoming a diverse range of learners—from different ages, backgrounds, and disciplines—this elective provides an inclusive platform to engage with Industry 4.0 concepts. The course has successfully run for six semesters at Purdue University and continues to evolve, reflecting technological advancements to ensure students remain at the forefront of smart manufacturing education.

The following sections of this article will explore the course's key features, assignments, and guiding philosophies that contribute to its success, making it a valuable and adaptable model for other institutions aiming to bridge the gap between academia and the demands of Industry 4.0.

COURSE DESCRIPTION

Course Philosophy

This course surveys the tools and techniques which are relevant to support the multiple levels of technical decisions that arise in modern integrated operation of manufacturing resources in the chemical, petrochemical and pharmaceutical industries. The real time generation and sharing of associated data and knowledge via relevant IT methodology and the effective use of this information in the various levels of the process operations management hierarchy are currently termed Industry 4.0 (Europe) and Smart Manufacturing (US). The topics covered in the course span all the technical components and decision levels in the operations decision hierarchy. Topics include the role of on-line and at-line process measurements, elements of sensor network design, information systems to support process operations, plant data reconciliation, detection and diagnosis of process faults, condition-based monitoring of plant assets, plant wide control, real time process optimization, production planning and scheduling, and supply chain management. Each topic is addressed by first summarizing the basic role and scope of that component, then discussing the elements of the decision problem, and outlining some representative tools available to address that decision problem. Each major topic includes a lecture given by an industrial practitioner who offers a perspective on the state of industrial practice.

Learning Outcomes

The Smart Manufacturing elective communicates a short list of learning outcomes to each student to serve as a target for the minimum goals that should be achieved over the course of the semester. They are as follows:

- Explain the key decisions that are made at each level of the operational hierarchy of an integrated process system.

- Define what the various types of manufacturing and enterprise data are, how they are generated and managed and what their functions are in supporting these decisions.

- Explain the role of models in supporting the decisions made at each level of the operational hierarchy.

- Evaluate and improve a plant wide control system for a given manufacturing system.

- Identify condition-based monitoring of a manufacturing system, how it is performed and what its outcomes should be.

- Explain the nature and role of planning and scheduling models and tools as applied at the plant and supply chain levels.

Critical Features

The success of the Smart Manufacturing elective can be attributed to several strategic course and curriculum design decisions. A few key elements that distinguish this course and contribute to its ongoing success are particularly noteworthy.

Firstly, offering this course exclusively online as an asynchronous learning opportunity enables access for engineers who are already in the field or industry, often with several years of professional experience. This format allows them to explore Industry 4.0 tools and gain insights relevant to their roles without the need to enroll in a traditional, in-person degree program. Such flexibility

is particularly valuable for experienced professionals, including older generations of engineers, who might otherwise find it challenging to engage in further education.

Another unique aspect of the course is the deliberate emphasis on open-source software packages, particularly those based in Python. These packages are integrated into various assignments and projects, ensuring that students gain proficiency in tools that remain accessible after their time at Purdue. This approach significantly enhances the transferability and adaptability of the skills learned, enabling integration into the industrial workflows of their (future) employers.

Finally, a critical factor in the course's success is the commitment to frequent and thorough updates to the curriculum. As the field of smart manufacturing evolves, new tools emerge, existing software packages improve, and industry standards shift. Staying current with these advancements is essential for a course centered on cutting-edge technologies. Regular updates ensure that students are equipped with the most relevant and advanced knowledge, keeping pace with the rapidly changing landscape of smart manufacturing. These foundational principles—broad accessibility, the use of open-source tools, and a commitment to staying at the forefront of technological advancements—are integral to the continued success and impact of the Smart Manufacturing elective.

Course Audience

The Smart Manufacturing elective is a 500-level elective course (for both undergraduate- and graduate-level students) offered through the School of Chemical Engineering although students across departments and education levels are encouraged to enroll. As a result, our student body actively enrolled in the course spans undergraduate, graduate (Master's and Ph.D.), and adult learners across multiple departments ranging from Industrial Pharmacy to Mechanical Engineering to Industry.

PROJECT DESCRIPTIONS

Data Reconciliation

The efficiency, safety, and overall success of chemical manufacturing operations rely on several critical factors, including robust process controls, effective monitoring, and sound process design. When sensors or process controls fail, undetected deviations can result in costly operational disruptions and potentially catastrophic safety incidents. As a result, one critical function of an operator and/or engineer is the ability to reconcile data and detect deviations. This concept appears in three of the course projects, however in this homework assignment, students are asked to approach data reconciliation through the lens of statistics, emphasizing confidence interval calculations and error minimization. The chosen application for communicating this technique was methanol synthesis reconciliation of flowrate data, represented as the network shown in Figure 1.
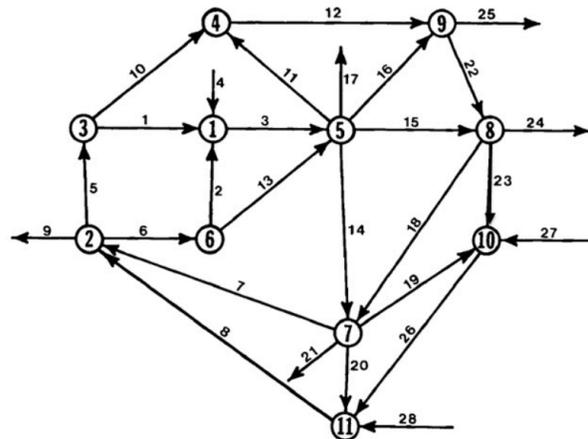
Figure 1. Network representation of process steam system for a methanol synthesis unit [Seth and Heenan, 1986].

After designing a simple optimization problem from the stream networks material balances, students reconcile the data by minimizing the error between the actual and desired stream flowrates. After this error function validation, students are asked to calculate the upper and lower bounds of specific stream flowrates that would have to be reached to trigger a fault. The magnitude of this range being determined by the established confidence interval.

Chemometrics and Fault Detection

Process monitoring can allow for deviation detection when coupled with various data handling tools. However, variable correlation that enables the association of cause with effect cannot be effectively determined with all the same tools. In a homework assignment, students are asked to apply Principal Component Analysis (PCA) and Partial Least Squares (PLS) to a sensor-based dataset which contains a known fault. Students are asked to leverage the chemometric tools to identify the onset time of the fault, the associated variables, and suggest a sound engineering reason for the fault. The process schema and associated points of data collection are represented in Figure 2.
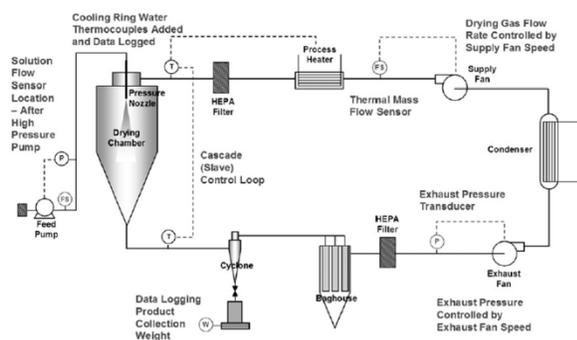
Figure 2. Spray-dryer flow diagram, [Garcia-Munoz S & Settell D, 2009].

This project serves as one of the most unifying projects because regardless of engineering discipline, the core descriptor of an engineer is the ability to think critically, and problem solve. Unlike other assignments where accuracy is determined by exact numerical values, this assignment is more open in terms of what is given full credit and not. One example would be after identifying that the greatest contributions to fault data were the variables "Outlet Temperature" and "Cyclone Differential Pressure" a potential engineering explanation could be but not limited to:

- Temperature sensor failure leading to fault in the cascade control loop around the spray dryer

- Clogging in the cyclone filter leading to a pressure build up and subsequent process temperature increase upstream

- Temperature sensor failure leading to unregulated temperature control, altering process conditions enough to change particle size, impacting cyclone performance

Digital Twin Development and Process Optimization

In the age of Industry 4.0, engineers have seen a boom in the leveraging of process modeling capabilities for applications such as design space analysis, sensitivity analysis, and process optimization. However, no catch all parameters exist that can make these process models universal for all systems. As a result, the development of digital twins is required for the robust consideration of these application spaces. In pharmaceutical manufacturing specifically such analyses aid in time to submission, reduced process uncertainty in a highly regulated market and other market specific benefits. As a result, this assignment asks students to consider the critical drug substance unit operation, crystallization. One key advancement in process modeling, particularly in the context of accessible education, was the development of the open-source, python-based software package, PharmaPy. Laid out in full detail, as a component of a complimentary course, by Laky D, et al. (2023) this crystallization assignment asks students to leverage the model libraries available in PharmaPy to progress through:

- Model Discrimination

- Parameter Estimation

Students then finalize the development of a system/species specific digitial twin which is then applied to single and multiple objective process optimization. Since students have previously been introduced to confidence interval calculations and error minimization in the first assignment, the learning curve for parameter estimation is reduced and allows for students to more fully engage with the process of model discrimination, and digital twin development without being a barrier to entry. Additionally, conducting this assignment through the usage of Jupyter notebooks reduces the computational learning curve for students that are beginners and novices in Python based coding [8]. An example of one of the process optimization prompts is illustrated in Figure 3, where students are asked to optimize a cooling temperature profile (linear and quadratic) to either minimize or maximize a predetermined set of critical quality attributes for drug substance manufacturing.
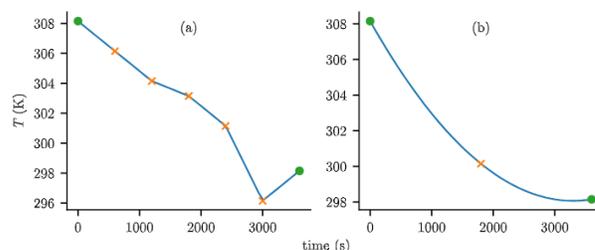
Figure 3. Examples of piecewise linear (a) and quadratic (b) temperature profiles. Internal points are equidistant decision variables marked orange 'x' symbols.

Machine Learning

The influence of artificial intelligence (AI) and machine learning (ML) are widespread, impacting many aspects of modern life, particularly in manufacturing. These technologies offer significant potential for growth, enabling advancements in decision-making processes and accelerating the pace at which those decisions are made. At the early stage of launching the Smart Manufacturing elective, AI and ML were still emerging, especially in terms of their representation in academic literature. Consequently, our machine learning-based assignment was intentionally designed to be straightforward. Students were tasked with exploring two distinct datasets: one related to regression (solubility

data) and another focused on classification (drug product quality data). Using these datasets, students developed machine learning models tailored to each scenario, providing a practical introduction to AI/ML applications in manufacturing.

Future iterations of this assignment will incorporate more advanced and challenging evaluations of AI and ML applications in the context of manufacturing. For example, a potential assignment could involve analyzing *in-situ* concentration trends as determined from raw analytical data using a machine learning model, and comparing the results to a chemometric based model such as PLS regression. A critical aspect of this evaluation is the ability to determine trade-off points, resource intensity, and overall payoffs when comparing the two choices.

This approach explores the ongoing trend of using Industry 4.0 tools to address persistent manufacturing challenges while fostering an understanding that no single tool is universally applicable. Such assignments aim to enhance students' ability to make informed, scientifically grounded decisions, a critical skill for all engineers working in manufacturing and industry-based roles.

Planning and Scheduling

Engineering process planning and scheduling is a long-established and critical aspect of process design and operation, essential for effective resource allocation and timing. While this skill is a common component of undergraduate engineering curricula (typically addressed in design courses), it is often taught with unbounded or flexible constraints. In contrast, industrial planning and scheduling problems are often highly constrained, requiring optimization procedures that can identify and explore this smaller feasible space. To bridge this gap, the penultimate assignment in this course involves a self-guided development of a knapsack problem [6]. Students are provided with specific constraints to follow, but the application and subject matter of their knapsack problem are entirely self-determined. This approach encourages students to critically evaluate real-world situations where a knapsack formulation would be valuable, such as equipment budgeting or resource allocation. As part of the assignment, students are required to construct a branch-and-bound tree for their problem, offering a visual representation of their solution process. Additionally, students are introduced to the concept of NP-completeness and other advanced algorithmic concepts, which are often absent from traditional undergraduate education but are increasingly relevant in modern industrial manufacturing.

Final Project

The planning and scheduling assignment serves as a capstone for the course prior to the final project. It emphasizes how every decision an engineer makes in manufacturing has upstream and downstream impacts. While engineers are often responsible for individual operations, decisions ranging from sensor placement to data handling, model building, and final planning and scheduling are interconnected. The final project is designed to reinforce these ideas by challenging students to think holistically about how Industry 4.0 advancements can positively influence the manufacturing environment. Students are asked to propose an engineering problem or application and develop a solution using at least two of the concepts introduced during the course. This open-ended approach fosters creativity, critical thinking, and a deeper understanding of how these tools can interact to address complex engineering challenges effectively.

Past project examples have included:

- PCA evaluation for identifying UV wavelength unique to a specific molecule coupled with PLSR for in-situ concentration modeling

- Machine learning evaluation of fitted kinetic parameters for pattern detection of parameter coupling

- Plantwide control schema coupled with sensor prioritization via scheduling decision making

- Batch versus continuous manufacturing evaluations following the development of a reaction with isolation process digital twin

- Fault detection from historic wind farm data and proposed process control schemas for switching between energy systems in the case of successful fault detection

Through these strategically designed assignments, students are equipped to think beyond isolated tasks, understanding how their decisions contribute to the broader manufacturing process and how moving forward they can leverage modern tools to improve industrial operations. In unique cases, this project gives non-traditional students the opportunity to apply smart manufacturing techniques to their real-life plant data and current vocational challenges to test the appropriate digital tools and innovate new workflows for their given industrial discipline.

ADJACENT COURSE DEVELOPMENT

Integration of the software tool PharmaPy into the Smart Manufacturing elective catalyzed student inquiries about process modeling outside of software encountered in undergraduate education like flowsheet packages. Encouraged by this and developed alongside an additional course offered at Purdue University through the school

of chemical engineering is CHE 553 - Pharmaceutical Process, Development and Design. This course focuses on similar process systems engineering challenges but dives deeper into pharmaceutical processes only and covers multiple unit operations, all using PharmaPy within Jupyter notebooks [8].

CONCLUSIONS

As digitalization increases in industry, the preparation of students for the new challenges of manufacturing in the Industry 4.0 era is paramount. We present six modules that address industrially relevant problems which can be solved with the implementation of smart manufacturing techniques. Such approaches do not exist within the inherited and established core curriculum across engineering, and in particular chemical engineering. The introduction of such modules in parallel with the curriculum and teaching philosophy presented in this manuscript have proven to successfully advance the industrial preparedness of undergraduate, graduate, and non-traditional students at Purdue University.

The Smart Manufacturing elective described in this manuscript can be readily developed by other universities. Manufacturing-based alumni can offer guest lectures to connect course concepts to practice. A Smart Manufacturing course is valuable for advanced undergraduate, graduate, and practitioner learning. Given the rapid pace of technology change, instructors should be prepared to evolve the course and assignments. Purdue University offers the Smart Manufacturing course as an elective every semester to 20-40 students.

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