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IoT Machinery Monitoring: An elective course to promote Industry 4.0 in the mechanical engineering curriculum

Juan C. Morales, PhD[1], Jesús M. Laboy, BSME[2]
[1]Universidad Ana G. Méndez-Recinto de Gurabo, Puerto Rico, jcmorales@uagm.edu
[2]VibrAnalysis, Inc, Puerto Rico, jesus.laboy@vibra-inc.com

Abstract*– This paper describes a new elective course that promotes Industry 4.0 skills in the mechanical engineering (ME) curriculum. The course is titled "IoT Machinery Monitoring" and was successfully offered in the Spring of 2022. It was created jointly with an engineer from industry who shares the interest of narrowing the gap between industry and academia. His company implements the Internet of Things (IoT) to conduct condition-based predictive maintenance in manufacturing plants in North, South, and Central America while monitoring remotely from their Puerto Rico office. The course includes an introduction to Industry 4.0, the importance of establishing a "culture of reliability", full coverage of Reliability Centered Maintenance concepts, accelerometers, digital signal processing theory, and machinery monitoring and diagnostics with vibration analysis. The paper includes the assessments and students' response from its first offering. It concludes with the details of an IoT-based laboratory setup that can simulate vibration faults so that students can practice machinery monitoring and diagnostics. The paper may be of interest to faculty who are considering options on how to implement Industry 4.0 in their ME programs.

Keywords-- IoT, Industry 4.0, condition-based-maintenance, predictive maintenance, reliability centered maintenance.

I. Introduction

The first author conceived the idea for the course during a presentation delivered by the second author. In essence, the 45-minute talk evolved into the 45-hour course presented here.

The talk was a case study on Industry 4.0. It took place on February 4, 2021, at the Trade and Learn Show sponsored by the Puerto Rico (PR) Mechanical Contractors Association (MCA). The MCA generously invited all the engineering students and faculty in PR to participate free of charge. The objective was to connect academia with industry to hopefully narrow the gap between them. This paper is evidence that the MCA's objective was fulfilled in at least one instance.

The major points of the talk are included in Table 1 and Figures 1 and 2. These summarize the evolution of VibrAnalysis (Table I), the benchmarking process that led the company to believe they could successfully adapt to Industry 4.0 (Fig. 1), and the overview of their IoT concept (Fig. 2).

The term "IoT" is the abbreviation for the Internet of Things, defined as "the concept of connecting any device to the internet and to other connected devices" [1].

The term "Industry 4.0" refers to the fourth industrial revolution, defined as a digital transformation that integrates "IoT, cloud computing and analytics, and artificial intelligence and machine learning into production facilities of manufacturers and throughout their operations" [2].

Industry and academia are both trying to adapt to Industry 4.0 to keep current with 21st century challenges. This paper presents one way in which it may be accomplished.

The paper contains the following sections: course outline, assessment of student learning, students' opinions, future hands-on experiences, discussion of Industry 4.0 in the curriculum, and conclusions.

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TABLE I
EVOLUTION OF VIBRANALYSIS, INC.

Year	Commentary
1994	*VibrAnalysis* started offering vibration analysis techniques for predictive maintenance. Technicians visited industry every month and collected vibration data which was then analyzed in their office to detect/identify problems before they occurred.
2006	*VibrAnalysis* changed its strategy from offering "nice-to-have technologies" to offering a new business model based on reliability. They offered tangible results such as, reduce maintenance costs, increase overall equipment effectiveness, reduce parts in inventory, increase production, and increase asset utilization (to avoid costly expansions). This level demanded a transformational "cultural change" in companies to a "culture of reliability". *VibrAnalysis* started promoting Reliability Centered Maintenance (RCM).
2016	The second author attended the Internet of Things (IoT) Solutions World Congress in Barcelona, Spain. Afterwards, he feared that *VibrAnalysis* would go bankrupt because industry giants like IBM and Microsoft were getting into predictive maintenance with IoT and machine learning to automate processes.
2016-2018	*VibrAnalysis* benchmarked with other companies to determine if they could implement IoT in predictive maintenance. It obviously required resolving Information Technology (IT) issues to handle the data, cloud storage space, hardware components, and software to integrate all the components into a coherent whole. However, they were also pleasantly surprised to discover that they were already accomplishing everything else with their ProActive Flow Model (Figure 1). *VibrAnalysis* hired IT consultants, software consultants, and partnered with National Instruments (Figure 2) to resolve the IoT implementation issues. As a result, instead of leading to bankruptcy, Industry 4.0 offered an opportunity to evolve and to grow their business.
2023	*VibrAnalysis* is now successfully providing IoT-based predictive maintenance services from their local office in Puerto Rico to companies in North, Central, and South America, and the Caribbean. In addition, *VibrAnalysis* is currently working with consultants to develop machine learning tools that will expand their diagnostics capabilities.

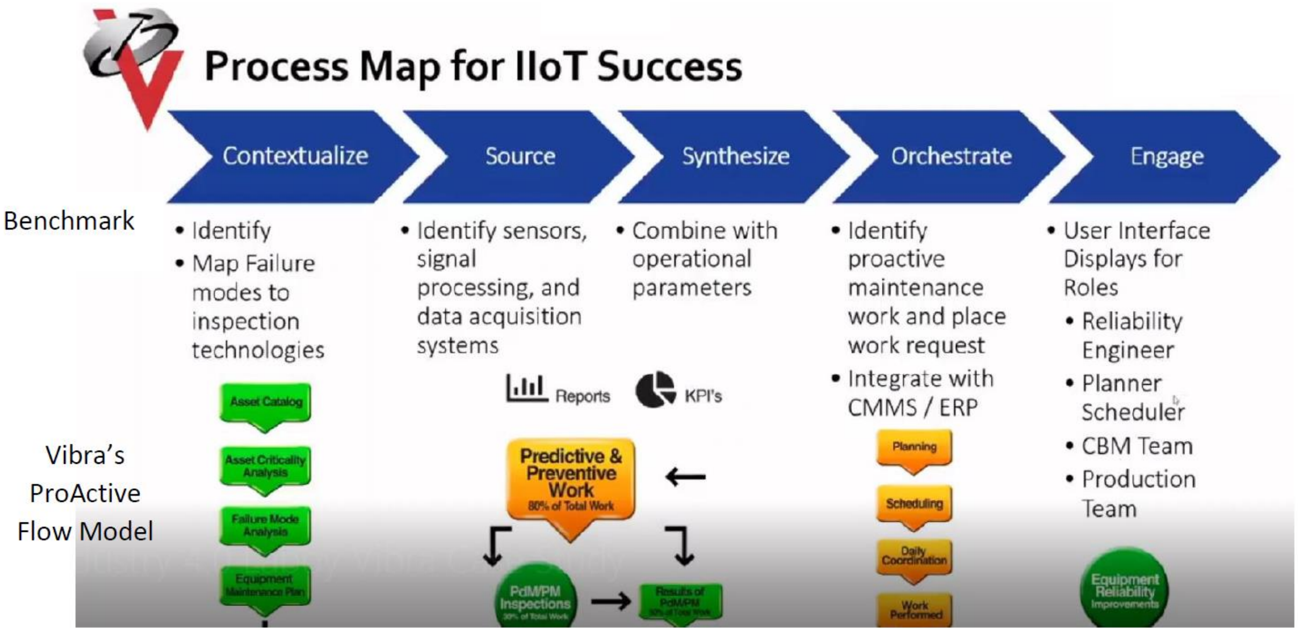


Fig. 1 Benchmark process map of how to implement IoT in predictive maintenance (top) and how it fit into the ProActive Flow model used by VibrAnalysis (bottom). With this exercise, VibrAnalysis concluded that they had everything in place to adapt to Industry 4.0 except for solving the details of implementing IoT technologies. Please refer to Table 1, 2016-2018 timeframe. (Credits: VibrAnalysis, Allied Reliability, and PTC).

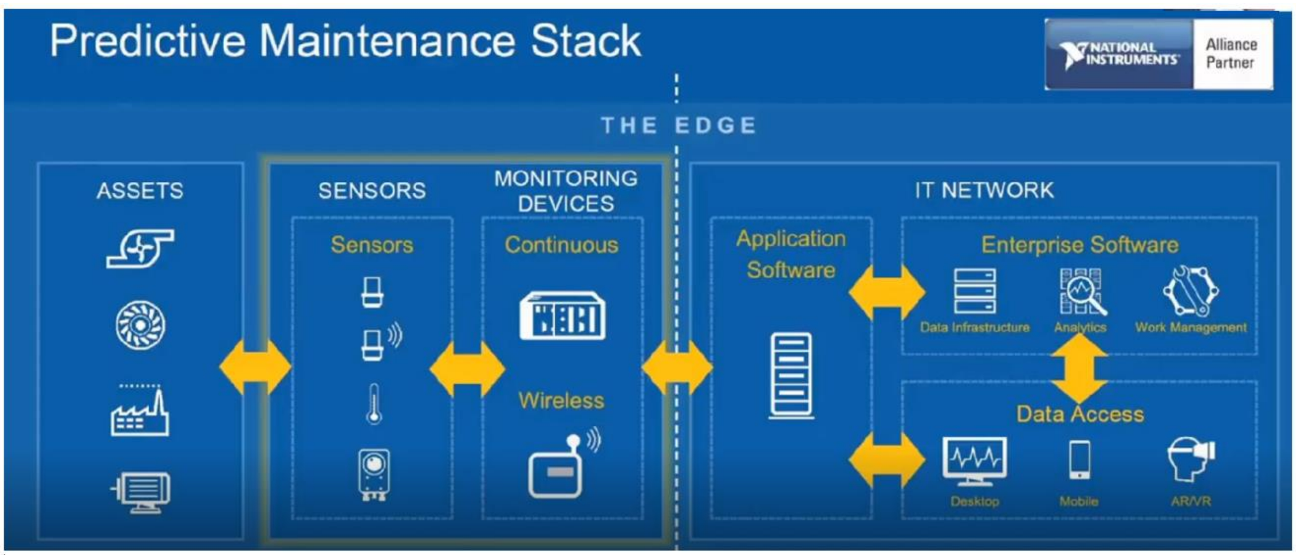


Fig. 2 Overview of the IoT concept used by VibrAnalysis. It shows how they resolved the details of implementing IoT technologies. VibrAnalysis partnered with National Instruments and incorporated its Predictive Maintenance Stack application. Proper "THE EDGE" devices must be coordinated with the IT group of each company and must accommodate a variety of sensors. VibrAnalysis also teamed with IT consultants and software developers to complete the transition to IoT-based predictive maintenance services. Please refer to Table 1, 2016-2018 timeframe. (Credits: VibrAnalysis, National Instruments)

II. Course Outline

The course outline is shown in Table II. The right column indicates the time dedicated to each of the four topics. The table also includes the references used to develop class materials.

The first topic (14% of the course) introduces Industry 4.0, basic maintenance definitions, and the concept of establishing a "culture of reliability" in a company.

The second topic (42% of the course) covers Reliability Centered Maintenance (RCM). RCM provides the foundation to create a "culture of reliability" and enables the attainment of the tangible results mentioned in Table I (see "2006" entry). If there is a phrase that captures the essence of RCM, it would probably be "know your assets". Knowledge of the assets is the prerequisite to establish efficient maintenance strategies, identify the sensors required to appropriately monitor the failure modes of the assets, and to reach good judgments regarding the asset's condition. The coverage of RCM in this course had an additional benefit. The ME curriculum lacked exposure in maintenance engineering concepts, even though many ME graduates accept maintenance-related and reliability-related job offers in Puerto Rico. This course now provides the opportunity to address this gap.

The third topic (20% of the course) covers accelerometers and the digital signal processing steps. These are required to obtain frequency spectra that are used in diagnostics.

The fourth topic (24% of the course) shows how to diagnose a condition using the periodic table of vibration faults (Fig. 3).

The table shows the four topics in the order that they are discussed in class (similar order to Fig. 1); however, they were conceived in reverse order. The main objective is topic IV, which may be thought of as training doctors that can monitor and diagnose the health of machine patients instead of human patients, while assisted by the IoT. But the analyst must first know about accelerometers and signal processing (Topic III) and the components and modes of failure of the asset (Topic II) that accelerometers can measure. RCM also provides the foundation to create a "culture of reliability" (Topic I). The expectation is that if a graduate does not find a "culture of reliability" in the workplace, that they will become the leaders who will help transform the company to a "culture of reliability".

TABLE II
OUTLINE OF THE COURSE IOT MACHINERY MONITORING

#	Topics	Hours (45 total)
I	**Introduction** *Vibra, Inc* case study. MCA video, Table I, Fig. 1, Fig. 2 Overview and basic concepts of maintenance engineering [3] Definitions of corrective, preventive, and predictive maintenance. [4] Introduction to the P-F curve [5] Transforming Morgan Foods to a culture of reliability. Video [6]	6 hr (14%)
II	**Reliability Centered Maintenance (RCM)** The seven basic questions of RCM: [5] 1. What are the functions (primary and secondary) and associated performance standards of the asset in its present operating context? Case study on not addressing "functions": Failure analysis of six 600-hp pumps that had broken 11 pump shafts in 8 months [7] 2. In what ways does the asset fail to fulfill its functions? Introduce the RCM Information Worksheet to compile asset information. 3. What causes each functional failure? (establish failure modes) Introduce ISO 14224 for asset decomposition and failure modes [4] 4. What are the failure effects when each failure mode occurs? Introduce ISO 17359 for failure mode and effect analysis [8] 5. What are the consequences of each failure mode? Criticality analysis [9] 6. Are there technically feasible proactive actions that can be taken to predict or prevent each failure? Details of the P-F curve [5] 7. What should be done if a suitable proactive task cannot be found?	19 hr (42%)
III	**Accelerometers and signal processing [10]** Fourier series and spectral analysis The Fast Fourier Transform (FFT) used to generate frequency spectra Low pass (anti-aliasing) filters Nyquist Theorem Analog to Digital (A/D) Converters Windowing Functions to reduce spectral leakage Averaging Accelerometer selection issues	9 hr (20%)
IV	**Diagnostics with vibration analysis** Typical failure modes diagnosed with vibration analysis [11] The vibration fault periodic table for diagnostics (Fig. 3) [12], [13], [14]	11 hr (24%)

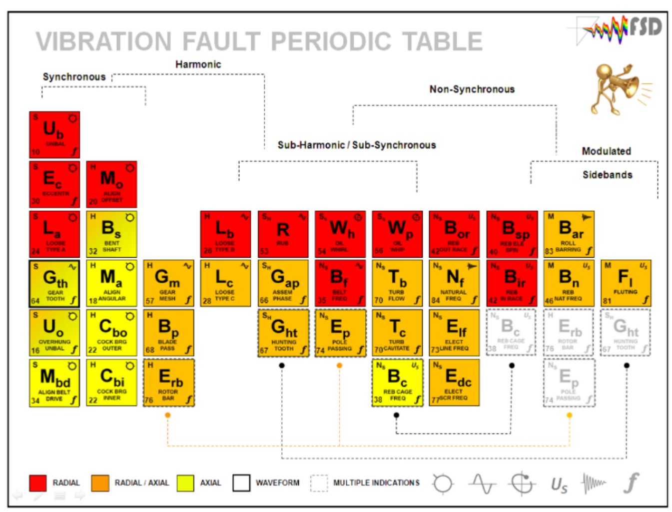
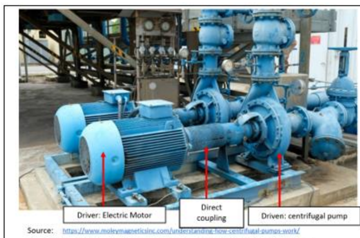


Fig. 3 The vibration fault periodic table created by Daniel Ambre [12] mentioned in Table II, Item IV. The diagnosis is based on an elimination process that narrows down the possibilities to one or two potential faults.

III. Assessment of Student Learning

Three assessments were conducted during the semester:

1. Assignment to provide comments on a P-F curve obtained from LinkedIn regarding its arrangement of corrective, predictive, and preventive maintenance regions within the P-F curve. Students had to rearrange the locations to satisfy ISO 14224 [4] definitions.
2. Assignment to create an RCM information worksheet for the Siemens SWT 2.3-101 2.3 MW wind turbine used in the Santa Isabel, Puerto Rico Wind Farm. This assignment was done in phases while the course progressed through "the seven questions of RCM" indicated in Table II. In addition, the authors organized a visit to the wind farm with the students to provide the real-world context (precautions were taken due to Covid-19). The students divided the wind turbine into its components and created an Excel spreadsheet that contained columns to identify each part, functions, functional failure, modes of failure, and failure effects.
3. Final exam with 18 questions. Figure 4 shows one of the exam questions.



a) How many uniaxial accelerometers would you specify?
b) Where would you place them? (use the figure or create a separate diagram)
c) If monitoring is conducted with IoT, what type of accelerometer installation would you recommend (adhesive, magnetic, screw)? Why?
d) If monitoring is conducted with a monthly route, what type of installation would you recommend (adhesive, magnetic, screw)? Why?
e) Suppose the pump impeller has 8 blades. In what frequency (in addition to 1xRPM) would you expect a peak in the frequency spectrum?
f) Explain in your own words how you would specify the alarm thresholds that would indicate a fault? Sketch a P-F diagram and specify the region in which you would conduct the study to specify the alarm thresholds.

Fig. 4 One of the 18 problems of the final exam. Statement: "You are interested in early detection of the maximum number of potential faults including unbalance, misalignment, bearing failures, impeller failure, cavitation, etc. Answer the following:".

IV. Students' Opinions

Eight students registered in the course (n=8). At the end of the course, they were asked six questions.

The first three questions were based on a Likert scale and the results are given in Table III.

The last three questions were open-ended and asked students to write what they liked best and least about the course and to offer any additional comments. The open-ended comments are included in Table IV.

The results shown in Tables III and IV of students' opinions provided a very clear assessment of the strengths and weaknesses of the new course. In summary, the course was very well received; however, students principally desired more hands-on experiences to practice with IoT technologies, predictive maintenance using vibration analysis, and RCM.

The next section (V) contains the future activities that are being organized to address the students' concerns regarding hands-on experiences.

TABLE III
STUDENTS' OPINIONS: LIKERT SCALE (N=8 STUDENTS)

#	Question (Likert scale is shown below) 5:Strongly Agree 4:Agree 3:Neutral 2:Disagree 1:Strongly Disagree	Average (5.0 max)
1	The course achieved its objective of narrowing down the gap between industry and academia.	4.63
2	I gained valuable knowledge regarding Reliability Centered Maintenance that I can apply in industry, including assisting in the transformation to a "culture of reliability".	4.63
3	I gained valuable knowledge regarding machinery condition monitoring that can be used as an excellent starting point to conduct predictive maintenance.	4.75

TABLE IV
STUDENTS' OPINIONS: WRITTEN COMMENTS (N=8 STUDENTS)

Theme	Comments
Liked BEST	-Everything because each area was important. But especially the approach of applying the knowledge in real-world circumstances. This is an excellent course that will help us a lot in industry. -Everything. The dynamic was excellent. Maintenance was what I was most interested in and to have a course in this area was perfect. -Reliability Centered Maintenance. -The trip to the wind turbine farm in Santa Isabel, PR. (2 comments) -RCM applications -Predictive maintenance -The focus on maintenance, and its importance in the daily life of an engineer.
Liked LEAST	-N/A (6 comments) -Perhaps add other predictive maintenance techniques in addition to vibrations, although I understand that there is a time limitation. -Not seeing an IoT system used for predictive maintenance.
ADDI-TIONAL comments	-Create a hands-on lab IoT lab for a real application. Do at least a simulation and create a report from a vibration analysis. -Have more courses in the area of maintenance. Consider opening a master's program in maintenance engineering or at least a minor. Add hypothetical cases in which students can put to use the learned material. -Nothing, the course was excellent. -Require vibrations as a prerequisite. -N/A (2 comments) -Very enriching course. -More related activities with industry.

V. Future Hands-on Experiences

Covid-19 prevented laboratory experiences from being developed and conducted in the Spring 2022 term (the course was taught remotely and there was no access to the university).

This section describes the lab setup that is being developed for the next offering of the course (Spring 2024).

The priority item is to configure an IoT setup to conduct machinery monitoring remotely. Figure 5 shows the components and the overall configuration of the IoT setup that is currently being assembled.

A comparison will reveal that Figure 5 is a simplified version of Fig. 2 which shows the IoT setup at VibrAnalysis.

The cost of the IoT setup is relatively inexpensive. For approximately $2,000, the company ERBESSD INSTRUMENTS, Inc. will include four wireless triaxial accelerometers, a gateway, 1 GB of cloud storage, an EI-Analytic account, and a DigivibeMX software license.

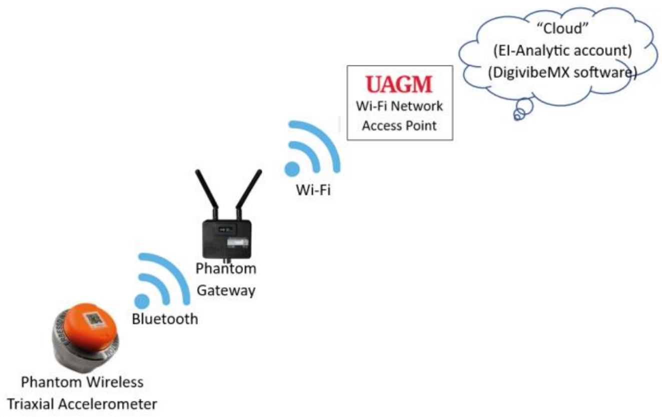


Fig. 5. IoT setup being assembled to remotely conduct machinery monitoring at UAGM. The Phantom wireless accelerometers communicate via Bluetooth with the Phantom Gateway which retransmits the signal via Wi-Fi to an access point of the university network. The data is then sent to the cloud via an internet connection where up to 1 GB of data can be analyzed on the EI-Analytic account with DigivibeMX software. (Credits: ERBESSD INSTRUMENTS).

The IoT setup will be mounted on a Machinery Fault Simulator by SpectraQuest (Fig. 6). The traditional accelerometers shown in the bearing blocks of Fig. 6 will be replaced by the wireless accelerometers of Fig. 5. The equipment comes with a variety of components (bearings, gears, etc.) that are damaged on purpose to simulate faults.

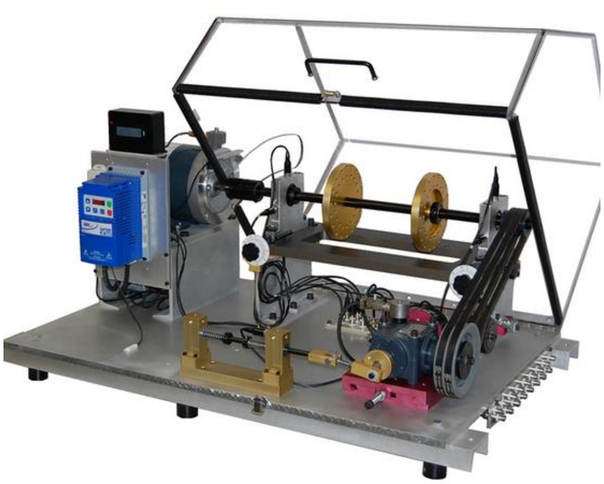


Fig. 6. Machinery Fault Simulator by SpectraQuest. This equipment can simulate typical faults such as imbalance and misalignment conditions. It also includes a variety of damaged components (damaged on purpose) such as bent shafts, ball bearings and gears that also simulate faults whose signatures can be detected by vibration analysis. (Credits: SpectraQuest)

The use of the Machinery Fault Simulator will allow students to practice diagnosing a wide variety of fault conditions that are readily detected by vibration analysis. It promises to be a very effective training device.

The simulator is located in the Controls and Vibrations laboratory which conveniently contains an access point to the university Wi-Fi network. The wireless triaxial accelerometers will be mounted on the bearing housings. The gateway will be mounted inside the laboratory. The proximity of all the components (wireless accelerometers, gateway, and access point) will ensure an excellent connection of the IoT setup that is shown in Fig. 5.

Table V includes a summary of all the hands-on activities that are being planned to address students' concerns.

TABLE V
ACTIVITIES THAT ARE BEING PLANNED OR CONDUCTED TO INCLUDE HANDS-ON EXPERIENCES

#	Activity
1	Buy the IoT setup from ERBESSD Instruments (see Fig. 5).
2	Mount the IoT setup on the Machinery Fault Simulator (Fig. 6).
3	Use the Machinery Fault Simulator to conduct IoT-based machinery monitoring and diagnostics (see Table II, items III and IV). It will be used both as a demonstrator and as a source of exercises for students to practice diagnostics.
4	Have students prepare an RCM information worksheet of the Machinery Fault Simulator (see Table II, item II). These worksheets list the functions, components, failure modes, and failure effects of the asset.
5	Buy an additional IoT setup that will be mounted on different machinery available at the university (pumps, air handlers, cooling towers, etc.). These assets will become a source of real-world projects. Include the preparation of RCM information worksheets on the selected assets.
6	Modify the syllabus of the required course MEEN 464 Mechanical Vibrations to include an introduction to condition monitoring and diagnostics using vibration analysis. The estimate is that 20% of the course will be altered to include the new material.
7	Evolve the required course MEEN 418 Experimental Methods to gradually start adopting an IoT-based data acquisition system (DAQ) in addition to PC-based DAQ. The objective is to start exposing students to IoT and Industry 4.0 technologies as early as possible.
8	Use the Machinery Fault Simulator (Fig. 6) as a source to conduct research projects at the undergraduate and graduate level.
9	The second author will visit the UAGM classrooms once per semester of the courses Mechanical Vibrations and IoT Machinery Monitoring to provide his real-world perspective.
10	The second author will provide internship opportunities in VibrAnalysis.
11	VibrAnalysis will train the first author and one other professor in ISO 18436-1 Category I Vibration Analysis [15]. This training will assist the faculty in calibrating the vibration-related courses in the curriculum.

VI. Discussion of Industry 4.0 In The Curriculum

The course is currently an elective. A simple way to increase its availability is to offer it every semester. In this manner, students who wish to enroll in the course would have the opportunity to do so.

If the enrollment is consistently high every semester, it would be a very good indicator that this elective should replace a required course in the curriculum. Which course is sacrificed would depend on the constituents of the program (students, faculty, alumni, and industry partners). A consultation should be conducted by surveying all the constituents and by holding meetings with them to discuss the survey data. This approach also satisfies ABET accreditation criteria.

Another way of introducing Industry 4.0 concepts in the ME curriculum is by including these concepts within existing courses, for example, evolving to IoT-based DAQ in the course MEEN 418 Experimental Methods and MEEN 464 Mechanical Vibrations, as mentioned in Table V. This approach would not alter the courses listed in the curriculum nor the total number of credits.

Finally, this course only addressed IoT technologies, which is just one element of Industry 4.0. A second course on Digital Twins and Machine Learning is in the planning stages.

The Computer Engineering department already offers a basic course on machine learning. On the positive side, the course does not address the design of new machine learning algorithms but rather the implementation of existing ones. This makes the course apt for mechanical engineering students who only wish to use machine learning as a tool.

On the negative side, the existing course does not teach the criteria to create data sets that can be used to train a machine learning algorithm. This is a concern. Real-world problems in mechanical engineering will require the creation of data for training the algorithm. Providing the knowledge to create training data is an issue that must be addressed if the course is to become truly useful. The course must also provide practice and feedback on creating data sets for training.

One alternative is to create a new course that just emphasizes "supervised machine learning" and the creation of appropriate data sets for training the algorithms. There are many applications where supervised learning is appropriate so the course would fill a gap. In other cases where unsupervised machine learning or deep learning is of interest to mechanical engineering, the gap could be filled with additional courses.

VII. Conclusions

This course effectively introduced Industry 4.0 concepts into the mechanical engineering curriculum. It will be even more effective when the IoT setup becomes operational.

In addition, it narrowed the gap between industry and academia by including three additional areas that were not in the curriculum. These provided the context for teaching Industry 4.0 technologies. These are:

1. To instill the importance of creating a "culture of reliability" and, if necessary, become a leader in the transformation of the company.
2. Reliability Centered Maintenance (RCM).
3. Machinery diagnostics with condition monitoring using vibration analysis.

These three areas are of interest to the student constituency in Puerto Rico. In other localities, perhaps the appropriate context to introduce Industry 4.0 concepts may be Smart Manufacturing. At any rate, adding context to the teaching of Industry 4.0 concepts seems to work very well.

The collaboration with an industry partner that has successfully adopted Industry 4.0 cannot be overstated. Nevertheless, in the case that an industry partner cannot be secured, this paper provides a detailed guideline to implement Industry 4.0 in the curriculum within the context of maintenance engineering.

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