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Contact us:

Philip D. Weinsier, Ed.D.

Editor-in-Chief
Bowling Green State University-Firelands
One University Drive
Huron, OH 44839
Office: (419) 372-0628
Email: philipw@bgsu.edu

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EDITORIAL OFFICE:

Philip Weinsier, EdD
Editor-in-Chief
Office: 419.372.0628
Email: philipw@bgsu.edu
Department of Applied Sciences
Bowling Green State University-Firelands
One University Drive
Huron, OH 44839

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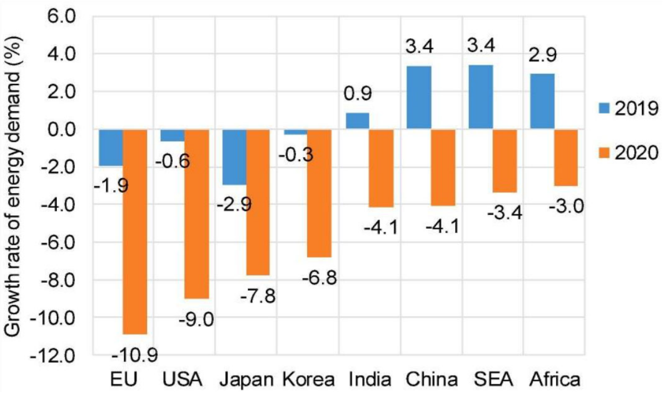
An International Look at Electricity Consumption during the COVID-19 Pandemic

Philip Weinsier, IJERI Manuscript Editor

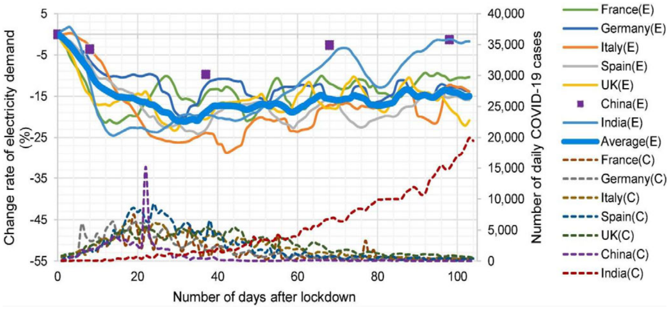
Something that I hadn't thought about: The change in energy consumption patterns during the COVID-19 pandemic. But now that I am thinking about it, I would not have guessed that the overall consumption of energy would have changed significantly—instead of people "going" to work, many, perhaps most worked from home. The end result, I would have guessed, would have been that energy usage declined at original places of employment and increased in homes, with the end result being a net zero overall change. And, as usual, I see that I would have been wrong! Now my question is, so what? Well, here's why maybe it did matter.

According to an NIH National Library of Medicine article by Jiang, Fan, & Klemes (*Appl. Energy*, 2021, *285*, 116441. https://doi.org/10.1016/j.apenergy.2021.116441), the year-by-year energy-related reduction of CO_2 emissions in 2020 significantly exceeded the reductions of any other emergency situation in history. During the COVID-19 lockdowns of the countries studied, CO_2 emissions decreased by 26% at their peaks. The problems associated with the lockdowns—i.e., the decline in energy demand and consumption—were associated with areas such as mobility, economic activity, construction, and manufacturing. By way of an example, at least 19 energy companies in the U.S. alone went bankrupt. The following figure (Figure 1b from this article) shows the projected changes in energy demand for a number of countries during 2019 and 2020.

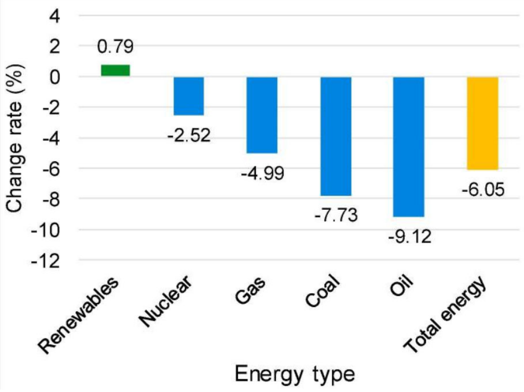


Short-term energy-demand declines were seen in the traditional fossil fuel industries, commercial, and industrial industries (though obviously not residential). The purchase of private cars, clothes and travel necessities declined as well; but, most notably, 56.3% of bus riders stopped using that form of mass transit.

This figure (Figure 3 from this article) shows the reduction of daily electricity demand (corrected for weather) during the lockdowns in select countries. The letter "E" denotes electricity, while the letter "C" denotes the number of cases.



This next figure (Figure 8a from the article) shows the projected change rates of primary energy demand in 2020 compared to 2019. [Data were retrieved from the International Energy Agency (IEA). Global Energy Review 2020: The impacts of the Covid-19 crisis on global energy demand and CO_2 emissions. Paris; 2020 <https://www.iea.org/reports/global-energy-review-2020.]



So after reading the featured article in this issue of TIIJ [p.5], I realize that, yes, energy consumption had a significant impact on many of the world's economies. In this featured study, the authors present a model for future domestic electricity consumption in pandemic scenarios, as well as machine learning or deep learning techniques that could be used to predict individual consumption per type of household or state. And since the EIA publishes energy demand surveys every four to five years, those data could be used to model residential consumption in every state, region, or climate zone within the U.S.

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RESIDENTIAL ELECTRICITY CONSUMPTION DURING THE COVID-19 PANDEMIC: A CASE STUDY

Manuel Mar, Purdue University; Eric Dietz, Purdue University

Abstract

The pandemic scenario caused by COVID-19 is an event that reminds the energy sector to study people's electricity consumption when staying most of their working hours at home. Residential electricity consumption can be studied to observe how energy loads and appliance usage have changed during the stay-at-home order weeks. In this current study, the authors analyzed household energy units, such as appliances and lighting systems. The data collection process was done through online surveys and publicly available data. Previous studies have successfully characterized residential electricity using surveys with stochastic models. The characterized electricity consumption data allow researchers to generate predictive models, make regressions, and understand the data. Therefore, data collection was not as costly as installing measuring instruments or smart meters. Behavioral characteristics of each participant will be presented here; additionally, the output of the analysis will be the estimated electricity consumption in kilowatt-hours (kWh). The authors examined how people evolved their loads during, before, and after the pandemic and results showed electricity consumption over time. This research can help us understand the change in electricity consumption of people who worked at home during the pandemic and generate energy indicators and costs, such as home office electricity costs in kWh/year. In addition to utilities, energy managers can benefit from clearly understanding domestic consumers during emergency scenarios such as pandemics.

Introduction

The COVID-19 pandemic affected all sectors of society such as manufacturing, information technology, and healthcare. Private and public institutions had to move their efforts to mitigate the pandemic effects, which generated a shift in their consumption habits. The energy sector was negatively affected; for instance, oil prices went down to historically low prices, reaching minus zero costs, which meant producers paid the traders to buy oil (Desjardins, 2020). Electricity and fuel load profiles changed for the biggest consumers: commercial, industrial, and residential. Globally, the electricity demand decreased between 2.5% and 4.5% in Q1 2020, not only because of COVID-19 but because the weather conditions were milder than in 2019 (International Energy Agency, 2020). This reduction happened because most people stopped going out, and activities such as office work, education, or shopping continued online. Additionally, the energy demand per country in 2020 was associated with the governments' containment measures. Limited restrictions produced a shift of 10% in Korea's and Japan's energy consumption; partial mandatory stay-at-home orders accounted for a 17% reduction in Europe, and total lockdowns averaged 25% to 30% in some cases (International Energy Agency, 2020).

In most U.S. states, people had to stay at home 6-8 weeks as part of the "stay at home order"; they could only go out for essential activities such as groceries or medical emergencies (U.S. News, 2020). This containment measure, referred to as lockdown or stay-at-home order, occurred between late March and early May. As a result of the containment measures and efforts to restrict people's mobility, the U.S Energy Information Administration (EIA) estimated that residential electricity usage per customer increased by 6% in April of 2020, compared to the previous five Aprils. On the other hand, the commercial and industrial sectors decreased by 10% and 9%, respectively (EIA, 2020).

Previous studies have been done on electricity consumer patterns (Chicco, 2012; Tsekouras, Hatziargyriou & Dialynas, 2007; Pan et al., 2017); however, researchers have not studied these patterns in depth and under diverse containment scenarios or work-from-home policies. During pandemic scenarios, most employees are requested to work from home for several weeks, which shifts electricity consumption drastically in urban areas, especially in the U.S, where most Americans' occupations occur in offices and buildings (U.S. Bureau of Labor Statistics, 2014). Most of the COVID-19 electricity impact analyses and studies have shown a general increase in residential demand (International Energy Agency, 2020; MISO, 2020). However, there is little information about the specific or granular demand, such as appliances, lighting usage delta, and demographic correlations. In other words, there are plenty of macro analyses but few granular consumer analyses.

In this current study, the authors analyzed historical data on household electricity consumption during the first ten months of 2020. The goal of the project was to describe how people changed electricity consumption over three different periods during 2020. People use diverse loads in a household, such as appliances, lighting systems, heating/cooling, and even generation of energy. Therefore, the authors expected to observe various highs and lows during the weeks of the stay-at-home order and the Fall of 2020. A quarantine can produce a significant shift in domestic electricity load; therefore, the authors hypothesized that there would be a strong correlation between the number of quarantine weeks and domestic electrical consumption. Another tentative assumption was that the electricity load would increase during lockdown in the residential sector since people do more home activities. The problem addressed by this study was providing an estimation of how the quarantine changed consumer behavior in residential clients. This work can help utilities with consumer profiling and in understanding people's electricity load behavior.

Methodology

The data analyzed for this research were collected from the Energy Information Administration (EIA) and surveys made in the Lafayette Metropolitan area in Indiana. Most of the survey respondents were workers and university students. They were asked about their appliance usage during 2020 and demographic data. After collecting and processing the data, a population summary was done with the behavior towards the usage of appliances at three different moments in 2020: pre-Covid or everyday conditions, stay-at-home order (Lockdown), and the Fall of 2020 when containment measures were relaxed. A comparison of three moments of the year was made in order to analyze trends and finally approximate with a load simulator how much more energy (in kWh) was used when restrictions for the pandemic started.

Stochastic Modeling for Characterization

Household electricity consumption has many variations since it is strongly tied to the number of people living in a dwelling and their lifestyle (Cagni, Carpaneto, Chicco & Napoli, 2004). Consequently, measuring or disaggregating the electric load of any dwelling is a complicated task requiring the use of several power meters in households. Electric companies measure total power usage; however, this is not informative enough to understand people's specific demands. A probabilistic analysis approach helps estimate the load power distributions at different dwellings without power meters. This analysis consists of asking survey questions of residential consumers; specifically, about their primary power appliances usage. Once usage data are collected, a stochastic analysis can characterize the load data in kWh (Carpaneto & Chicco, 2008; Sandwell, Chambon, Saraogi, Chabenat, Mazur, Ekins-Daukes & Nelson, 2016). This approach has been used previously in low-income countries where utilities need to quantify the aggregated demand from a given micro-population (Boait, Advani & Gammon, 2015). For instance, the following statements are questions that can be asked in each survey.

- The family unit (number of people, sex, age, activity, and frequency of presence at home)
- The characteristics of the houses (size, number of rooms)
- Electrical appliances (type, number, electrical data, and usage)

Carpaneto and Chicco (2008) demonstrated that gamma, normal, binomial, and log-normal are the most suitable distributions to fit the data with the actual load patterns. The survey used for this current study is included in Appendix 1 and was made based on the studies mentioned above. Figure 1 shows the load simulator algorithm, which requires as its primary input the number of devices of each participant household and weekly utilization; after that, a random process is executed to yield the final system load per month of each participant, a method described by Boait et al. (2015).

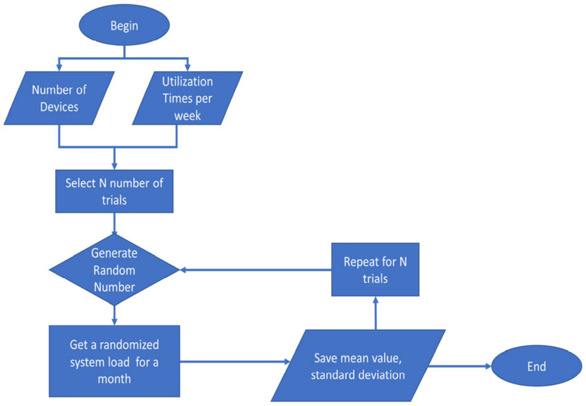


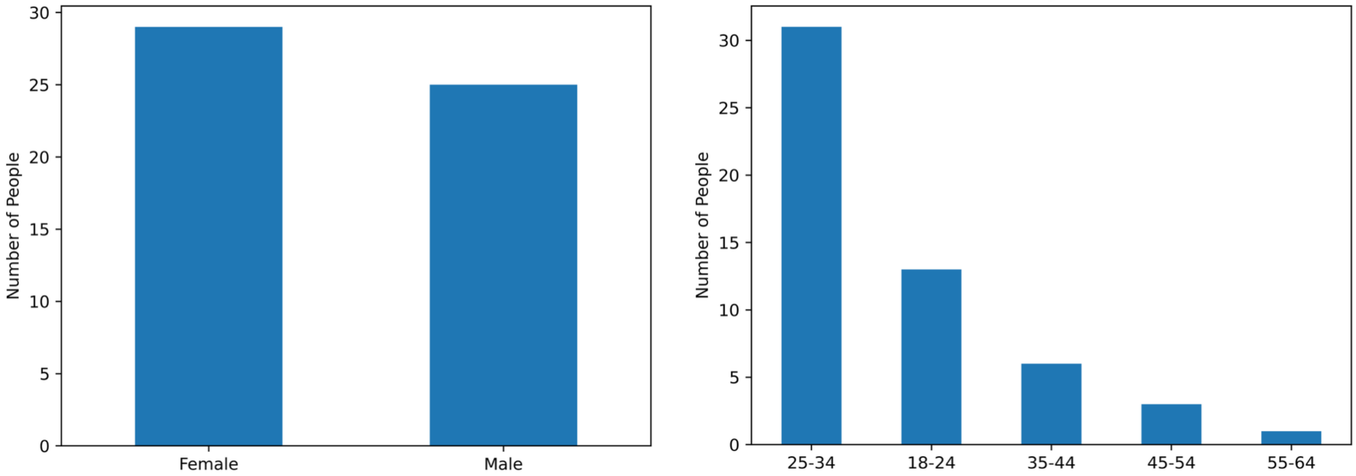
Figure 1. Load simulator algorithm.

Population Summary

Figure 2 shows the participants' demographics. Most participants lived in apartments with at least one roommate, whereas 41 out of 59 lived in apartments. Females were more responsive, having 54% of all answers, and the most common dwelling size was 700-1000 sq. ft., an average apartment size.

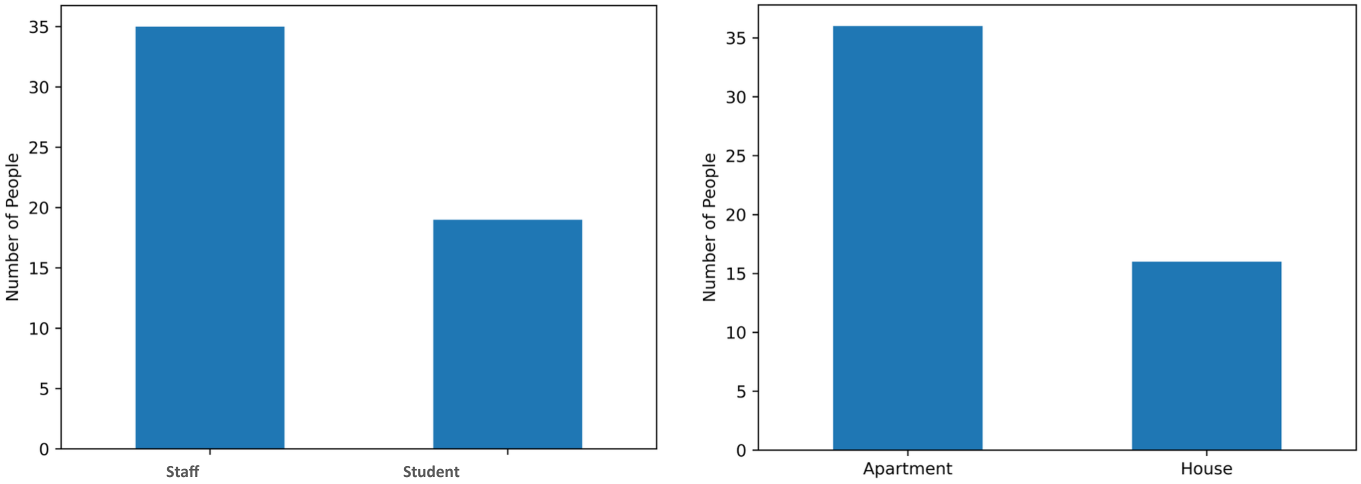
Change in Daily Activities

Participants were asked about their consumption behavior before the stay-at-home order in late March of 2020. In addition, they shared their daily on-campus activities at work from January to March and August to December. These activities were performed between Monday and Friday, or working days. As expected, most participants, who were university workers and students, had meetings, studied, did research, and the likes. Such activities needed electrical appliances; for example, during study sessions or research, people generally used computers or lab equipment such as laptops, microscopes, or oscilloscopes. Also, meetings or virtual sessions required projectors; eating at work probably required a microwave or a kitchen with electrical appliances. Figure 3 shows the change in daily activities before and after the lockdown; there is a reduction in activities noted at the workplace. For instance, activities such as teaching and eating were the most affected since they involved physical interaction, while research was the least affected since it did not require much contact. Usually, researchers require larger machines to work on-campus; therefore, research as activity showed more minor changes among all activities reported, as presented in Figure 3.



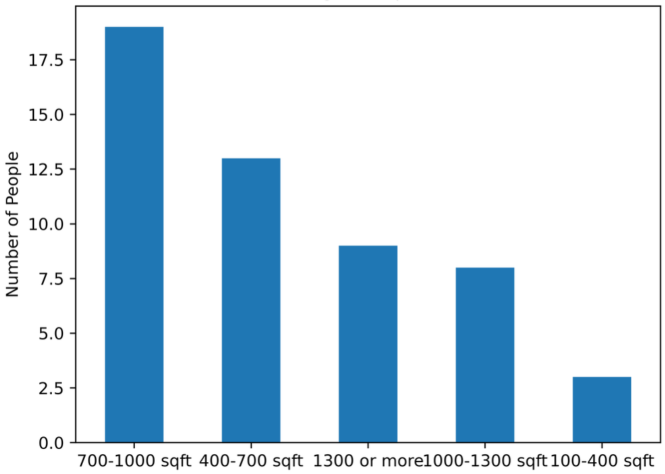
a) Gender distribution.

b) Age.



c) Position.

d) Type of housing.



e) Dwelling area in square feet.

Figure 2. Surveyed population demographics and summary.

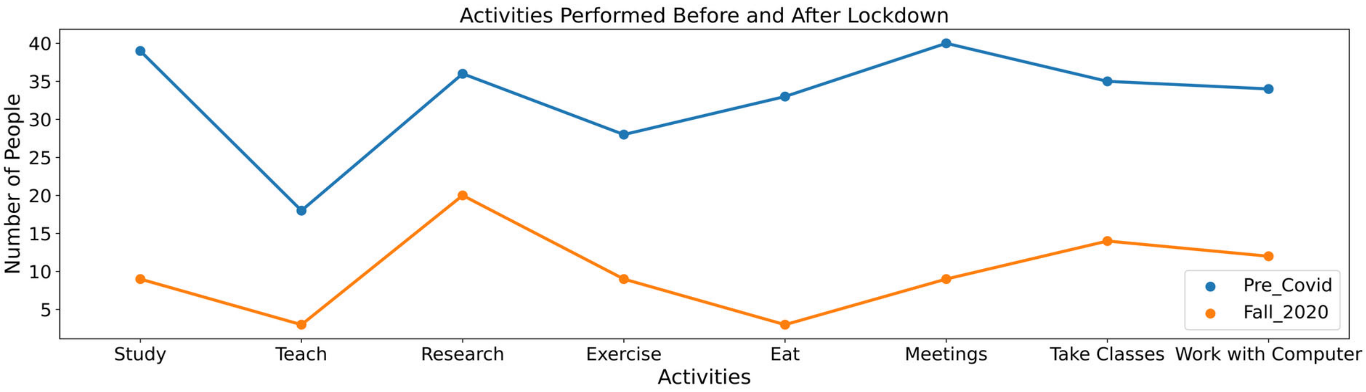


Figure 3. People's activities in the workplace; pre-post lockdown.

A pandemic scenario with lockdown reduced people's footprint in the workplace, where activities such as working with a computer were no longer performed. Taking classes became a remote task, with some exceptions. Figures 3 and 4 show how activities performed at the workplace were moved from work to households, consequently moving electric usage to apartments and houses. Figure 4 shows time spent at the workplace through 2020; in this section, participants answered questions about the range of hours spent on campus. Before the stay-at-home order, at least 72% of participants spent 5-15 hours on campus, Monday to Friday. On the other hand, lockdown made people work from home, moving more than 45% of full-time workers to perform activities in their household units (Bick, Blandin & Mertens, 2021). Although some essential activities were still done on-site, such as building or server maintenance, 34% of U.S jobs could be performed remotely (Dingel & Neiman, 2020).

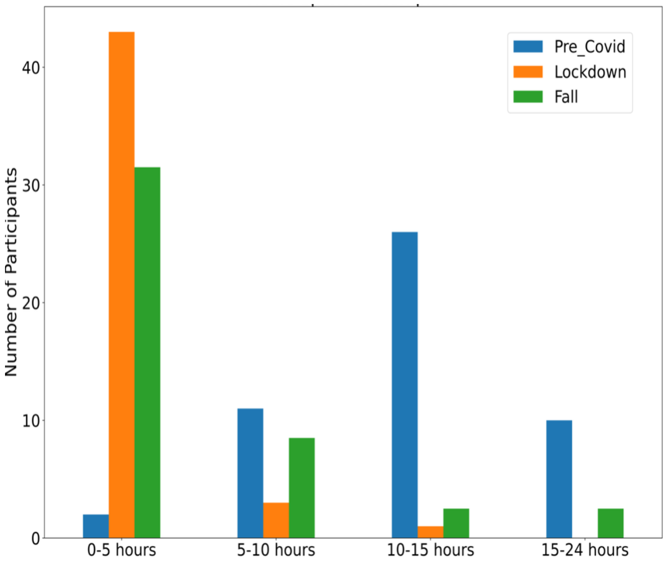


Figure 4. Time spent at the workplace.

Appliance Usage

Figure 5 shows the appliance usage change through 2020. The pre-Covid usage is indicated by red dots, showing usage under normal conditions before the pandemic. Meanwhile, the blue and green dots show the change in appliance usage percentage during stay-at-home orders and the Fall of 2020. Since workers and students stayed out of the workplace after March of 2020, home appliances were expected to increase; Figure 5 shows these changes for the most common appliances in a residential household. TV and chore appliances, like the dishwasher or vacuum cleaner, recorded among the most significant changes after March of 2020; the increase rate of these appliances was above 40%. Office appliances such as laptops and desktops also increased around 25% throughout the year. Appliance usage depended on the season; devices such as fans were primarily used in summer and water heaters in winter. Even though lockdown or stay-at-home orders ended in late May, usage habits persisted during the Fall of 2020, where more than 50% of all appliance usage increased by at least 15% as shown in Figure 5.

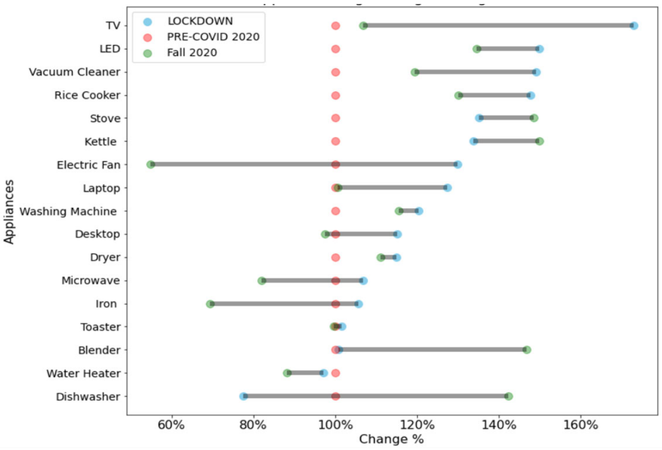


Figure 5. Appliance usage through 2020.

Correlation Analysis Between Appliances

The following figures show heatmaps that highlight the appliance usage that is more and less correlated with each other; red blocks represent a Pearson value "r" of one, and the intense blue is close to minus one, which means appliance usage would not be correlated. Participants were not asked why they used certain appliances more; however, a correlation analysis could better identify meaningful relationships between variables and show device interdependencies. For instance, workers who use laptops to work will have a router or modem turned on; also, when using the dishwasher, people are very likely to use the stove or oven.

Figure 6 shows the r values for the clothes dryer and the washing machine (r = 0.95), kettle and microwave (r = 0.55), or laptop and lights (r = 0.47). Nevertheless, there are opposing pairs, such as laptops and desktops (r = -0.34) or toasters with almost all the appliances. Similarly, Figures 7 and 8 show stay-at-home-order heatmaps. In this case, more pairs showed up. For instance, kettles were more associated with appliances such as blenders, irons, and microwaves (r = 0.55). On the other hand, the vacuum cleaner correlated with other appliances such as irons, stoves, washing machines, and clothes dryers. These changes could have increased because people spent more time at home and used more appliances, as previously shown in Figures 4 and 5.

Characterization of Surveyed Data into Daily Electricity Consumption

A stochastic load simulator (Sandwell et al., 2016) was used to estimate daily electricity consumption for each month of 2020, which was part of the participant's appliance usage results. Figure 9 shows a boxplot of the daily electricity consumption of participants at three moments: pre-Covid, stay-at-home order, and Fall, 2020. Figure 9 shows that the stay-at-home order showed the biggest kWh daily consumption close to the Fall, 2020, results, while pre-Covid daily home consumption was 15-20% less. Table 1 shows a statistical comparison between the self-made survey and the EIA 2015 survey for all residential consumers in the U.S. The EIA 2015 dataset validated the self-made survey results and allowed for the development of a predictive model using the more extensive data set. Yearly average residential electricity consumption before COVID was approximately 2000 kWh less than the stay-at-home order for Fall, 2020. Figure 8 shows that people used more appliances during the pandemic, while the EIA 2015 data show more kWh/year consumption. One reason was because participants were from all parts of the U.S., and the dwelling types varied more. In contrast with the self-made survey, the EIA survey interviewed many more houses, which increased the average kWh/year consumption. In the self-made survey, almost 70% of the dwellings were apartments.

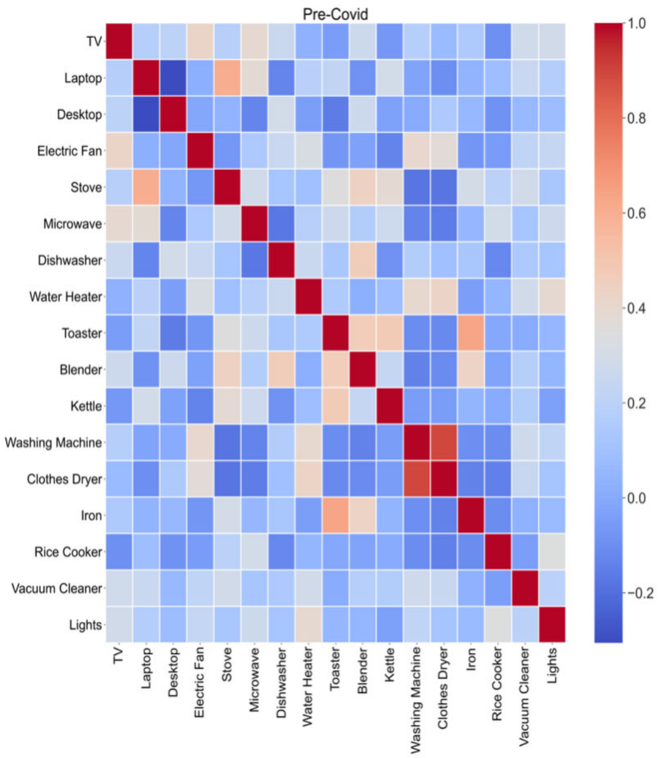


Figure 6. Appliance correlation matrix – pre-Covid.

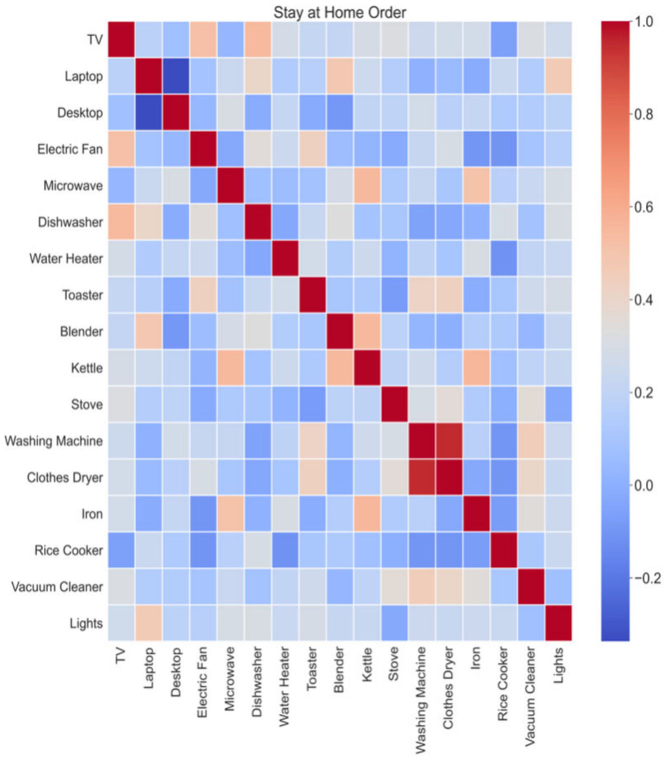


Figure 7. Appliance correlation matrix – Stay-at-Home order.

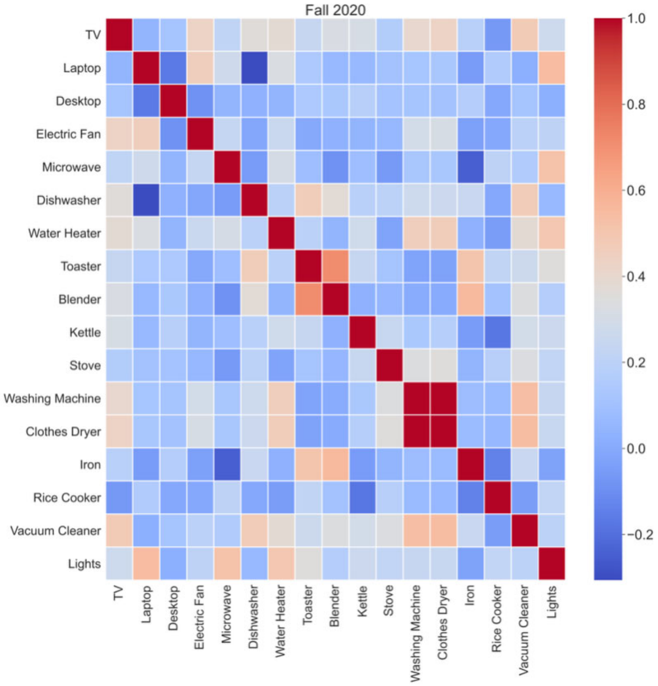


Figure 8. Appliance correlation matrix – Stay-at-Home order (Fall, 2020).

Conclusions and Future Work

Overall appliance usage increased 20-30% during the stay-at-home order and 10-15% during the Fall of 2020. One of the main reasons for this was the rapid shift from working at the office to working from home. As a result, people started using laptops as part of their work and extended their work hours from 7-8 hours to almost 10 hours daily. At the same time, laptop usage affected other appliances positively and negatively. For instance, vacuum cleaners and laptops were negatively correlated, meaning people who worked more on their computers used cleaning appliances less frequently. Even though office appliances reflected relatively minimal consumption, they accounted for hundreds of dollars, when adding consumption in a kWh/year period.

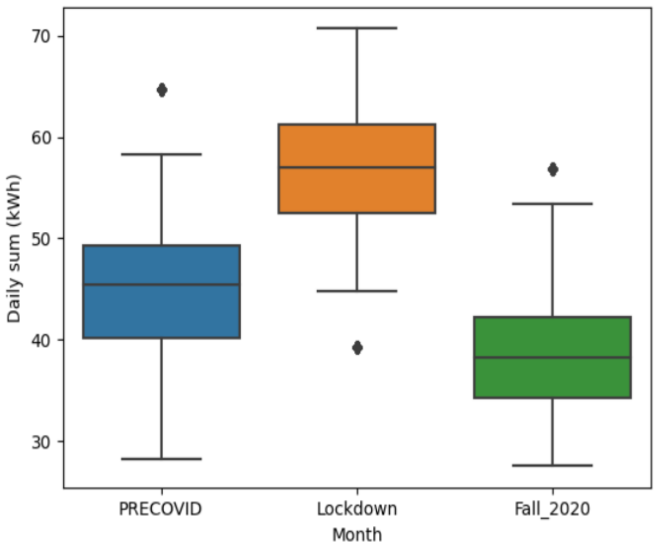


Figure 9. Daily kWh consumption at different moments in 2020.

Indeed, this study showed that appliance usage increased during the pandemic with the lockdown as a containment measure. For instance, pre-pandemic, a home-office worker would pay roughly $40; during the stay-at-home order, this amount went up to $55.71; and, in the Fall of 2020, it went down to $39. These numbers are relatively low compared to the average salary of a worker in the U.S. However, when multiplying this number by remote workers, it can add up to hundreds of thousands of dollars.

Finally, one can highlight that less usage of devices/appliances in the workplace might mean less maintenance and, consequently, fewer maintenance costs. This study could model future domestic electricity consumption in pandemic scenarios; and, machine learning or deep learning techniques could be used to predict individual consumption per type of household or state. In addition, the EIA publishes energy demand surveys every four to five years; therefore, those data could be used to model residential consumption in every state, region, or climate zone within the U.S.

Table 1. Comparison of survey data with the EIA survey of 2015.

	Survey			
	Pre-COVID	Stay-at-Home order	Fall 2020	EIA 2015 Survey
Annual Average Electricity Consumption (kWh)	8,468	10,031	10,659	11,055
Standard Deviation	4,620	4,892	5,661	7,039
Max	23,821	21,496	23,564	63,217
Min	3,049	3,209	2,528	1,058
Median	7,200	8,870	8,446	9,559
Observations	54	46	45	5,672

Acknowledgments

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Biographies

MANUEL MAR received his MSc in Computer Information Technology in 2021 from Purdue University and his BS in Energy Engineering from the University of Engineering and Technology in Peru. His research interests include energy technologies—such as smart grids, predictive analytics, and demand planning—electric vehicle security and simulation, and autonomous vehicle powertrain and planning. Mr. Mar may be reached at mmar@purdue.edu

J. ERIC DIETZ graduated from the Rose-Hulman Institute of Technology with a BS (1984) and MS (1986) in chemical engineering. He also holds a PhD (1994) in chemical engineering from Purdue University. Dr. Dietz's research interests include measurement and optimization of emergency response, homeland security and defense, energy security, and engaging veterans in higher education. As Director of the Purdue Military Research Institute, Dr. Dietz organizes faculty to involve current and former military in Purdue research. As Director of the Purdue Homeland Security Institute, Dr. Dietz organizes interdisciplinary homeland security research, including increasing the impact of Purdue research on society and organizing interdisciplinary projects within the university. Dr. Dietz may be reached at jedietz@purdue.edu

Appendix. Survey Questions

Q14 What is your gender?
- ☐ Male
- ☐ Female
- ☐ Other (specify) ______________________________

Q1 How old are you?
- ☐ 18-24
- ☐ 25-34
- ☐ 35-44
- ☐ 45-54
- ☐ 55-64
- ☐ 65 or over

Q39 Select your status at Purdue University
- ☐ Faculty
- ☐ Staff
- ☐ Graduate Student with RA or TA
- ☐ Graduate Student
- ☐ Undergraduate Student
- ☐ Other

Q108 Specify what is your position

____

Q3 What type of housing do you live in?
- ☐ House
- ☐ Apartment
- ☐ Other Specify ______________________________

Q7 How large is your living space in square feet? *You may find for this information in the webpage of your residence building.*
- ☐ 100-400 sqft
- ☐ 400-700 sqft
- ☐ 700-1000 sqft
- ☐ 1000-1300 sqft
- ☐ 1300 sqft or more

Q8 How many other people do you live with?
- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5 or more

Q16 Do you have smart meters? *A smart meter is an electronic device that records information such as consumption of electric energy, voltage levels, current, and power factor.*
- ☐ Yes
- ☐ No

Q76 Select the appliances you have at home
- ☐ TV
- ☐ Microwave
- ☐ Laptop
- ☐ Desktop
- ☐ Dishwasher
- ☐ Water Heater
- ☐ Stove
- ☐ Washing Machine
- ☐ Dryer
- ☐ Refrigerator
- ☐ Toaster
- ☐ Iron
- ☐ Blender
- ☐ Electric Fan
- ☐ Rice Cooker
- ☐ Vacuum Cleaner
- ☐ Electric Kettle
- ☐ Air Conditioner
- ☐ Heating

Q18 What type of lights do you have at home? Select all that apply
- ☐ Fluorescent
- ☐ LED Bulbs
- ☐ Tube Fluorescent
- ☐ Incandescent Lamp
- ☐ Other ______________________________________

Q63 When you set up your workspace in your OFFICE, what electric objects do you use? Select all that apply
- ☐ Laptop
- ☐ Desktop (CPU)
- ☐ 1 Monitor
- ☐ 2 Monitors
- ☐ 3 Monitors
- ☐ 3 or more monitors
- ☐ TV
- ☐ Lamp
- ☐ Spotlight
- ☐ Cellphone
- ☐ Wireless Mouse
- ☐ Wireless Headphones
- ☐ Wireless Keyboard
- ☐ Modem-Router
- ☐ Speakers
- ☐ Heater
- ☐ Humidifier
- ☐ Fan
- ☐ Other ______________________________________
- ☐ N/A

Q61 When you set up your workspace at HOME, what electric objects do you use? Select all that apply

☐ Laptop
☐ Desktop (CPU)
☐ 1 Monitor
☐ 2 Monitors
☐ 3 Monitors
☐ 3 or more monitors
☐ TV
☐ Lamp
☐ Spotlight
☐ Cellphone
☐ Wireless Mouse
☐ Wireless Headphones
☐ Wireless Keyboard
☐ Modem-Router
☐ Speakers
☐ Heater
☐ Humidifier
☐ Fan
☐ Other ________________________________

Q101 PRE COVID-19 Routine
Answer this information related to your routine during the semester previous COVID-19 stay at home order (before mid-March).

Q4 On average, how many hours did you spend at home during a typical weekday (Monday through Friday)? [Pre COVID-19]

☐ 0-5 hours
☐ 5-10 hours
☐ 10-15 hours
☐ 15-20 hours
☐ 21-24 hours

Q98 On average, how many hours did you spend at home during a typical day over the weekend (Saturday and Sunday)? [Pre COVID-19]

☐ 0-5 hours
☐ 5-10 hours
☐ 10-15 hours
☐ 15-20 hours
☐ 21-24 hours

Q43 On average, how long did you spend on campus during the academic year on a daily basis? [Pre COVID-19]

☐ 0
☐ 0-2
☐ 2-4
☐ 4-6
☐ 6-8
☐ 8-10
☐ 10-12
☐ 12-14
☐ 14-16
☐ 16-18
☐ 18-20
☐ 20-22
☐ 22-24

Q38 Which building did you spend most of your time in? [Pre COVID-19]

☐ KNOY
☐ EE
☐ WALC
☐ ME
☐ MSEE
☐ PHYS
☐ FRNY
☐ HAMP
☐ ARMS
☐ POTR
☐ HEAV
☐ STEW
☐ HIKS
☐ PMU
☐ MGL
☐ WANG
☐ COREC
☐ Other ________________________________

Q55 On average, how many hours did you spend in the building selected in the previous question on a daily basis? [Pre COVID-19]

☐ 0-3
☐ 3-6
☐ 6-9
☐ 9-12
☐ 12 or more

Q46 Before COVID-19, what activities did you used to partake in on Campus? [Pre COVID-19]

- ☐ Study
- ☐ Teach
- ☐ Research
- ☐ Exercise
- ☐ Eat
- ☐ Meetings
- ☐ Take Classes
- ☐ Work with a Computer
- ☐ Socialize
- ☐ Other ________________________________

Q80 On average, how long (hours) did you use the following appliance/device on a given weekday (Monday through Friday)? [Pre COVID-19]

- ☐ TV
- ☐ Laptop
- ☐ Desktop
- ☐ Electric Fan
- ☐ Stove

Q79 On average, how often (times) did you use the following appliance/device on a given weekday (Monday through Friday)? [Pre COVID-19]

- ☐ Microwave
- ☐ Dishwasher
- ☐ Water Heater
- ☐ Toaster
- ☐ Blender
- ☐ Electric Kettle

Q81 On average, how often (times) did you use the following appliance/device per WEEK? [Pre COVID-19]

- ☐ Washing Machine
- ☐ Dryer
- ☐ Iron
- ☐ Rice Cooker
- ☐ Vacuum Cleaner

Q82 On average, how long (hours) did you keep your lights on per day on a given weekday (Monday through Friday)? [Pre COVID-19]

- ☐ 0
- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5
- ☐ 6
- ☐ 7
- ☐ 8
- ☐ 9
- ☐ 10
- ☐ 11
- ☐ 12
- ☐ 13
- ☐ 14
- ☐ 15
- ☐ 16
- ☐ 17
- ☐ 18
- ☐ 19
- ☐ 20
- ☐ 21
- ☐ 22
- ☐ 23
- ☐ 24

Q102
Answer this section with information related to your routine during the stay at home order or Lockdown established in Indiana in mid-March until May 1st.

Q5 On average, how long (hours) did you spend at home during the Lockdown on a given weekday (Monday through Friday)?

- ☐ 0-5 hours
- ☐ 5-10 hours
- ☐ 10-15 hours
- ☐ 15-20 hours
- ☐ 21-24 hours

Q93 On average, how long (hours) did you spend on Campus on a daily basis? [LOCKDOWN]

- ☐ 0-2
- ☐ 2-4
- ☐ 4-6
- ☐ 6-8
- ☐ 8-10
- ☐ 10-12
- ☐ 12-14
- ☐ 14-16
- ☐ 16-18
- ☐ 18-20
- ☐ 20-22
- ☐ 22-24

Q83 On average, how long did you use the following appliance/device on a given weekday (Monday through Friday)?

- ☐ TV
- ☐ Laptop
- ☐ Desktop
- ☐ Electric Fan
- ☐ Stove

Q84 On average, how often (times) did you use the following appliance/device on a given weekday (Monday through Friday)?

- ☐ Microwave
- ☐ Dishwasher
- ☐ Water Heater
- ☐ Toaster
- ☐ Blender
- ☐ Electric Kettle

Q85 On average, how often (times) did you use the following appliance/device per WEEK?

- ☐ Washing Machine
- ☐ Dryer
- ☐ Iron
- ☐ Rice Cooker
- ☐ Vacuum Cleaner

Q86 On average, how long (hours) did you keep your lights on per day throughout the whole week?

- ☐ 0-2
- ☐ 2-4
- ☐ 4-6
- ☐ 6-8
- ☐ 8-10
- ☐ 10-12
- ☐ 12-14
- ☐ 14-16
- ☐ 16-18
- ☐ 18-24

Q103

Answer this section with information related to your routine during the semester of Fall 2020 until now.

Q91 On average, how many hours do you currently spend at home on a given weekday (Monday through Friday)? [FALL SEMESTER 2020]

- ☐ 0-5 hours
- ☐ 5-10 hours
- ☐ 10-15 hours
- ☐ 15-20 hours
- ☐ 21-24 hours

Q92 On average, how long (hours) do you spend on Campus on a daily basis during a given weekday (Monday through Friday)? [FALL SEMESTER 2020]

- ☐ 0-2
- ☐ 2-4
- ☐ 4-6
- ☐ 6-8
- ☐ 8-10
- ☐ 10-12
- ☐ 12-14
- ☐ 14-16
- ☐ 16-18
- ☐ 18-24

Q94 What activities do you partake in on Campus currently?

- ☐ Study
- ☐ Teach
- ☐ Research
- ☐ Exercise
- ☐ Eat
- ☐ Meetings
- ☐ Take Classes
- ☐ Play
- ☐ Work with a Computer
- ☐ Move around Campus
- ☐ Other ______________________________

Q87 On average, how long (hours) do you use the following appliance/device on a given weekday (Monday through Friday)? [FALL SEMESTER 2020]

- ☐ TV
- ☐ Laptop
- ☐ Desktop
- ☐ Electric Fan

Q88 On average, how often (times) do you use the following appliance/device on a given weekday (Monday through Friday)? [FALL SEMESTER 2020]

- ☐ Microwave
- ☐ Dishwasher
- ☐ Water Heater
- ☐ Toaster
- ☐ Blender
- ☐ Electric Kettle

Q89 On average, how often (times) do you use the following appliance/device per WEEK? [FALL SEMESTER 2020]

- ☐ Stove
- ☐ Washing Machine
- ☐ Dryer
- ☐ Iron
- ☐ Rice Cooker
- ☐ Vacuum Cleaner

Q90 On average, how long (hours) do you keep your lights on per day? [FALL SEMESTER 2020]

- ☐ 0-2
- ☐ 2-4
- ☐ 4-6
- ☐ 6-8
- ☐ 8-10
- ☐ 10-12
- ☐ 12-14
- ☐ 14-16
- ☐ 16-18

TEACHING DATA ACQUISITION THROUGH THE ARDUINO-DRIVEN HOME WEATHER STATION PROJECT

Sheryl Dutton, Old Dominion University; Kurt Galderisi, Old Dominion University; Murat Kuzlu, Old Dominion University;
Otilia Popescu, Old Dominion University; Vukica Jovanovic, Old Dominion University

Abstract

The main objective of this paper is to present one possible way to engage undergraduate students in designing a system that uses the Internet of Things (IoT) strategy for data acquisition and management. The MATLAB home weather station project presented here was developed by a team of students for the senior design course in the Electrical Engineering Technology undergraduate program at Old Dominion University (ODU). The main purpose of this project was for undergraduate students to learn how to create a localized, compact, and precise weather station. Utilizing various sensors, both homemade and sourced online, this weather station is capable of reading and displaying many useful weather details. Since a large variety of home weather stations are already available commercially, students started this project by investigating the existing designs and comparing the commercially available solutions. Then they started developing their own solutions, tailored to their own expectations for a weather station system.

In this paper, the authors also include the steps of the design process done by a team of undergraduate students who were focusing on the real-life aspects and were coming up with a new model of a home weather station. Following the steps of the project presented here, one would gain the tools to create, calibrate, and customize their own Arduino home weather station. This is an all-in-one, self-sustaining station that collects outside weather details from the area where the user needs localized weather data and transmits that data wirelessly over Bluetooth to the point where the user is located so they can collect and visualize the data from the comfort of their own home. The data are collected outdoors using various sensors connected to an Arduino UNO. Using a Bluetooth transmitter, the Arduino UNO wirelessly communicates sensor data to a receiver connected to the USB slot of an indoor computer. The computer runs a MATLAB program that takes the data received through the USB and graphically displays plots of the temperature, humidity, air pressure, precipitation, wind speed, wind direction, and cloud cover. With such a project, various teaching objectives can be accomplished, and students can learn about a broad variety of topics, including sensors, microcontrollers, communication systems, as well as data acquisition and processing.

Introduction

There are various commercially available solutions for home weather stations that can be easily integrated into home automation systems through the Internet of Things (IoT) technologies. They usually integrate humidity, temperature, and barometric pressure sensors (Bäfverfeldt, 2016; Mao, Paul, Yang & Li, 2018; Molnár, Kirešová, Vince, Kováč, Jacko, Bereš & Hrabovský, 2020). These integrated solutions typically focus on measuring temperature, relative humidity, and air pressure (Bäfverfeldt, 2016) once coupled with some form of data logging and data streaming. They provide a great resource for students to build on their understanding of cloud-based instrumentation. Students can also build skills related to coding and creating relationships among measured data and given streaming outputs (Caccamo, Calabrò, Cannuli & Magazù, 2016). Involvement in such projects is especially beneficial for undergraduate students who can learn more about IoT technology, which can be better understood through a hands-on project to which the students can easily relate (Molnár et al., 2020). Being engaged in designing a physical mockup of the system that can be used for a better understanding of the environmental parameters in their surroundings cost-effectively and flexibly can be done with the home weather project (Majumdar, 2018). Engaging more students in IoT-related hands-on projects, the authors of this current project also attempted to address the shortage problem of workforce capable of working on IoT projects that are highly needed in industry. The project showcased here represents the work done by a team of undergraduate students for their senior design project course in the Electrical Engineering Technology program at ODU.

The curriculum of the Electrical Engineering Technology (EET) program at Old Dominion University culminates in a senior design project that students must complete for graduation. This project is completed through a sequence of two courses: a 1-credit-hour course during the first senior semester in which students select a topic and make a project proposal, and a 3-credit-hour course in the second senior semester in which the project is completed. This second course is also an intensive writing course that requires students to submit a written report in which they must demonstrate their ability to write technical reports and incorporate technical references. The project ends with a live demo presentation of the project. The grade for the senior project course is calculated based on a rubric that includes technical implementation, writing, and presentation. The bulk of this paper was developed based on the senior project report prepared by a student team in the fall of 2021. A team of two students built this MATLAB home weather station project with the main goal of learning how to create a localized, compact, and precise weather station to allow individuals to appropriately prepare for the specific weather conditions in their area.

When watching the weather on the news, the information is given for a wide geographic area, usually the overall region. This information is not always pertinent to an exact location. If an individual keeps outside animals or equipment that require specific temperatures and humidity, and the generalized weather report from the news calls for conditions that should be favorable, but in that individual's exact location they are not, the individual could potentially lose valuable livestock or equipment. The Arduino home weather station project presented in this paper would provide accurate data such that the users can better understand specific local weather conditions (Bäfverfeldt, 2016).

The MATLAB home weather station is an all-in-one, self-sustaining station that collects outside weather details where the individual needs localized weather data and transmits that data wirelessly over Bluetooth. This way, the individual can collect and visualize the data from the comfort of their own home. The data are collected outdoors using various sensors connected to an Arduino UNO, an open-source microcontroller board based on a Microchip ATmega328P microcontroller developed by Arduino.cc—initially released in 2010 (Arduino, 2022; Blum, 2013). Using a Bluetooth transmitter, the Arduino UNO wirelessly communicates sensor data to a receiver connected to the USB slot of an indoor computer. The computer runs a MATLAB program that takes the data received through the USB and graphically displays plots of the temperature, humidity, air pressure, precipitation, wind speed, wind direction, and cloud cover.

The temperature data are presented in both degrees Fahrenheit and Celsius on individual line graphs. Humidity data are presented on a line graph in terms of relative humidity as a percentage. Air pressure data are presented in Pascals (Pa) on a line graph. Precipitation data are presented on a line graph in millimeters of water covering the water level sensor. Wind speed data are presented on a line graph in miles per hour (mph). Wind direction data are presented on a circular plot with the cardinal directions. Cloud cover data are presented on a line graph as a percentage, with 0% equated as dark/night and 100% meaning bright/clear skies.

Main Considerations

The design of the MATLAB home weather station included various sensors, an Arduino UNO, a Bluetooth dongle, a homemade anemometer, a homemade wind vane, a solar-powered power source, and the station itself, which included PVC pipe and a base of a plastic bin for containment and stability. The temperature, humidity, air pressure, and precipitation sensors were purchased online and were wired to the Arduino UNO. The students built the wind speed sensor using an anemometer with a stationary reed switch and a small magnet mounted to a spinning shaft that closes the sensor once every revolution. This way, the number of revolutions can be determined during a set amount of time and, in turn, the wind speed calculated. The wind direction sensor utilized a wind vane connected to a continuous single-turn potentiometer connected to a 5V source. Using analog-to-digital conversion, the value read from the potentiometer could then be converted to degrees of revolution from which the wind direction could be derived. The cloud cover sensor used a photoresistor that decreased resistance as bright light shone on it. The voltage read on this resistor using an ADC conversion can be attributed to a 0-1023 digital value. This could then be mapped in Arduino to a scale of 0-100 in order to display brightness as a percentage. Figure 1 shows the different parts of the MATLAB home weather station setup: each of the four arms, the sensors that were included, and schematics of how each sensor connected to the Arduino UNO.

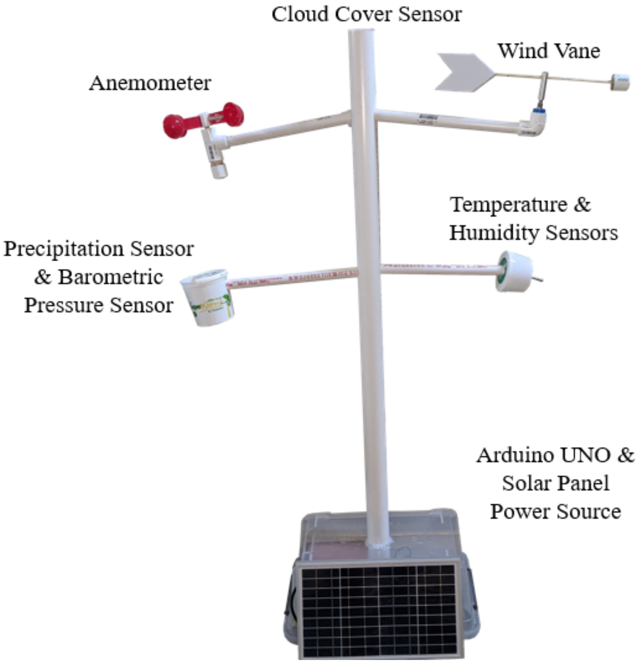

Figure 1. MATLAB home weather station physical setup.

Wireless Communication via Bluetooth Construction Guide

This section of the design involved the USB Bluetooth dongle 4.0 and the HC-05 wireless Bluetooth RF transceiver, with the aim of getting the PC to communicate wirelessly with the Arduino UNO via the HC-05 over Bluetooth. First, the Bluetooth dongle 4.0 was inserted into a USB slot on a PC with Windows 10 installed. Once the program automatically installed all necessary drivers, all of the available Bluetooth devices should appear. Next, the Bluetooth HC-05 was chosen, and a password of "1234" was used to connect. The Bluetooth dongle assigned itself to a serial COM port at which the data transmitted from the HC-05 could be found. To connect the HC-05 to the Arduino UNO, the Vcc pin was connected to 5V, the ground pin was connected to the ground pin, and the Rx data pin on the

HC-05 was connected to pin D1 on the Arduino UNO. Note that the Tx pin on the HC-05 was not used, as no data were being sent to the Arduino UNO. Figure 2 shows how the HC-05 was connected to the Arduino UNO.

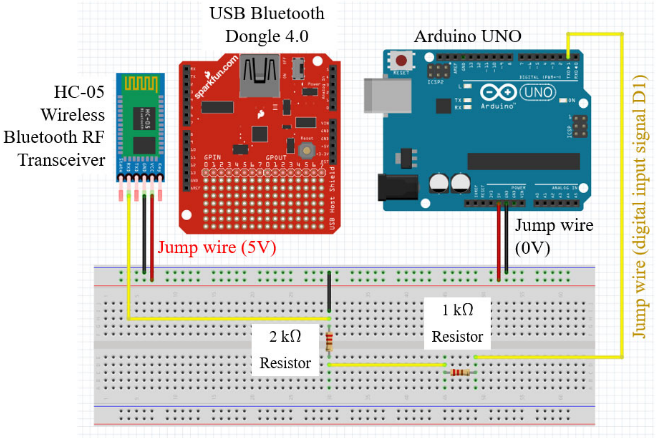

Figure 2. HC-05 and Arduino UNO diagram.

Outdoor Temperature Including Wind Chill Guide

This section of the design involved the DS18B20 temperature sensor and the Arduino UNO. The goal of this section was to get the DS18B20 temperature sensor connected to the Arduino UNO and to test the sensor for accuracy. First, the sensor was connected to the Arduino UNO by connecting a yellow data wire to digital pin 13, a red wire to 5V, and a black wire to ground. Next, a simple test code (see Appendix D) was inputted into the Arduino program to display data read from the sensor. The serial monitor should display temperature in degrees Fahrenheit and degrees Celsius. Accuracy was tested by comparing the data to a known good thermometer. Figure 3 shows how the DS18B20 was connected to the Arduino UNO.

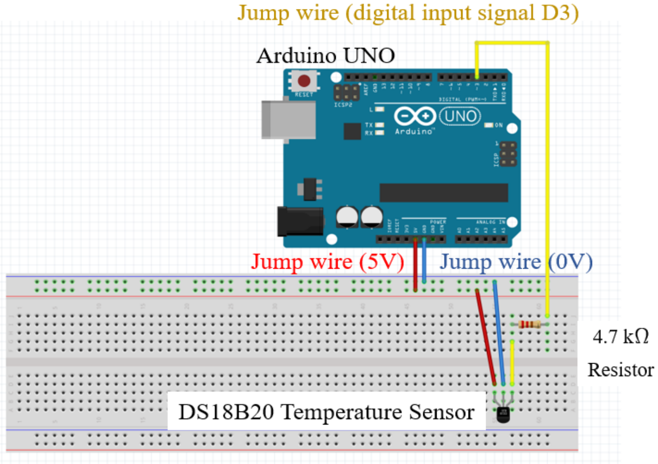

Figure 3. DS18B20 temp and Arduino UNO diagram.

Outdoor Temperature and Humidity Guide

This section of the design involved the DHT22 digital temperature and humidity sensor and the Arduino UNO. The goal of this section was to get the DHT22 temperature and humidity sensor connected to the Arduino UNO and to test the sensor for accuracy. First, the sensor was connected to the Arduino UNO by connecting the ground pin of the DHT22 to ground, the VCC to 5V, and the middle "signal" pin to digital pin 12 on the UNO. Next, a simple test code (see Appendix C) was inputted into the Arduino program to display data read from the sensor. Accuracy was tested by comparing the results with a known good thermometer and hygrometer. Figure 4 shows how the DHT22 connected to the Arduino UNO.

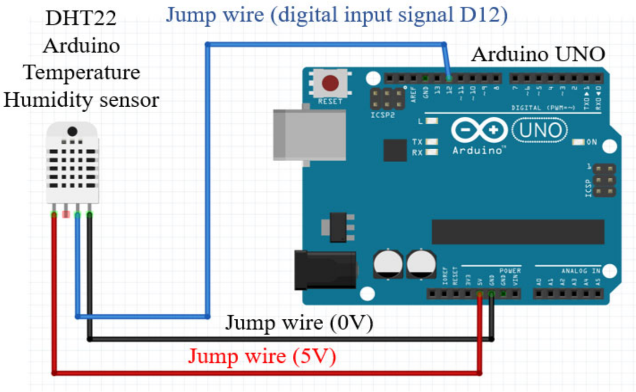

Figure 4. DHT22 temp & humidity and Arduino UNO diagram.

Precipitation Sensor Guide

This section of the design involved the water depth sensor and the Arduino UNO. The goal of this section was to get the water depth sensor connected to the Arduino UNO and to test the sensor for accuracy. The water depth sensor functions by treating water as a variable resistor; the higher the water level, the more energy flows, and the sensor outputs a higher voltage to then be converted using ADC. The water level could be determined and graphed by performing the ADC conversion on the values viewed on the serial monitor from pin A3. This was done by first noting the initial values viewed from the serial monitor; these initial values will be between 0 and 1023, increasing with depth. To find the ADC values for each increment of 5mm, the ADC values at each increment of 5mm were read and then the converted values on the serial monitor were displayed as the sensor was placed deeper in the water. The ADC values at these increments could be used to make an else-if loop in the Arduino program to display depth in mm. During construction, the sensor was first marked in increments of 5mm with a waterproof marker. Figure 5 shows that the water depth sensor was connected to the Arduino UNO by connecting the positive terminal to 5V, the negative terminal to ground (0V), and the "S" terminal to analog pin A3 on the UNO.

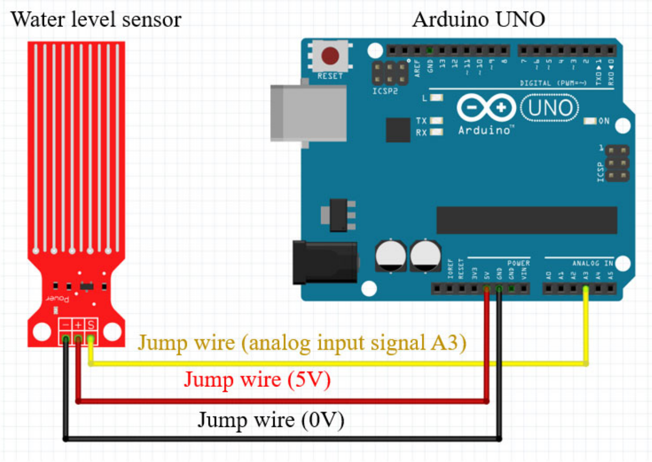

Figure 5. Rain sensor and Arduino UNO diagram.

A simple test code was inputted into the Arduino program to display data read from the sensor as follows:

```
//Note this code works for finding average ADC values and
need to be recorded to create depth ranges
int DepthValue; //create integer storage for ADC values
void setup()
{
//Begin serial communication
 Serial.begin(9600);
}
void loop()
{
 DepthValue = analogRead(A3); //read data from analog
pin and store it to value variable
 Serial.println(DepthValue); //display the ADC value
 delay(4000); //long delay to observe values at depth incre-
ments
 getDepth(); //create this once average ADC is observed
and subroutine written
}
//subroutine created to display depth in millimeters from
average ADC values at that depth
void getDepth()
{
 if (DepthValue<=300){ //always empty below this ADC
value
  Serial.print("00");
 }
 else if (DepthValue>300 && DepthValue<=350){
  Serial.print("05");
 }
 else if (DepthValue>351 && DepthValue<=400){
  Serial.print("10");
 }
 else if (DepthValue>401 && DepthValue<=450){
  Serial.print("15");
 }
else if (DepthValue>451 && DepthValue<=500){
 Serial.print("20");
}
else if (DepthValue>501 && DepthValue<=550){
 Serial.print("25");
}
else if (DepthValue>551 && DepthValue<=600){
 Serial.print("30");
}
else if (DepthValue>601 && DepthValue<=650){
 Serial.print("35");
}
else if (DepthValue>651){ //always full at this ADC value
 Serial.print("40");
```

Air Pressure Sensor Guide

This section of the design involved the BMP180 GY-68 digital barometric pressure sensor and the Arduino UNO. The goal of this section was to get the BPM180 barometric pressure sensor connected to the Arduino UNO and to test the sensor for accuracy. First, the sensor was connected to the Arduino UNO by connecting Vin on the BMP180 to 3.3V on the UNO, Gnd to ground, SCL to A5, and SDA to A4. This sensor needed to be connected at 3.3V instead of the typical 5V, as the sensor would overload at 5V. Next, a simple test code (see Appendix A) was inputted into the Arduino program to display data read from the sensor. Accuracy was tested by comparing the results with a known good barometer. Figure 6 shows how the BMP180 was connected to the Arduino UNO.

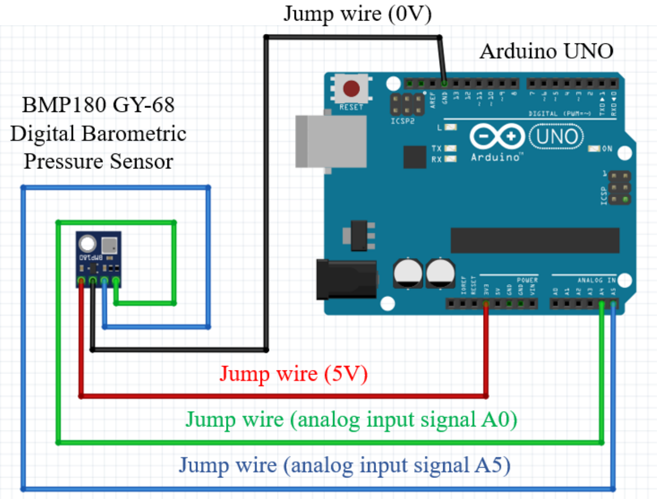

Figure 6. BMP180 air pressure and Arduino UNO diagram.

Cloud Cover Sensor Guide

This section of the design involved the photoresistor photo light-sensitive resistor and the Arduino UNO. The goal of this section was to get the photoresistor connected to the Arduino UNO. First, the sensor was connected to the Arduino UNO by connecting the photoresistor with one lead connected to the ground and the other lead connected to a 10k-ohm resistor, which was then connected to 5V. At the junction of the 10k-ohm resistor and the photoresistor, a lead was connected to pin A3 of the Arduino UNO. A simple test code (see Appendix B) verified and tested the sensitivity of the photo light-sensitive resistor. Figure 7 shows how the photoresistor was connected to the Arduino UNO.

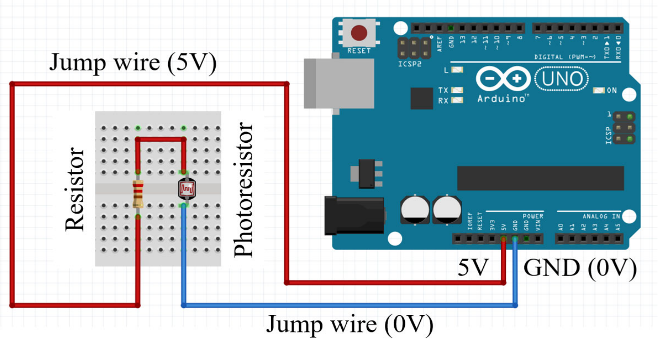

Figure 7. Photoresistor and Arduino UNO diagram.

Wind Direction Potentiometer Guide

This section of the design involved the 20k-ohm potentiometer and the Arduino UNO. The goal of this section was to get the potentiometer connected to the Arduino UNO. This sensor works by performing an analog read on pin A0 of the UNO in order to generate a value of 0-1023, based on the position of a single turn of the potentiometer. This value can then be "mapped" to correlate to a direction value of 0 to 360 degrees, corresponding to the eight cardinal directions (N, NE, NW, S, SW, SE, E, and W) when processed in an else-if subroutine in the Arduino programming. To calibrate, a known good compass was used to determine the true North. The test program (see Appendix F) could then be run to find where the ADC conversion resulted in the values 1023, 0, or 1, followed by a marking of the potentiometer where these values represented the North values; the assembled device then needed to be placed in this direction when installed. During construction, the sensor was first connected to the Arduino UNO by connecting a red lead to the CW pin on the potentiometer and then to 5V. Next, a black lead was connected to the CCW pin and then to ground. Then, a yellow lead was connected to the center pin, which was itself connected to analog pin A0 on the Arduino UNO. Figure 8 shows how the potentiometer was connected to the Arduino UNO.

Wind Vane Construction Guide

Once the potentiometer is connected to the Arduino UNO, the rest of the wind vane needs to be constructed. This section of construction involved a PVC end cap, a ½-inch, 90-degree L-shaped PVC connector, a ⅜-inch wooden dowel, a metal washer, wind vane tails cut out from a Sterlite bin lid, an aluminum spacer, and the potentiometer. Three long 22 AWG wires were measured and cut to reach the Arduino UNO at the base of the station. These wires were then soldered to the potentiometer contacts to ensure a stable connection. Next, a one-foot length of the ½-inch PVC pipe was connected to the PVC L-shaped connector, which was then connected to the main 1-½-inch PVC vertical of the station. The potentiometer wires were fed through the elbow, the ½-inch pipe, and then down the center pipe. The vane consisted of an aluminum spacer with an inner diameter that fit snugly to the turnscrew of the potentiometer. A 3/16-inch hole was drilled through the top of the spacer, which allowed a one-foot length, 3/16-inch diameter wooden dowel to be pressed through.

Two wind vane tails were cut from a Sterlite bin lid and hot glued on either side of one end of the wooden dowel. On the other end of the dowel, a nose weight was made from a PVC end cap and metal washer glued together. Because the wind vane works most efficiently if properly balanced, the home weather station should be installed on a flat, level surface. If the vane tilts to one side, the dowel can be pushed more to one side so that it stands up without tilting. The wind vane will only measure properly if first aligned to true North; to do this, ensure that the station is installed with the marked line of the potentiometer facing true North. Figure 9 shows a photo of the completed wind vane.

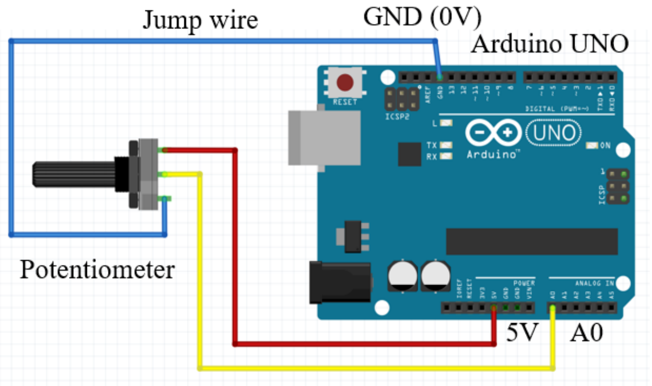

Figure 8. Potentiometer and Arduino UNO diagram.

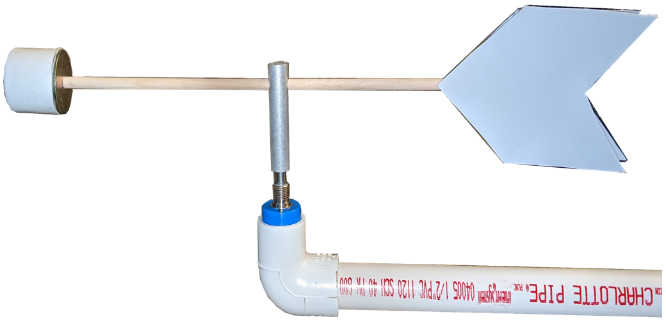

Figure 9. Photo of completed wind vane.

Wind Speed Guide

This section of construction involved a reed switch, magnet, two 47-ohm resistors, and the Arduino UNO. The goal of this section was to get the reed switch, magnet, and 47-ohm resistors connected to the Arduino UNO. This sensor works by creating a closed loop via the reed switch and the magnet each time the anemometer cups make a revolution about the wooden dowel. Each time the magnet passes the normally open reed switch, the switch closes, completing the circuit and allowing the Arduino UNO to see one revolution. In order to calculate the wind speed from this information, calculations on the spinning radius, circumference, and revolutions per hour are needed. The assembled anemometer had a spinning radius of four inches. This gives a spinning circumference of 2.093 feet can be determined using Equation 1:

$$\text{Circumference } = 2\pi r = (2)(\pi)(4) = 25.14in/12 = 2.093ft \qquad (1)$$

When exposed to a 1 mph wind, the anemometer should turn 2522 revolutions per hour. This is calculated (see Equation 2) by dividing the number of feet in a mile (5280) by the circumference in feet (2.093).

$$\frac{\text{5280 feet per mile}}{\text{2.093 feet}} = \text{2522 revolutions per hour} \qquad (2)$$

Equation 3 can be used to reduce this value into seconds per revolution by dividing the number of seconds in an hour (3600) by the revolutions per hour (2522). This results in a seconds-per-revolution value of 1.427.

$$\frac{\text{3600 seconds per hour}}{\text{2522 revolutions per hour}} = \text{1.427 seconds per revolution} \qquad (3)$$

These values were used in the programming to correctly calculate wind speed. Equation 4 can be used when creating the code:

$$V = P(\text{seconds per revolution}/T) \qquad (4)$$

where, V equals velocity in mph, P equals pulses sensed by the Arduino interrupt, and T equals the time period of the sampling.

Equation 4 was sourced from the spec sheet of a popular anemometer from Davis Instruments (see Appendix M). Because this value is only truly accurate in a frictionless environment, a calibration was needed to adjust the seconds-per-revolution value to that of an accurate and known store-bought anemometer. This was done by comparing the wind speed of a constant source, such as that from a free-standing home fan to both the store-bought anemometer and the homemade anemometer. The difference in wind speed measurement from the homemade anemometer was plugged into the Arduino velocity equation to compute a more accurate wind speed measurement. The test fan output was about 5.5 mph on the store-bought anemometer. By using the guess-and-check method of altering the seconds-per-revolution value in the Arduino program and comparing the mph values read, the new seconds per revolution value that most closely matched the 5.5 mph of the store-bought anemometer was 2.5. The maximum speed this wind vane could withstand was not determined. Therefore, the final equation plugged into the Arduino programming was determined using Equation 5:

$$V = P*(2.5/T) \qquad (5)$$

In construction, the magnet was first placed so that it closed at only one point of the complete anemometer rotation. Then, two 47-ohm resistors were placed on both sides of the reed switch to prevent overload. One lead of the switch went to ground, while the other lead connected to digital pin 11 of the Arduino UNO with a 4700-ohm pull-up resistor also connected to pin 11 where the switch closed. Next, a simple test code (see Appendix G) was inputted into the Arduino program to display data read from the sensor. Figure 10 shows how the anemometer was connected to the Arduino UNO.

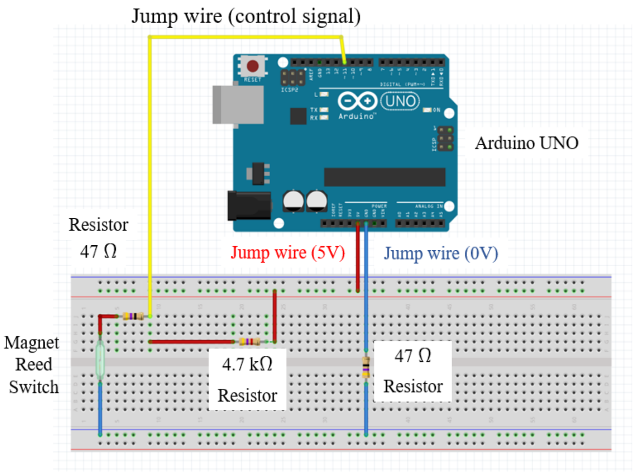

Figure 10. Anemometer and Arduino UNO diagram.

Wind Speed Anemometer Construction Guide

Once the reed switch was connected to the Arduino UNO, the rest of the anemometer needed to be constructed. This section of construction involved two PVC end caps, a ⅜-inch wooden dowel, a PVC SxSxS Tee, and four Betty Crocker measuring spoons. First, two long 22 AWG wires were measured and cut to connect the reed switch to the Arduino UNO at the base of the station. The wires were soldered to the ends of the reed switch and pulled through a one-foot length of ½-inch PVC pipe that connected to the main 1-½-inch vertical PVC pipe. The reed switch was superglued to the PVC pipe so that it just barely stuck out the end of the pipe. Next, a ball bearing was pressed inside one of the PVC end caps to fit snugly and level. To properly connect the two pieces, the PVC cap with the bearing was then connected to the PVC SxSxS Tee connector with a two -inch length of the ½-inch PVC. The other PVC end cap had four 3/16-inch holes drilled perpendicular from each other, and a 3/16-inch diameter wooden dowel was cut into four 3-inch segments, which were pushed through the holes of the PVC end cap. Four plastic Betty Crocker measuring spoons, of the tablespoon size, were cut and superglued to the dowels sticking out of the PVC end cap. The cups' total length from the center of the end cap was four inches, which was needed in calculating wind speed.

Next, a 5-inch long, ⅜-inch diameter wooden dowel was pressed into the inner diameter of the bearing of the PVC SxSxS Tee joint with a ball bearing cap. Once the exposed top of the dowel to the PVC end cap with cups connected was made watertight, it was important to get the dowel and cup cap to seat as level as possible, or it would not spin properly. Next, a magnet was hot glued to the dowel shaft that went through the middle of the SxSxS Tee connector. This way, the reed switch, glued to the inside of the SxSxS Tee connector, would close every time the magnet connected to the dowel made a full revolution. A diagram of the internals of the anemometer (the PVC spacer between the bottom end cap and the SxSxS Tee connector is not shown for internal clarity). Figure 11 shows a photo of the completed anemometer. This project included the initial design of the weather station, though limitations of each instrument built are not included here.

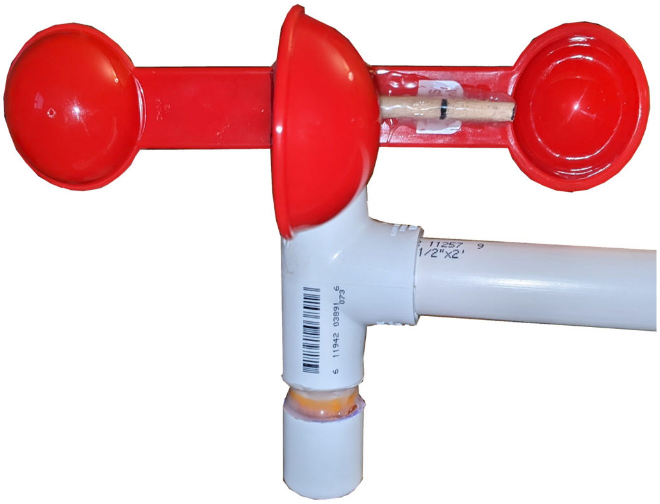

Figure 11. Photo of completed anemometer.

Main Housing Guide

This section of construction involved the PVC pipes, a 12-qt plastic bin, super worm cups, the power supply, wiring, and the Arduino UNO. The goal of this section was to get all the sensors and power supply connected to the Arduino UNO inside the PVC pipes and plastic bin. The main housing was designed to be placed on the ground and maneuverable so that the wind vane could be aligned North and tall enough so that wind could be caught in the anemometer cups and wind vane tail. A 12-qt plastic container was used as the base of the station, where the Arduino UNO and power supply were stored.

First, the 12-qt bin was turned upside down and a 1⅞-inch hole was drilled in the center of the bottom of the container. Then, a four-foot-tall 1-½ inch PVC pipe was fitted snugly into the hole and secured with hot glue. The PVC pipe acted as the center conduit for the sensor wires and the four arms of the home weather station. Next, four ⅞-inch holes were drilled into the 1-½-inch PVC; the first two were drilled six inches from the top of the pipe, while the other two holes were twelve inches below those holes. These holes were for the four, one-foot-long lengths of ½-inch PVC pipe that would act as the sensor arms. The top two sensor arms contained the homemade wind sensors, while the lower two arms contained the manufactured sensors. Because the lower two arms had sensors that needed protection from the elements, modified super worm cups were fitted over the ends of the sensor arms to provide protection. The top of the main PVC pipe contained the cloud sensor and was sealed with clear plastic to keep the station watertight.

A store-bought solar panel with an attached rechargeable battery was purchased for the power source. The rechargeable battery was placed inside the plastic bin, while the solar panel was placed outside. The bin was cut to allow the cord to pass through and sealed with hot glue to remain watertight. Because the rechargeable battery outputted a voltage of 12V and the Arduino UNO can only take 7-12V without overload, a buck converter was installed between the battery and UNO for safety. This buck converted took the battery output voltage of 12V and converted it into an input voltage to the UNO at 9V. Whereas the Arduino UNO can receive up to 12V, to make the home weather station more reliable, the buck converter was implemented as a safety net. The cloud cover and wind direction data were represented separately in MATLAB. MATLAB is a programming platform to analyze and design systems by engineers and scientists. It offers many features, such as plotting functions and data, algorithm development, customized user interfaces, as well as interacting with other systems.

With the goal of creating a localized, compact, and precise weather station to allow individuals to prepare for their specific atmospheric conditions, the home weather station delivers. The home weather station could measure temperature in degrees Celsius and degrees Fahrenheit, humidity, barometric pressure, wind speed, wind direction, cloud cover, and precipitation. On top of having all this sensing capability, the home weather station transmits the sensing data completely wirelessly over Bluetooth, while the station itself is self-sustaining via a solar-powered battery device. Using the powerful program, the home weather station is able to take the data from the sensors and display it in easy-to-read graphs. This way, the user of a home weather station can keep track of their outside conditions from the comfort and safety of their own homes, while the station withstands the elements with its rugged and watertight construction. Figure 12 shows the data acquisition dashboard in MATLAB.

It should be noted that these results were gathered in a test environment and do not necessarily represent realistic weather conditions. During the design and construction of this project, not all went smoothly and without issue. As this report outlines, several problems were encountered and had to be overcome, sometimes creatively. Some problems were small, such as poorly designed reed switches purchased from Amazon—where even with the utmost care and precision of trying to bend the leads, the glass-encased switch shattered— and some problems were larger, where the anemometer by design would not be completely accurate. A store-bought anemometer needed to be purchased to compare the two to calibrate the homemade anemometer correctly. At the completion of a project of this complexity, it is easy to look back and contemplate what could have been done differently along the way. More experience in cutting and manipulating PVC, as well as more precise tools, would have been helpful in getting the station to look more polished, along with using different-colored PVC for each arm to make it easier to know where each sensor was placed. In conclusion, the MATLAB home weather station project completed all the goals originally set and more.

Conclusions

The project presented in this paper was completed by a group of two undergraduate students as part of their senior project requirement for the BS degree in electrical engineering technology. To complete the project, students had to learn how to properly set up and wire each sensor to the Arduino UNO unit, solder wires where necessary, program the Arduino processor, and write code in MATLAB. The project drew on knowledge learned through the courses of the Electrical Engineering Technology program and was also an opportunity to research and learn new knowledge and techniques. The project merged the hands-on work specific to electrical engineering with hardware design and construction, since the students had to work with PVC, hot glue, circular saws, and more, learning along the way. It is expected that the level of detail and the step-by-step approach presented in this paper will help anyone wishing to create and use their own home weather station.

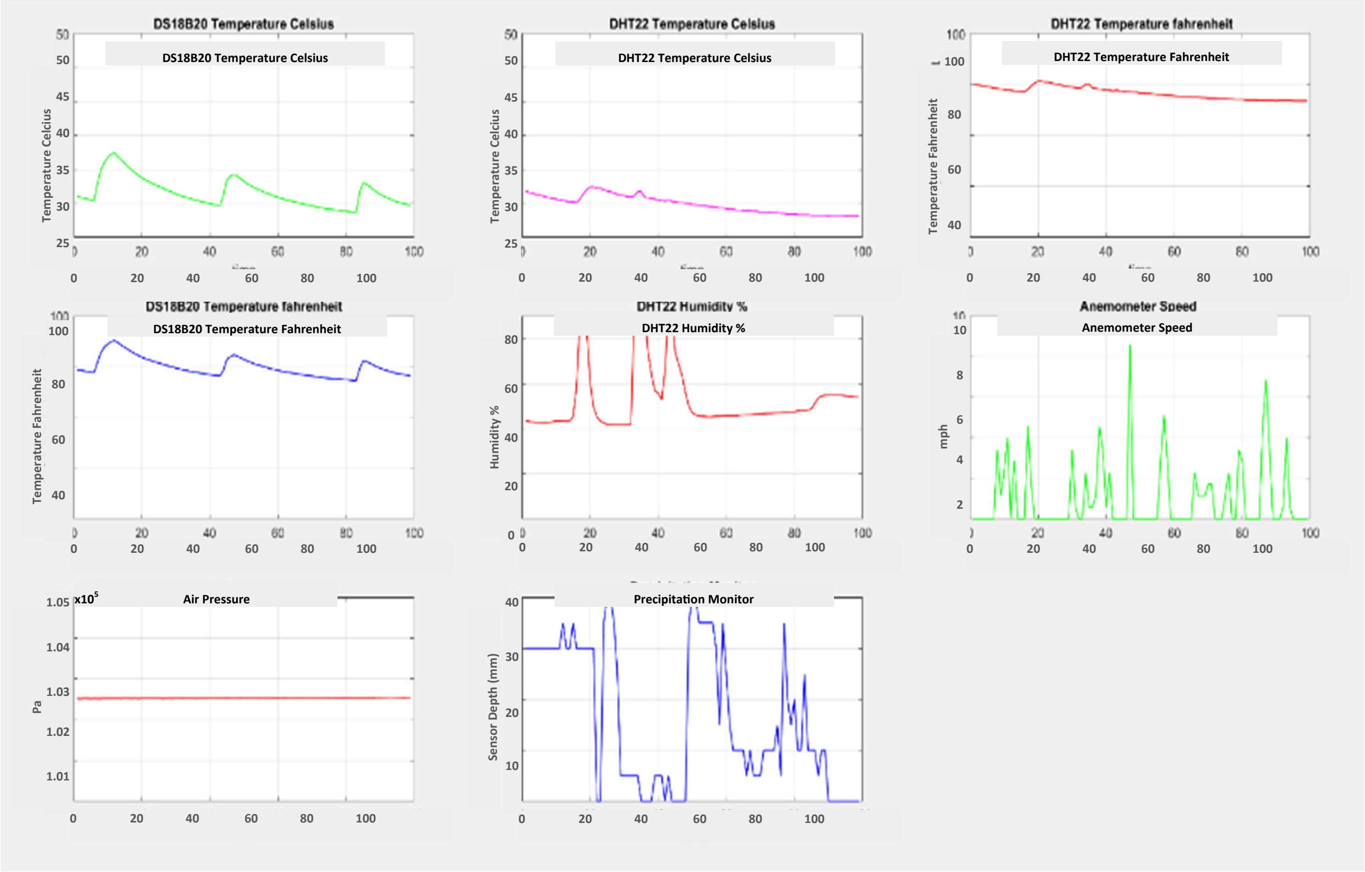

Figure 12. Data acquisition dashboard in MATLAB.

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Biographies

SHERYL DUTTON was an undergraduate student during this senior design project and received her BS degree in engineering technology, majoring in electrical engineering technology, from Old Dominion University. Ms. Dutton may be reached at sdutt005@odu.edu

KURT GALDERISI was an undergraduate student during this senior design project and received his BS degree in engineering technology, majoring in electrical engineering technology, from Old Dominion University. Mr. Galderisi may be reached at kgald001@odu.edu

MURAT KUZLU is an assistant professor of engineering technology at Old Dominion University. He received his BSc, MSc, and PhD degrees in electronics and telecommunications engineering from Kocaeli University, Turkey, in 2001, 2004, and 2010, respectively. From 2005 to 2006, he worked as a Global Network Product Support Engineer at Nortel Networks, Turkey. In 2006, he joined the Energy Institute of TUBITAK-MAM (Scientific and Technological Research Council of Turkey – The Marmara Research Center), where he worked as a senior researcher. Before joining ODU, he worked as a research assistant professor at Virginia Tech's Advanced Research Institute. His research interests include smart grids, demand response, smart metering systems (AMR, AMI, and AMM), home and building energy management systems, co-simulation, wireless communications, and embedded systems. Dr. Kuzlu may be reached at mkuzlu@odu.edu

OTILIA POPESCU is an associate professor of engineering technology and the program director of the electrical engineering technology program at Old Dominion University. She received her Engineering Diploma and MS degree from the Polytechnic Institute of Bucharest, Romania, and her PhD degree from Rutgers University, all in electrical and computer engineering. Her research interests include the general areas of communication systems, control theory, signal processing, and engineering education. In the past, she worked for the University of Texas at Dallas, the University of Texas at San Antonio, Rutgers University, and the Politehnica University of Bucharest. Dr. Popescu may be reached at opopescu@odu.edu

VUKICA JOVANOVIC is the Chair, Batten Endowed Fellow, and Associate Professor of Engineering Technology at Old Dominion University. She holds a PhD from Purdue University, Magistar (PhD candidate) degree in industrial engineering and management, focused and dipl.ing. degrees from the University of Novi Sad, Serbia. She has funded research in broadening participation efforts of underrepresented students in STEM funded by the U.S. Department of Education, focusing on computer science and cybersecurity pathways, and from the Office of Naval Research, focusing on mechatronic pathways. She is part of the ONR projects related to the additive manufacturing training of the active military. She is also part of the research team that has multiple projects funded by the NSF, focusing on veteran pathways and their success in engineering. She leads the team that delivers the summer program to ninth graders that focuses on broadening the participation of underrepresented students into STEM (ODU BLAST), funded by the Virginia Space Grant Consortium. Dr. Jovanovic may be reached at v2jovano@odu.edu

Appendices

Appendix A

BMP180 Air Pressure Test

```
//Required libraries
#include <Adafruit_BMP085.h>
//Create BMP180 object
Adafruit_BMP085 bmp;

void setup() {
//put your setup code here, to run once:
Serial.begin(9600);
bmp.begin();
Serial.println("Weather Station Sensor Test");
Serial.println("AirPressure");
}
void loop()
{
//put main code here, to run repeatedly:
 float bmpT = bmp.readTemperature(); //Must do a temp read on bmp before a pressure read
//Read pressure of bmp after the temperature
 float Press = bmp.readPressure(); //Air pressure is initially in Pa
  Serial.print(Press); Serial.print(" Pa\t");
  delay(2000);
}
```

Appendix B

Photoresistor Brightness Test

```
int LuxValue; //Value associated with photoresistor ADC
int LuxPercent; //ADC value converted to 0-100 range

void setup() //This is setup section for code to run once
{
//Begin serial communication
  Serial.begin(9600);//baud rate at 9600
}
void loop() //This is loop section for code to re-run
{
  LuxValue = analogRead(A2); //perform ADC on analog pin A3 and store in LuxValue
  LuxPercent = map(LuxValue, 0, 1023, 100, 0); //map for brightness percent
  Serial.println(LuxValue); //print the resulting ADC number to assign brightness range
  Serial.println(LuxPercent); //display the percent range of ADC value
  delay(2000); //slight delay to record ADC values to levels of brightness
}
```

Appendix C

DHT22 Temperature Test

```
#include <DHT.h> //include the DHT library
//Definition section
#define DHTPIN 12 //define what pin DHT22 is connected to any digital I/O can be used
#define DHTTYPE DHT22 //define that a DHT22 is used
//create DHT22 object
DHT dht(DHTPIN,DHTTYPE);
void setup()
{
// put your setup code here, to run once:
  Serial.begin(9600);
  Serial.println("Weather Station Sensor Test");
  Serial.println("t22Temp (C)\t22Temp (F)\t22Humidity"); // title for serial monitor view
  dht.begin(); //start dht sensor
}
void loop()
{
//put your main code here, to run repeatedly:
  float humi = dht.readHumidity(); //read humidity data and store in float
//Read temperature as Celsius (the default)
  float temp = dht.readTemperature(); // read temp data and store in float
//Read temperature as Fahrenheit (isFahrenheit = true)
  float tempf = dht.readTemperature(true); // read temp data and store in float
  Serial.print(temp); //Serial.print(" *C\t"); //display temperature in celsius
  Serial.print(tempf); //Serial.print(" *F\t"); //display temperature in fahrenheit
  Serial.print(humi); //Serial.print("%\t\t"); //display humidity percentage
  delay(2000); //2 second delay to observe results
}
```

Appendix D

DS18B20 Temperature Test

```
#include <DS18B20.h>
// Create DS18B20 object
DS18B20 ds(13);
void setup()
{
//put your setup code here to run once
   Serial.begin(9600);
   Serial.println("Weather Station Sensor Test"); //title for serial monitor view
   Serial.println("DSTemp (C)\tDSTemp (F)"); //title for serial monitor view
}
void loop()
{
```

```
//put your main code here, to run repeatedly
  Serial.print(dtempC); Serial.print(" *C\t"); //display temperature in celsius
  Serial.print(dtempF); Serial.print(" *F\t"); // display temperature in fahrenheit
  delay(2000); //2 second delay to observe results
}
```

Appendix F

Wind Vane Test

```
int VaneValue; //raw analog value from wind vane
int Direction; //translated 0 - 360 direction
void setup()
{
 Serial.begin(9600);
 Serial.println("Vane Value\tDirection\tHeading");
}
void loop()
{
 VaneValue = analogRead(A0);
 Direction = map(VaneValue, 0, 1023, 0, 360);
{
 Serial.print(VaneValue); Serial.print("\t\t");
 Serial.print(Direction); Serial.print("\t\t");
 getHeading(Direction);
}
//Converts compass direction to heading
void getHeading(int direction)
{
 if(direction < 22)
 Serial.println("N");
 else if (direction < 67)
 Serial.println("NE");
 else if (direction < 112)
 Serial.println("E");
 else if (direction < 157)
 Serial.println("SE");
 else if (direction < 212)
 Serial.println("S");
 else if (direction < 247)
 Serial.println("SW");
 else if (direction < 292)
 Serial.println("W");
 else if (direction < 337)
 Serial.println("NW");
 else
 Serial.println("N");
}
```

Appendix G

Wind Speed Test

```
#define WindSensorPin (2) //The pin location of the anemometer sensor
int Rotations; //cup rotation counter used in interrupt routine
unsigned int BounceTime; //Timer to avoid contact bounce in interrupt routine
float WindSpeed; //speed miles per hour
void setup()
{
 Serial.begin(9600);
 pinMode(WindSensorPin, INPUT);
 attachInterrupt(digitalPinToInterrupt(WindSensorPin), isr_rotation, FALLING);
 Serial.println("Wind Speed Test");
 Serial.println("Rotations\tMPH");
}
void loop()
{
 Rotations = 0; //Set Rotations count to 0 ready for calculations
 sei(); //Enables interrupts
 delay (3000); //Wait 3 seconds to average
 cli(); //Disable interrupts
//V = P(1.427/3) = P *
 WindSpeed = Rotations * 0.4757;
 Serial.print(Rotations); Serial.print("\t\t");
 Serial.println(WindSpeed);
}
//This is the function that the interrupt calls to increment the rotation count
void isr_rotation ()
{
 if ((millis() - BounceTime) > 15 ) { //debounce the switch contact.
 Rotations++;
 ContactBounceTime = millis();
}
}
```

Appendix M

Davis Instruments Anemometer Spec Sheet

URL: https://www.davisinstruments.com/product_documents/weather/spec_sheets/6410_SS.pd

RENEWABLE ENERGY SYSTEMS TRAINING PROJECT DEVELOPMENT

Mohsen Azizi, New Jersey Institute of Technology

Abstract

Renewable energy resources encompass several technologies, mainly including hydroelectricity, wind farms, solar photovoltaics, biomass, and geothermal power plants. Worldwide, solar- and wind-based energy production has been growing considerably in the past few years, and the trend is increasing over time. Therefore, it is predicted that within a few years there will be a high demand for technicians and engineers with hands-on skills in solar and wind technologies. In this current National Science Foundation-sponsored project, the author focused on solar photovoltaic technology. In this project, a new state-of the-art laboratory and its associated course were developed at the New Jersey Institute of Technology in close collaboration with industry partners. Moreover, K-12, faculty development workshops, and undergraduate research and senior design projects were other significant activities of this project. Finally, a dedicated public website was created to disseminate all the instructional materials.

Introduction

The renewable energy share in the U.S. energy production market is growing rapidly, while the fossil energy share is declining (Mohtasham, 2015; Owusu & Asumadu-Sarkodie, 2016; Department of Energy). According to the Energy Information Administration, the percentage of renewable energy production (out of total energy) has risen from 12.1% in 2012 to 19.7% in 2021. Hydro has constituted a major share of the renewable energy generation, but its trend over the years has been almost constant. The same constant trend was observed for biomass and geothermal. However, the share of solar and wind has been growing considerably in the past few years, and the trend is increasing over time. Due to the advancement of relevant technologies, it is expected that these trends will continue with steeper slopes in the following decades.

In 2018, the state of New Jersey passed two bills that require power companies to generate 35% and 50% of their electricity demand from renewable energy resources by 2025 and 2030, respectively (Corasaniti & Plumer, 2018). These legislative goals would put New Jersey in line with some of the leading states on the issue, such as New York and California. To this end, development of renewable energy skills among STEM students is important in today's economy. Education and training in the realm of renewable energy technologies are central to the growth and wellbeing of America's industries and technological sectors. Electrical engineers and technicians require a wide spectrum of knowledge and skills to effectively contribute to this rapidly growing sector of electricity generation and distribution industries. According to the Energy Information Administration, the net electrical energy generation by solar sources increased from 24.9 TWh in 2015 to 115.2 TWh in 2021. Based on information from the Bureau of Labor Statistics, employment of solar photovoltaic installers is projected to grow 27% from 2021 to 2031, which is much faster than the average for all occupations.

The typical entry-level education requirement is a high school diploma or equivalent. About 2500 openings for solar photovoltaic installers are projected for each year, on average, over the decade. These statistical data indicate the importance of curriculum development for solar energy technology to train hands-on students and technicians to meet the future demand of the solar electricity power generation industries. Figure 1 depicts this current, multi-objective National Science Foundation-sponsored project. The renewable energy systems training (REST) laboratory and the associated curriculum were developed for engineering technology students and faculty development workshops. Moreover, the REST-portable package was developed for outreach to K-12 students through summer camp programs. In addition, the REST website was created to disseminate all of the developed materials and results. The project was conducted in close collaboration with industry partners.

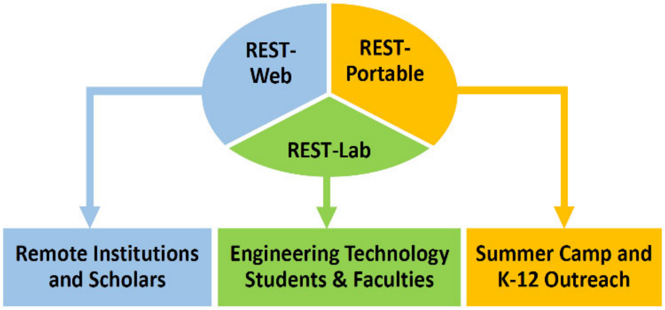


Figure 1. An overview of the Renewable Energy Systems Training (REST) project.

Similar efforts have been undertaken by other institutions to develop NSF-funded renewable energy laboratories and curricula. Santa Monica College launched a solar photovoltaic installation program that included outreach activities to K-12 students. Daytona State College in partnership with the University of Central Florida developed a program on solar photovoltaic installation and service. The University of Arkansas Little Rock established a photovoltaic test station and integrated it into several courses.

CUNY Bronx Community College established a series of continuing education certificate courses with concentrations in energy assessment, operations and maintenance, resource management, and alternative fuel vehicle operations and maintenance. Their program includes a faculty professional development activity. El Paso County Community College developed a program in the field of photovoltaic and solar thermal installation and maintenance. Madison Area Technical College developed a series of online courses and offered face-to-face faculty development workshops in the field of alternative transportation, photovoltaic, solar home design, wind power, and biomass. Cabrillo College started a program to attract and retain students by involving them in a sustainable energy summer internship preparation program, and providing counseling, mentoring, and tutoring support.

As compared to the aforementioned projects, the REST project presented here is unique in that it develops laboratory and curriculum materials, while concurrently targeting several comprehensive activities. These activities include the following: outreach to K-12 students, faculty development workshops, undergraduate research and senior design projects, and online training resources for remote scholars, which all together greatly contribute to STEM education across the U.S. Moreover, this REST project was developed based on a close collaboration between university and industrial partners. The contribution of this paper is to present all the activities fulfilled and the results obtained in the development process of the NSF-funded REST project. These activities and results are presented in seven sections, as follows: (i) new course and laboratory development; (ii) course evaluation and student feedback results; (iii) external advisory committee feedback results; (iv) faculty development workshop and survey results; (v) outreach to K-12 students; (vi) undergraduate research experiences; and, (vii) online training resource development. This complete project development process is presented for the first time in this paper.

New Course and Laboratory Development

The REST laboratory was developed at the New Jersey Institute of Technology (NJIT) to offer the new solar photovoltaic (PV) planning and installation course for engineering technology students and faculty development workshops. The REST-Lab provides state-of-the-art training equipment to teach site analysis, planning, installation, troubleshooting, protection, startup, and commissioning of solar PV systems. The new hands-on course trains students with skills immediately required by renewable energy power companies. It targets real industrial demands in the field and is being designed, developed, improved, and enhanced continuously in close collaboration with energy and power industry partners. The REST curriculum plays an educative and informative role, provides operational knowledge, and develops understanding of facts, concepts, principles, and technologies. The desirable educational features and benefits of the curriculum include the following.

- Develop student awareness about energy challenges, renewable energy resources and technologies, and their development and utilization.
- Cover all renewable energy resources in general with a focus on solar PV system topics, including solar radiation, sun path characteristics, site planning, panel orientation, system analysis, wire selection and sizing, troubleshooting, protection, installation, startup, commissioning, and standards.
- Provide a balance between theory (lectures, tutorials, assignments, etc.) and practice (laboratory and demonstration experiments, hands-on skills training, troubleshooting, etc.).

Several vendors were considered and their products were closely tested and examined. The renewable energy products from Amatrol Inc. (n.d.) were found to be the best fit for this project. After consultation with the external advisory committee (EAC), the following products were purchased and utilized to develop the laboratory experiments: the Solar Site Analysis Learning System (see Figure 2), the Solar PV Installation Learning System (see Figure 3), the Solar PV Troubleshooting Learning System (see Figure 4), and the Solar Thermal Troubleshooting Learning System (see Figure 5).

Figure 2. Solar site analysis (Amatrol Inc.). Reprinted with permission.

A textbook by Warmke (2021) was selected for the new course, based on which lectures were designed and developed. Table 1 shows the course schedule and contents, while detailed course objectives and contents, including the lecture notes and laboratory experiments, are presented in articles by Azizi and Fuentes (2022a/b). The assessment method was a combination of knowledge tests, hands-on troubleshooting scenarios of embedded faults, and a final research project.

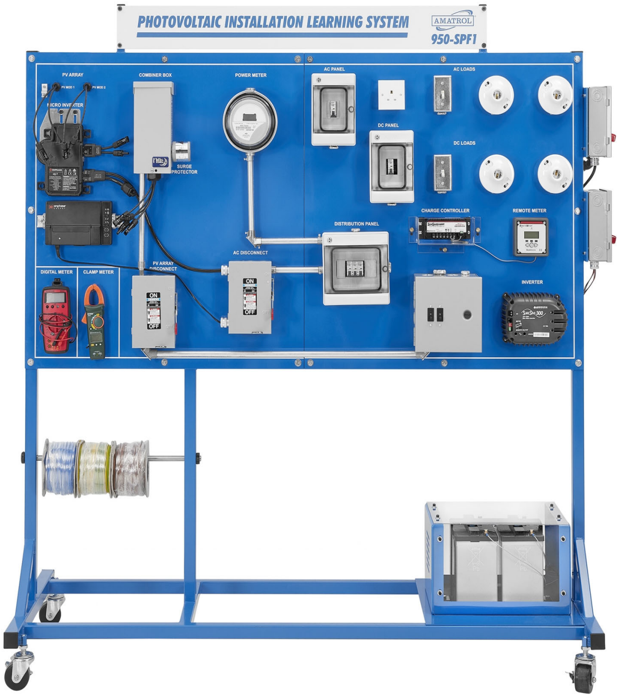


Figure 3. Solar PV installation. Reprinted with permission.

Figure 4. Solar PV troubleshooting. Reprinted with permission.

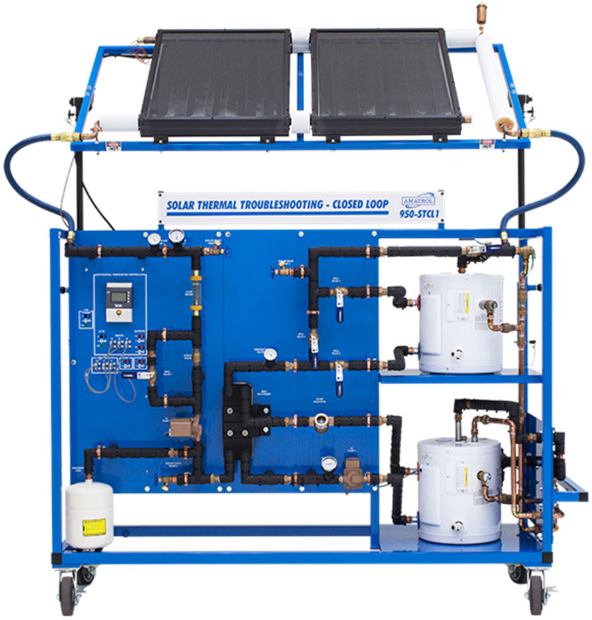


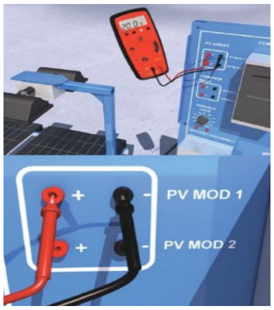
Figure 5. Solar thermal troubleshooting. Reprinted with permission.

Table 1. Course schedule.

Lecture (Lec) Topics and Laboratory (Lab) Experiments		Week
Lec 1	Introduction to solar PV systems and types	1
Lec 2	Parts of PV system and electrical concepts	2
Lec 3	Site survey and PV system design	3
Lec 4	Electrical system installation and testing	4
Lec 5	Introduction to solar thermal systems	5
Lec 6	Solar radiation fundamentals	6
Lec 7	Sun path characteristics	
Lec 8	Solar panel orientation	
Midterm Exam		7
Lab 1	Solar PV system installation, site planning	8, 9
Lab 2	Solar PV system troubleshooting	10, 11
Lab 3	Solar thermal system troubleshooting	12, 13
Final Project		14

Table 2 provides a sample of the laboratory protocol in which a short experiment with the open-circuit voltage measurement of PV modules. The instructional materials developed in this project were evaluated in three different ways: a) course evaluation and student feedback; b) external advisory committee including industry representatives from relevant companies; and, c) faculty development workshop survey including faculty members and instructors from other institutions, universities, and community colleges across the U.S.

Table 2. Sample laboratory experiment: Measuring the open-circuit voltage of a PV module.

Step 1	Put on safety glasses.
Step 2	Position the lamp directly above the PV modules and turn the lamp on.
Step 3	Use a multimeter to measure the voltage for PV module 1 between terminals PV MOD 1 (+) and PV MOD 1 (-), and for PV module 2 between terminals PV MOD 2 (+) and PV MOD 2 (-).
Step 2 	Step 3 

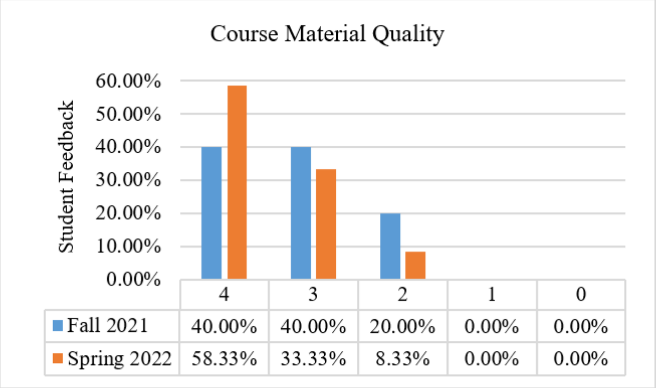


Figure 6. Student feedback for course material quality: fall 2021 (mean 3.20 and standard deviation 0.79) and spring 2022 (mean 3.50 and standard deviation 0.67). Horizontal axis scale: 4 (excellent), 3 (good), 2 (satisfactory), 1 (fair), and 0 (poor).

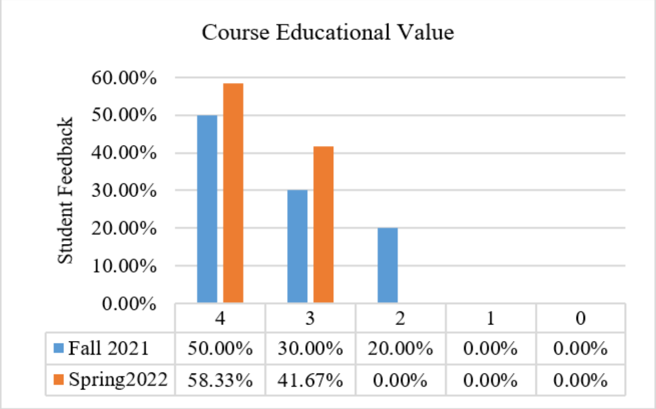


Figure 7. Student feedback for course educational value: fall 2021 (mean 3.30 and standard deviation 0.82) and spring 2022 (mean 3.58 and standard deviation 0.51). Horizontal axis scale: 4 (excellent), 3 (good), 2 (satisfactory), 1 (fair), and 0 (poor).

Course Evaluation and Student Feedback

The new Solar PV Planning and Installation course was offered to engineering technology students at NJIT during the 2021-2022 academic year. In fall 2021 and spring 2022 semesters, the numbers of enrolled students were 13 and 12, respectively. The course was an elective for engineering technology undergraduate students. It was a three-credit-hour course with two hours per week of lecture and two hours per week of laboratory experiments. It was open to sophomore or higher-level students, but mostly junior- and senior-level students took it. The university's standard end-of-semester questionnaire, which includes three questions about the course and eight questions about the instructor, was provided to the students. Figures 6 and 7 show the aggregated results of the two questions about *course material quality* and *course educational value*, respectively, for both semesters. The course evaluation was completed by 11 of 13 students enrolled in the fall 2021 term (85% response rate) and all 12 students enrolled in spring 2022 term (100% response rate).

Student feedback was obtained using a scale ranging from 4 (excellent) to 0 (poor). The captions of Figures 6 and 7 also show the means and standard deviations for course material quality and course educational value. These figures indicate an increase in student satisfaction level. This was due in part to integrating their suggestions for improvement, which included: i) adding more instructions and explanations on the conduct of the laboratory experiments, and ii) adding a real-life solar PV system design exercise. The increase in student satisfaction level was also due to implementing suggestions from the external advisory committee (EAC).

In the future, the indices of student enthusiasm and deep understanding will be explored in close collaboration with colleagues whose research focuses specifically on engineering education. It is expected that the enrollment number will increase as students get to know more about the course, thereby providing more statistical data for engineering education research.

External Advisory Committee (EAC)

The EAC included industry partners who reviewed, evaluated, and advised the project team. The EAC was comprised of industry representatives from the S&C Electric Company, Energy Vault, GE Power, and SunLight General Capital. The feedback form provided to the EAC requested that they evaluate the course in four main areas, including lecture notes, laboratory experiments, student evaluation methods, and overall course quality. Their feedback included minor technical changes, which were all applied to the lecture notes and laboratory manuals. The major suggestion was to add an exercise on PV sizing and siting using a website or software. This was addressed by adding the three hands-on laboratory experiments listed in Table 3. The details of these experiments are presented in the study by Azizi (2023).

Table 3. Additional labs in response to the EAC's suggestion.

PV Sizing and Siting	
Lab A	Perform load analysis using the Whole House Load Calculation in the following website: gensizer.assurancepower.com
Lab B	Perform PV system design using the following website: pvwatts.nrel.gov
Lab C	Perform PV site survey using the website in Lab B.

Faculty Development Workshop

The REST-Lab was used to develop and offer two, one-day workshops entitled "Solar PV Installation and Troubleshooting" to faculty members and instructors from other institutions, universities, and community colleges across the U.S. Table 4 lists the lecture topics, laboratory experiments, and additional topics presented in the workshop.

Table 4. Faculty development workshop contents.

Lecture (Lec) Topics, Laboratory (Lab) Experiments, and Additional Materials	
Lec 1	Certification programs, electrical codes, and standards
Lec 2	Solar panel ratings, and types and parts of PV systems
Lec 3	Load analysis, site survey, and PV array sizing
Lec 4	Financial overview and benefits
Lab 1	Connecting and operating a stand-alone AC PV system
Lab 2	Troubleshooting a stand-alone AC PV system
Lab 3	Designing a residential PV system using online tools
Add'l.	Designing and developing a similar course and laboratory at other institutions, and planning for budget, equipment, and course materials.

A total of 16 participants attended the workshops in person. At the end of the workshops, participants received an evaluation form, which was a self-measure of the following four areas:

- Participation in the workshop
- Interest in the subject
- Learning of materials in lectures
- Learning of concepts in hands-on activities

The workshop evaluation was completed by all 16 participants (100% response rate). Overall, the participants reported that the one-day workshops were very helpful for them to gain exposure to the principles of solar PV systems, specifically in the stand-alone mode of operation. Suggestions included future workshops that are longer in length and cover grid-connected and grid-interactive modes of operation. Figure 8 provides a summary of the participants' feedback.

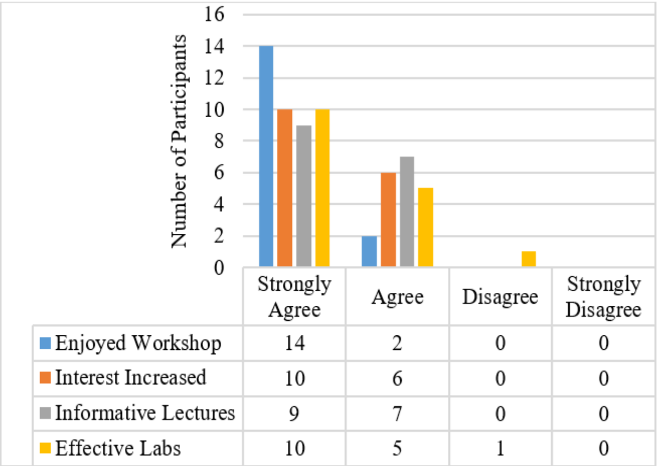


Figure 8. Faculty development workshop evaluation summary (16 total participants).

Outreach to K-12 Students

The REST-Portable package was developed to include small-scale renewable energy training equipment, which was used for demonstration to middle school students through mini-workshops at summer camp programs sponsored by the Center for Pre-College Programs (CPCP) at NJIT. Table 5 summarizes the contents of the workshop, including lectures and laboratory experiments.

Table 5. K-12 workshop contents.

Lecture (Lec) Topics and Laboratory (Lab) Experiments	
Lec 1	Preliminaries: current, voltage, series/parallel
Lec 2	Renewable versus nonrenewable energies
Lec 3	Solar energy and solar PV systems
Lec 4	Hydro and wind energies
Lab 1	Power a motor by a battery and a variable resistor
Lab 2	Use PV panel to power a LED and a motor
Lab 3	Use series PV panels to power a motor
Lab 4	Use a wind turbine to power a motor

Figure 9 shows the Renewable Energy Science Kit from Horizon Educational Inc. that was used. The REST-Portable package included brief and simplified laboratory experiments and step-by-step instructions to guide the middle school students through the experiments. The workshop was offered virtually to 12 students in the summer of 2021, and in person to 20 students in the summer of 2022. The summer camp programs offered by CPCP specifically target first-generation, minority, and other underserved and underrepresented populations. The programs facilitate student exposure to, and interest development in, STEM education in the fields of renewable energies, robotics, environmental science, mechanical engineering, chemistry, computer coding, and general college-prep classes. CPCP annually serves more than 3000 elementary and secondary students and their teachers.

Figure 9. Renewable Energy Science Kit (Horizon Educational Inc.). Reprinted with permission.

Undergraduate Research Experience

Undergraduate research involvement has a positive impact on students' intellectual growth and retention rates (Depaola, Brey, Teymour, Anderson, Cammino, Haferkamp & Mohammadi, 2015; Atkins, Allison & Sandage, 2021). Several studies have supported the hypothesis that undergraduate research helps promote career pathways for members of underrepresented groups by increasing the retention rate of minority undergraduate students (Bickford, Peterson, Jensen & Thomas, 2020). The REST-Lab developed in this current project was used to enhance undergraduate research involvement and senior design projects in the field of renewable energy systems. The following opportunities have been provided to undergraduate students at NJIT:

- Undergraduate Research Project (spring 2022): Laboratory Development for Microcontroller Communication. Multiple microcontrollers were connected to cooperatively simulate a renewable energy system, which is computationally too expensive to be conducted on a single microcontroller.
- Senior Design Project (fall 2022): Solar Powered Speed Radar Measurement, Display, and Logging. A solar PV system was designed and implemented to power a speed control system including a radar sensor, camera, microprocessor, and data logging system.

Online Training Resource Development

A new website (http://research.njit.edu/res) was created and publicized for use by all universities and colleges, and is being continuously updated. The website includes all lecture notes, course materials, and laboratory and classroom videos that were developed for REST-Lab and the associated new course, as well as all relevant publications. It also includes information about the K-12 and faculty development workshops. Moreover, there is a section on undergraduate research and senior design projects. An online feedback form is provided for users to provide suggestions for improvement.

Conclusions

The objective of this NSF-sponsored Renewable Energy Systems Training project was to develop a new state-of-the-art laboratory and curriculum at NJIT to train engineering technology students with hands-on skills required to fill the gap between market demand and workforce. Based on the new laboratory, the new Solar PV Planning and Installation course was developed and offered. The new laboratory was also used for undergraduate research and capstone senior design projects to improve student retention rates and academic progress. Moreover, one-day faculty development workshops were developed and offered for faculty members and instructors at 2- and 4-year institutions across the U.S. In addition, a portable instructional package was developed and served as the basis for K-12 workshops that were offered through summer camp programs. All instructional materials in this project were developed and enhanced in close collaboration with industry partners. A dedicated website was created to disseminate the materials resulting from the project. This project's long-term vision is to train and prepare a new class of engineers and technicians who can quickly integrate into and thrive in the renewable energy industry sector.

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Biographies

MOHSEN AZIZI is an assistant professor in the School of Applied Engineering and Technology at the New Jersey Institute of Technology. He received his MSc and PhD degrees in electrical and computer engineering from Concordia University, Montreal, Canada, in 2005 and 2010, respectively. From 2010 to 2013, he was an R&D engineer at Pratt & Whitney Canada, Inc., where he designed and developed control and fault diagnosis systems for jet engines. His research interests include decentralized control and fault diagnosis techniques in microgrids, renewable energy systems, mechatronics, and aerospace. Dr. Azizi may be reached at azizi@njit.edu

PPAP AS AN APPLIED STUDENT CAPSTONE PROJECT

Neil Littell, Ohio University; Mustafa Shraim, Ohio University; Daniel Sheets, Ohio University

Abstract

The production part approval process, or PPAP, is a process intended to prove that a supplier can provide the parts needed by an original equipment manufacturer, or OEM (AIAG, 2006; AIAG, 2008). While this tool is standard in the modern manufacturing environment, it is not a process that is commonly taught in academic settings. Upon review of the components of the PPAP, the authors realized that students are covering the vast majority of the elements in their academic classes but were never combining these components into a comprehensive deliverable. The authors leveraged their manufacturing engineering-based capstone to provide an authentic PPAP experience to enable students to synthesize the PPAP firsthand. The history and background of the PPAP was also provided. The authors then tied the PPAP components to the curriculum through the Society of Manufacturing Engineers' (SME) four pillars of manufacturing engineering knowledge. A description of the authors' execution of the PPAP as a capstone experience is provided here with a discussion of observed dynamics and potential future work.

A Manufacturing Vignette: Part I

A project manager launched a new product for the marketplace. The bills of materials (BOM) was complete, the work instructions were in place, and employees were on the line to begin manufacturing. Over the weeks immediately preceding the launch of the new product, several trial, or pilot, runs had been completed with sample parts from suppliers, resulting in a great success. The sample parts had been consumed and the actual production was about to begin. As the first real production products started to be manufactured, multiple problems with the production parts were identified. Some parts did not have the same surface finish as the sample parts. Mounting holes on some parts did not line up correctly, and some electrical components had different wire colors than the original sample parts. The project manager reflected on this disaster of a launch and researched what could have been done to ensure that the suppliers could meet the requirements of the company with actual production parts versus the sample parts that were originally shipped. The project manager discovered an article about how a standard process and documentation set, called the production part approval process, or PPAP, had been used in the automotive and other industries for years in order to address these supplier dynamics. The project manager brought up the concept of the PPAP in a post-launch review as a potential methodology for helping to mitigate supplier issues for future projects. Management and the team agreed to let the project manager attempt a PPAP on an upcoming project as a feasibility exercise.

Overview

The modern manufacturing environment exists as a symphony of people, parts, technology, suppliers, and the operational dynamics dictated by the market and customer. As products become more complex with advanced features and multiple configurations, manufacturing, in many cases, has evolved towards the assembly of complex systems of parts supplied by external business partners (Tang, 2022). With this outsourcing of complexity, manufacturers can be held hostage by the capability of their suppliers. One tool to enable due diligence of some manufacturers is the production part approval process, or PPAP. The PPAP is a set of standard documents that have been identified by the AIAG (Automotive Industry Advisory Group). The AIAG was founded by Ford, GM, and Chrysler. Today, the AIAG is staffed by over 900 volunteers and is comprised of virtually every major manufacturing company in America, representing over 4000 member companies that have agreed to adopt the standards, such as the PPAP, within the supply chains for these companies (AIAG, n.d.). The purpose of the PPAP is to enable the supplier to validate that they have the capability to "run at rate"; that is, produce parts to the required specifications at the volume needed by the customer (AIAG, 2006; Lafayette, Li & Webster, 2017). Typically, this type of documentation is limited to special-purpose parts, not standard parts such as fasteners, batteries, and other commonly available items.

The PPAP is necessary because as a company launches a new product, it will require a surge of parts from each of the suppliers. During the new-product development process, part suppliers are typically only needed to produce relatively few sample parts used for pilot builds, manufacturing and assembly verification, product certification, and testing purposes. For the supplier, fabricating production intent parts at volume can be a challenge, especially if the supplier requires new equipment, additional employees, or new processes to make the parts. The PPAP provides a mechanism for the supplier to prove to their customer that they can provide the parts needed and meet the specifications at the quantity required for full-scale production. The PPAP serves to capture some of the most common causes of rejected parts. The documentation is completed against what the supplier believes to be a robust process for creating the parts with the expected quality characteristics at the rate required by the OEM.

Because the documentation is typically completed early in the production cycle, the documentation should be completed and approved before production starts on the parts. The PPAP can then be used to troubleshoot issues, should they arise, with many aspects of the part. It is felt that the documentation included in the PPAP helps avoid many types of quality issues with parts and ensures that the supplier has executed some due diligence toward providing high-quality parts to the OEM in order to meet their demand. The PPAP is a living document, which is updated when required by changing processes, materials, people (in some cases), tooling, or any other change that might impact the production parts. While there are 18 components to a PPAP, the AIAG recognizes that not all changes require that the "full" PPAP be executed. The standard allows provisions for the supplier and the OEM to agree to one of five different levels of a PPAP, depending on the situation being faced by the supplier.

In a study by Lafayette, Li, and Webster (2017), the authors reported that the primary purpose of the PPAP is to reduce risk. The authors believe that this is a better perspective than simply measuring the effectiveness of "run at rate." The perspective that the PPAP is used only to determine if a company can produce quality parts at the quantity needed at the start of production shortchanges some of the additional benefits of the PPAP. For example, the PPAP can also be used to troubleshoot when parts begin to be rejected because of myriad reasons, including material, process, equipment, or other deviations from the initial production state. "PPAP is beneficial in its helpfulness to maintain the product (design) and process (manufacturing) integrity of parts" (Lafayette, Li & Webster, 2017).

Lifecycle of a PPAP

The PPAP process begins once the engineering specification for the component is complete. This includes the engineering drawings and applicable requirements concerning, but not limited to, performance, appearance, expected quality, and general acceptance criteria for the parts. This beginning phase of the PPAP is essential, as it gives the OEM and supplier a consistent methodology for communicating these critical characteristics before the supplying company makes large investments in infrastructure. This is also helpful for the supplier to properly scope out the project and provide realistic expectations for the manufacturing execution of the components back to the OEM. One of the hopes is that the PPAP will enable the supplier to provide realistic quotes for parts, while also minimizing wasteful back-and-forth negotiations. This documentation process reduces back-and-forth communications and helps to ensure that suppliers can meet the demands of the OEM.

Industrial Applications of PPAP

According to Stamatis (2021), the PPAP process focuses on answering six fundamental questions concerning the production of a part. These questions are:

- Does a process owner exist?
- Is the manufacturing process defined?
- Are the processes properly documented?
- Are linkages of a process identified and established?
- Are the processes monitored, analyzed, and continuously improved?
- Are records maintained?

Tang (2022) further states that the purpose of the PPAP is:

- To ensure that the supplier is able to meet all the requirements of the parts and supply these satisfactory parts to the customer.
- To provide evidence that the supplier (and its sub-tier suppliers) properly understood and fulfilled all customer requirements.
- To validate that the supplier is prepared for pre-launch volume to mass production outputs.
- To show that the supplier's process can produce parts that consistently meet requirements during an actual production run at the quoted production rate.

The authors believe that the final point made by Tang (2022) is at the crux of the PPAP; that is, the concept of run at rate. This means that the supplier has proven that they can produce (run) parts that meet the requirements of the OEM at the quantity (rate) demanded by the OEM to meet the production goals of the OEM. There are 18 typical components of the PPAP, although many companies will add additional requirements, depending upon their requirements. A detailed description of each of these components is beyond the scope of this paper but is available in the de facto PPAP standard provided by the Automotive Industry Advisory Group (AIAG, 2006).

Design Records

The PPAP begins with the formal presentation of released (approved for production by the OEM) parts. The design package should be provided with detailed callouts for both critical and noncritical features and defining tolerances and any special GD&T (geometric dimensioning and tolerancing) and other requirements.

Authorized Engineering Change Documents

The OEM-supplied documents will account for any engineering change orders that require any changes to the parts being supplied. In the case of new parts, this would be an initial release without a change order. Note that many suppliers will use engineering changes as an opportunity to increase part costs, and should therefore be avoided or reduced when possible. Engineering approval is granted from the customer (OEM) to enable the supplier to produce parts. In the event that the PPAP is not completed or there is a risk of an engineering change order, the approval might be issued as a deviation to send parts to the supplier before the PPAP. This practice should be minimized whenever possible. Design Failure Mode and Effects Analysis (DFMEA) is a formal document reviewed and approved by both the

OEM and the supplier. This document steps both parties through all the ways that the part can fail in application and is used as a tool to identify parts that should be redesigned early in the design process to mitigate waste from parts that do not meet the performance requirements of the customer.

Process flow diagrams indicate the production sequence of events leading to the successful production of the parts. Production failure mode and effects analysis (PFMEA) analyzes the production process and works to identify potential problem areas with respect to the production processes early on. Control plans follow the PFMEA and provides a plan for controlling the production process with respect to the items identified in the PFMEA. As issues are identified in the production process, the PFMEA and the control plan will need to be updated. Measurement system analysis (MSA) is conducted to validate and verify the equipment and procedures used to measure the critical characteristics identified in the engineering specification (design records). Dimensional results include a list of critical dimensions and other product characteristics. The goal of the dimensional results is to develop a report of "go/no go" or "ok/not ok." Usually, a sample of parts is used for this report to gain insight into dimensional variation across the sample of parts for establishing upper and lower control limits with respect to the nominal dimensions and the intended function of the parts.

Records of material/performance tests include performance measurements of every non-metrological part metric. This includes validation and verification of materials for the actual component versus what is specified on the engineering specification. Ultimately, the expectation is that both the OEM and the supplier will review these results and sign off on the tests. Initial process studies present the statistical process control (SPC) charts that affect the critical characteristics of the components. The expectation is that the supplier will also conduct a process capability analysis. As the supplier increases production rates to fulfill the run-at-rate requirement of the PPAP, these reports become critical for communication process stability to the OEM. Qualified laboratory documentation is the inclusion of standard certification documentation from any labs that were used to perform any testing on any aspect of the PPAP. This documentation should also include internal calibration certificates for machines and metrology equipment used in the production environment.

These certification and calibration documents are used by the supplier to illustrate that the equipment used to test materials and generate performance reports and dimensional reports have been externally certified to be operating properly. This external certification serves as an extra layer of due diligence towards robust processes for managing equipment and the metrological results of that equipment. The appearance approval report is used for class A (customer facing) surfaces. Usually, samples are retained as a visual baseline at both the OEM and the supplier sites. The OEM might further define the visual inspection procedure for customer-facing parts. Sample production parts are provided by the supplier. Usually, some of these sample production parts are kept as an initial baseline by either the OEM, the supplier, or both. Sometimes, some of these parts are used for pilot builds, product testing, production training, and/or product certification testing. The master sample is a sample part signed off on by both the customer and the supplier, which is used as a baseline for the initial run of production parts. Checking aids are developed when special tooling is used for part inspection; the owner of the checking aid must include relevant information concerning tooling, including pictures, storage location, calibration records, technical drawings, etc.

Customer-specific requirements include any information that might be part-, assembly, or application-specific should also be included in the PPAP, in addition to specific information requested by the OEM as one of their requirements. A part submission warrant (PSW), or simply warrant, is a summary of the PPAP process and documentation. Essentially, all of the other parts of the PPAP should support the warrant. In the event of any open issues, such as deficiencies, atypical results, or outstanding engineering changes/deviations, they should also be noted on the warrant as reasons for why the PPAP could not be submitted. These deficiencies must be shared with the OEM to facilitate discussions towards issue resolution so that the PPAP can be completed.

Levels of PPAPs and Their Typical Applications

The PPAP starts with the submission of standardized documentation to the OEM. The supplier then responds to the initial submission from the OEM to complete the PPAP package. The level of detail of the completion of the PPAP depends on the requirements of the OEM. There are five PPAP levels.

- PPAP Level 1: Warrant (PPAP paperwork) only. This level is used for low-risk parts. For example, an existing production part that is painted a different color.
- PPAP Level 2: Level 1 with sample parts and some relevant supporting (test) data. This would be used for a low-risk part or a slightly different configuration of an existing and stable production part.
- PPAP Level 3: The most common PPAP level for new parts, PPAP Level 3 includes all information for Levels 1 and 2 and adds complete supporting production documentation.
- PPAP Level 4: PPAP Level 4 includes all PPAP Level 3 information, as well as any information deemed appropriate by the OEM.
- PPAP Level 5: PPAP Level 5 includes all information included in PPAP Levels 3 and/or 4, as well as a site visit to audit the contents of the PPAP.

In many cases where a new part is being supplied to the OEM, a Level 3 PPAP is typical. Level 1 and Level 2 PPAPs are used for noncritical parts and minor changes. Because the PPAP is a living document, the supplier would be required to complete additional documentation in the event of a change within the production environment that impacts the parts being supplied in any way. However, for low-risk changes, such as adding a new machine to the production process, a Level 2 PPAP might be required to validate the new production process versus the due diligence of Levels 3-5. Very small changes might be paperwork-only changes, such as the supplier implementing a new metrology system. This type of change does not impact the parts directly, but it affects the inspection process and should, therefore, be accounted for in the PPAP warrant at a minimum (because the Gauge R&R component of the warrant would need to be executed on the new equipment).

Academic Applications of PPAP

Frequently, many of the typical components of the PPAP are executed discretely in separate courses within many engineering and engineering technology programs. By developing an exercise that requires students to complete a mock PPAP, students are able to see how each of the parts of the PPAP are connected to enable manufacturing execution. Additionally, this exercise allows students to articulate to potential employers their expertise with PPAPs and manufacturing execution, potentially opening new doors to exciting opportunities. As faculty and staff in a manufacturing engineering program, the authors strive to remain current and relevant. One way to accomplish this is by validating the curriculum through strategic alignments to industry standards, such as the PPAP. One of the other items the authors use for external validation is the SME four pillars of manufacturing knowledge. This illustration was created by the Society of Manufacturing Engineers (SME) with the goal of communicating the foundational manufacturing engineering domains.

SME's Four Pillars of Manufacturing Knowledge was created in 2011 and has been updated periodically by the organization. This illustration was developed by a committee comprised of both industry and academic professionals. This illustration attempts to map manufacturing knowledge into a concise yet comprehensive visual guide, essentially a visual guide to the SME body of knowledge (Mott et al., 2012). The two most prolific manufacturing education accrediting groups, the Association of Technology, Management, and Applied Engineering (ATMAE) and the Accreditation Board for Engineering and Technology (ABET), have adopted the SME Four Pillars as a guide toward specific knowledge and skills that a manufacturing-based curriculum should address. These four pillars have been implemented by ABET as one of the inputs to guide their ABET-ETAC accreditation program, which clearly maps back to the SME Four Pillars. From the ABET accreditation standard (ABET, n.d.; Plouff, Pung & Jack, 2014):

- Materials and Manufacturing Processes
- Product Design Processes, Tooling, and Assembly
- Manufacturing Systems, Automation, and Operations
- Statistics, Quality, and Continuous Improvement, and Industrial Organization and Management

Figure 1 illustrates that these four criteria map to the product enterprise section of the SME Four Pillars almost verbatim. The ATMAE (2021) accreditation guide includes this statement:

> Programs in manufacturing at the Associate, Baccalaureate, and Masters levels should review and consider for adoption as a quality improvement tool, the SME 4 Pillars of Manufacturing as may be appropriate for their respective Programs. ATMAE Accreditation has formally adopted this concept for use as a model quality improvement tool and encourages manufacturing programs to utilize components that apply to their programs. The Pillars are applicable to both technical manufacturing and to manufacturing management curricula. (p.8)

The current authors, working in a manufacturing engineering program, reviewed the SME Four Pillars for overlap between the curriculum offered through the lens of the PPAP. Table 1 illustrates the significant overlap identified by the authors.

Competencies Addressed through PPAP

By applying the PPAP as an academic exercise, many manufacturing-based engineering competencies can be realized. Because the PPAP exists as the documented proof that the supplier can produce parts at the rate required by the OEM, the PPAP can be used as a method to enable students to prove mastery of many manufacturing engineering core competencies. When analyzing the competencies covered by the PPAP, the authors quickly noticed significant overlaps between their own manufacturing engineering-based curriculum, as one would expect. The authors developed Table 2 to identify course coverage when listing the courses as they relate to coverage with the SME Four Pillars, as articulated in Table 1.

Deploying the PPAP in an Academic Setting

In the authors' manufacturing-centric capstone course, the authors implemented a PPAP process on a part that was designed and fabricated by the students. Students in the capstone course were required to design a product and then execute a production run of between fifteen and thirty products within a few hours. The design team created all of the artifacts required for production, including the design itself, production tooling, work instructions, an inventory control system, and a quality management plan. The managing team

Figure 1. The SME Four Pillars of manufacturing engineering. (Mott et al., 2012; Mott et al., 2013; SME, n.d.). Reprinted with permission.

Table 1. Competencies defined by the SMI Four Pillars (see Figure 1) tied to course coverage. Course descriptions can be found in Appendix 1. Bolded items indicate that the item is a heading with sub-items listed below each of the four highlighted categories.

SME Pillars	Course Coverage			
Materials and Manufacturing Processes	Course 3	Course 2	Course 6	Course 7
Engineering Sciences	Course 6	Course 7	N/A	N/A
Materials	Course 3	Course 6	Course 7	N/A
Manufacturing Processes	Course 2	Course 6	Course 7	N/A
Product Tooling and Assembly Engineering	Course 5	Course 2	Course 6	Course 7
Product Design	Course 2	Course 6	Course 7	N/A
Process Design	Course 4	Course 5	N/A	N/A
Equipment/Tool Design	Course 5	Course 2	N/A	N/A
Mathematics and Science	All Courses Listed			
Manufacturing Systems and Operations	Course 9	Course 6	Course 7	N/A
Production System Design	Course 9	Course 6	Course 7	N/A
Automated Systems and Control	Covered In Different Courses			
Manufacturing Competitiveness	Course 4	Course 9	Course 6	Course 7
Quality and Continuous Improvement	Course 4	Course 9	N/A	N/A
Manufacturing Management	Course 6	Course 7	N/A	N/A
Personal Effectiveness	Course 6	Course 7	N/A	N/A

Table 2. PPAP topic area tied to course coverage.

PPAP Topic	Course Coverage			
1. Design Records	Course 1	Course 2	N/A	N/A
2. Authorized Engineering Change Documents	Course 2	Course 6	Course 7	N/A
3. Engineering Approval	Course 2	Course 6	Course 7	N/A
4. DFMEA or Design Failure Mode and Effects Analysis	Course 2	Course 6	Course 7	N/A
5. Process Flow Diagram	Course 8	Course 9	Course 6	Course 7
6. PFMEA or Production Failure Mode and Effects Analysis	Course 5	N/A	N/A	N/A
7. The control plan	Course 4	Course 6	Course 7	N/A
8. A Measurement System Analysis (MSA)	Course 4	Course 6	Course 7	N/A
9. Dimensional Results	Course 3	Course 2	Course 4	Course 7
10. Records of Material/Performance tests	Course 4	Course 6	Course 7	N/A
11. Initial Process Studies	Course 6	Course 7	N/A	N/A
12. Qualified laboratory documentation	Course 4	N/A	N/A	N/A
13. Appearance Approval Report	Course 6	Course 7	N/A	N/A
14. Sample production parts	Course 6	Course 7	N/A	N/A
15. Master sample	Course 6	Course 7	N/A	N/A
16. Checking Aids	Course 4	N/A	N/A	N/A
17. Customer-Specific Requirements	Course 2	Course 6	Course 7	N/A
18. Part Submission Warrant (PSW)	Course 6	Course 7	N/A	N/A

responsible for the execution of the production run was not allowed to touch parts during the production run, as they were managing their classmates who rotated as workers on the production line.

Because of the nature of this capstone experience and the competencies the students completed during their experiences in the program, the instructors felt that a PPAP project was a tremendous summative experience for the students. To execute the PPAP, the instructors provided the students with a PPAP lecture. The instructors then worked with the students to identify an appropriate part from their product to be used as a PPAP part. The students began work on the PPAP package and then produced the quantity of that part needed for their production run (usually 15-30 parts). While the authors recognized that this was not sufficient for an industrial PPAP, this dynamic did provide an opportunity for the authors to discuss the run-at-rate aspect of the PPAP and the importance of a number of parts sufficient to determine variation. Because students were not able to produce a large enough sample size of parts to truly determine the production capability, the authors, therefore, used the specification limits of the parts. That is, the authors compared the as-produced parts to the critical and noncritical dimensions, paying particular attention to how close the dimensions were to nominal (perfect) dimensions. This dynamic provided an opportunity for the instructor to reinforce the difference between production capability analysis contrasted with the design intent. Additionally, this further reinforced the importance of proper tolerancing of parts, as parts that had tight tolerances were problematic for the students to produce and measure. This led to discussions around the actual intent of tolerances and reinforced the added expense of implementing unnecessarily tight tolerances. One student remarked after the assignment:
“Half of our parts were bad.”

After part inspection, several groups found that their processes were not nearly as capable as they expected. Typically, this was due to an unnecessarily tight tolerance. The students worked with their professor to identify an appropriate part from their product to be used as a PPAP part. Students were allowed to act as though they were a supplier to the OEM with this part and followed the standard PPAP Level 3 processes and documentation. They produced approximately 25 production intent parts, which required them to develop engineering specifications, identify critical dimensions, design and develop tooling required to produce the parts, and inspect procedures—including a gauge R&R study as well as the final production warrant. Instructors wishing to deploy a PPAP project in their own classroom can easily do so with commonly available parts. For example, simple common parts such as a washer or a screw could be used for a PPAP exercise with students. Through this process, the students were able to experience the holistic PPAP experience as it relates to production activities. The students were able to use the PPAP part in their production run activity as they produced their products.

Student Perspective

Because of the nature of this capstone experience and the competencies the students completed during their experiences in the program, the instructors felt that a PPAP project was a tremendous summative experience for the students. At the conclusion of the experience, the authors offered an informal discussion with the students to assess their understanding of the PPAP process. Of the students who participated, none reported the PPAP as a negative experience. The instructor of the course remarked that there were no comments in their course evaluation pertaining to the PPAP. While formal surveys were not implemented, the authors were able to record informal comments from the students by asking them about their perceptions of the PPAP as a tool to be applied in a manufacturing setting. Approximately 20 students participated in the capstone PPAP project, and about half of them provided the following responses:

“My experience with PPAPs is limited, but they were utilized in our capstone during the production run and ended up being quite useful.” The student perhaps felt a bit uneasy, because this was their first PPAP, but they did recognize the value of the experience.

“I think it is an excellent, holistic tool.” The student recognized that the PPAP captured the manufacturing process requirements as well as the critical characteristics of the parts they are manufacturing.

“The PPAP ensures parts are within spec and have the proper dimensions. If quality is not ensured, then the parts will not fit together.” The students recognized that the purpose of the PPAP is to work towards robust and capable manufacturing processes.

“It’s a good thing to have and something I had no real idea about before.” The students recognized the usefulness of the PPAP as a tool to mitigate issues.

“It’s a big assignment and needed the whole team to complete it successfully.” The students recognized that the point of including multiple people with different perspectives and expertise were value added for the successful completion of the PPAP.

“The PFMEA caused us to redesign our tooling.” The students found an issue, while completing the PFMEA that had a high RPN, that a small tooling change would eliminate.

“Consistency in details is important”- making sure all of the forms were consistent with part numbers, part names, revisions, etc.

“Measuring takes a lot of time.” The students recognized that part inspection took much longer than some groups expected. Some groups had features that were difficult to measure and had to develop inspection fixtures.

"They asked about a PPAP during my interview." This student was interviewing for a Quality Engineer position and was asked about the PPAP during their interview; they were able to talk about their experience with the PPAP.

Feedback from students was very positive with but a few negative comments. The negative comments the authors did observe were generally related to failures identified by the PPAP process, not the PPAP process itself. For example, the students who mentioned that half of their parts failed were able to identify and remediate their situation before the parts were needed for actual production. This is precisely the purpose of the PPAP; to help mitigate issues before they impact production. The students did generally agree that the concept of PPAP should be introduced earlier in the program so that students can begin to see how their courses work together earlier. While the authors generally agree with this approach, attempts will be made to expand collaboration with additional instructors, as the authors work towards increasing collaborations across multiple courses.

A Manufacturing Vignette: Part II

A project manager is in the midst of launching a new product for the marketplace. The bills of materials (BOMs) are complete, the work instructions are in place, and employees are on the line to begin manufacturing. The project manager reflects on their last project, which experienced many part issues on the line. For this project, the project manager was able to pilot a PPAP process on some of the parts involved in the new product launch. As the first actual products began to be manufactured, the project sponsor noticed that the parts with a completed PPAP were available and generally did not have as many issues as the production parts where a PPAP was not completed. From a risk mitigation perspective, the project manager is very happy. While executing the PPAPs against the new production parts did create some work for both the OEM and the supplier, the results were worth the effort and is now considered to be a best practice by the OEM.

Discussion and Future Work

The student experience with the PPAP was well received by the students in the program, as indicated by their responses to questions about their experiences. The authors executed this PPAP project as a component of the capstone three times with similar results. The next steps should include creating a formal survey, perhaps with partner companies, to identify additional elements that can be incorporated into the PAPP project. While the PPAP process has been proven to ensure that a supplier can provide parts needed for production, there remain opportunities to modernize the documentation process to incorporate digital engineering elements. For example, many modern manufacturers have large initiatives to implement model-based systems engineering methodologies to help speed up product realization processes. Shortcomings of the PPAP process include the fact that it is relatively labor-intensive, and the perceived value might be less than the actual value of the PPAP exercise. This potentially yields opportunities for rubber stamping or careless work on either the OEM or the supplier (Pries & Quigley, 2013). This shortcoming of the PPAP process introduces opportunities for the instructor to discuss the dangers of rubber stamping; that is, automatic approval of paperwork without appropriate due diligence.

Finding an easy-to-use PPAP template to deploy in the classroom could be very helpful, and many companies will readily provide their PPAP template if asked. An instructor in manufacturing engineering could leverage the deployment of a PPAP project in the classroom as an opportunity to engage with manufacturers that are hiring graduates of the program. This type of interaction will hopefully not only illustrate the instructors' efforts to embrace current and relevant manufacturing practices but could also introduce further opportunities for collaboration between the instructors and industry. As of the writing of this paper, PPAP templates were easily retrieved via a simple google.com search. For instructors wishing to leverage the PPAP in their own classrooms, the authors suggest providing simple sample parts, such as washers or 3D-printed parts. The students can then work through the PPAP by creating the drawings, discussing the manufacturing processes, and completing other documentation. Students can complete a gauge R&R with simple calipers. The PPAP provides a robust mechanism for these deep discussions on manufacturability, documentation, quality assurance, and, most importantly, how the PPAP is applied to help ensure that component parts work as intended and are available in the quantity and quality demanded.

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Biographies

NEIL LITTELL is the Director of Project Management Programs, an associate professor, and Kraft Family Scholar in the Engineering Technology and Management department in the Russ College of Engineering and Technology at Ohio University, where he has worked since 2014. Dr. Littell earned his PhD in Workforce Development and Leadership from Mississippi State University. He earned his PMP (#1876209) in 2015 and is also an ATMAE Certified Senior Manufacturing Specialist. Dr. Littell may be reached at littellw@ohio.edu

MUSTAFA SHRAIM is an associate professor in the Department of Engineering Technology & Management at Ohio University. He received his PhD in Industrial Engineering from West Virginia University. He teaches courses in quality management systems, statistical quality control, and leadership. His research interests include quality engineering, management, and the Deming management methods. Mustafa is a Certified Quality Engineer (CQE) and Six Sigma Black Belt (SSBB) by ASQ, and a certified QMS Principal Auditor by IRCA. He is also an ASQ Fellow since 2007. Dr. Shraim may be reached at shraim@ohio.edu

DANIEL SHEETS is an assistant professor of instruction at Ohio University with a background in metal stamping and fabrication for aerospace, automotive, and nuclear companies. He earned both a Master's in Engineering Management (2018) and a Bachelor of Science in Engineering Technology and Management (2012) from Ohio University. Dr. Sheets may be reached at sheetsd1@ohio.edu

Appendix 1. Course descriptions from Table 2.

The authors are including the following course descriptions from the university undergraduate catalog:

Course 1: Engineering Graphics Fundamentals
Basic theory and practice in engineering drawing. Topics include geometric construction, orthographic projection, dimensioning, and auxiliary, section, and pictorial views. Lab activities include free-hand sketching and computer-aided design (CAD) using AutoCAD and SolidEdge software.

Course 2: Product Design
Study of product design from concept to release for production, with emphasis on design for manufacturability. Lab activities include the design, development, and creation of mockups and prototypes.

Course 3: Production Metal Machining
Theory and practice of production techniques for metal machining using manual and computer numerical control (CNC), machine tools, and non-conventional methods such as electrical discharge machining (EDM). Includes part print analysis, process analysis and planning, quality assurance factors, and computer-aided design and machining (CAD/CAM). Lab activities include programming CNC turning and machining centers to create molds and mass-produce parts.

Course 4: Quality Management Systems
Theory and practice of quality assurance principles in manufacturing. Includes statistical process control, process capability, gage capability, and quality management.

Course 5: Production Tooling
Theory and Practice of Designing and constructing tooling to improve productivity and quality in various manufacturing applications. Lab activities include using computer aided design (CAD) software to design work holding jigs and fixtures. Also includes construction and testing of jigs, fixtures, and gages.

Course 6: Operations Management Capstone I

Operations Management and Capstone I requires student teams to use knowledge from previous technical and business courses to develop a manufacturing operation plan for a product. This includes production planning and control, resource planning, product cost considerations. Students will experience current concepts of the new product development process. Emphasis will be placed on teamwork, project management, computerized production documentation, lean manufacturing, integration and optimization of business technical functions, operations within a manufacturing enterprise, Quality assurance planning and six sigma, product design and development. Lab activities include prototype and engineering builds of the product designed by the student teams. This is the first of the Capstone I and II series, which has to be taken in consecutive semesters.

Course 7: Operations Management Capstone II

The enrolled students use the documentation and project plan developed as a part of their culmination experience in Course 6. Based on this documentation they develop a production management plan, tooling, an inventory control system, work instructions and a quality control plan to execute a production run. Students gain supervision and management experience through this where each group manages their peers to produce 15-25 products in a 6-hour time period. Students evaluate their peers as part of the assessment. The same student groups from Course 6 are maintained and so students complete Course 6 and Course 7 in two consecutive semesters. Under special circumstances students are assigned to one of the teams in Course 7 by the instructor.

Course 8: Introduction to Engineering and Technological Sciences

This Course introduces the interdisciplinary scientific principles that drive modern engineering and how the scientific process is applied for practical means. The course includes the study of materials and processing, mechanical reasoning, documentation, and design. The course is open to students of all disciplines and does not require a background in sciences and engineering for successful completion.

Course 9: Lean Enterprise Methods

In today's world, organizations compete in a global marketplace. In order to compete successfully, organizations must eliminate all forms of waste from their process, through continuous improvement processes. Lean enterprise principles provide methods to achieve these goals. Lean operational approaches provide an organization with a set of methods and tools to assist in the identification and then continuous eliminations of waste and enterprise improvements.

DIGITAL TWIN INTEGRATION FOR SMART-CITY FRAMEWORK DEVELOPMENT

Wesley Conwell, University of Alabama at Birmingham; Leon Jololian, University of Alabama at Birmingham

Abstract

The development of smart cities requires a framework for managing the complexities of operating growing cities. Unfortunately, current smart-city framework implementation techniques do not take full advantage of potentially useful information generated by a given city, leading to wasted opportunities. From this study, the authors propose an integrated architecture that monitors the use and consumption of city resources, intending to manage these resources proactively in meeting citizen demands in a smart city. The components of the architecture comprise an Internet-of-Things (IoT) framework for data collection, big-data analytics for mining the data, a machine learning engine for discovering patterns, and a digital twin framework for the simulation of alternative solutions in the configuration of resource management.

Introduction

Whether driven by population shifts due to the global COVID-19 pandemic, a war in Ukraine, or other factors, population flows continue growing in city regions worldwide. Cities are the main poles of human and economic activity and hold the potential for creating synergies, allowing great developmental opportunities for their inhabitants. However, they also generate a wide range of problems that can be difficult to tackle, as they grow in size and complexity. The world's cities are growing in both size and number. In 2016, there were 512 cities with at least one million inhabitants globally. By 2030, a projected 662 cities will have at least one million residents (United Nations, 2016). In North America, more than half of the population lived in cities with 500,000 or more inhabitants in 2016, and one in five people lived in a city of five million or more. Current smart-city implementations promise to create systems that effectively manage growing cities' complexities. However, current smart-city framework implementation techniques squander the system's potentially useful generated information, leading to wasted resources. In this paper, the authors proposes a digital twin architecture for a smart city to more productively use existing data and establish a problem-solving architecture to manage the complexities assessed in the sub-domains of a smart city, such as smart energy, smart health, and smart transportation. This paper contributes to the growing area of smart-city research by exploring resource consumption in smart cities at varying levels of complexity. The proposed work highlights the advantages of a digital twin implementation structure in distinguishing between current and future frameworks for managing smart cities.

Basic Concept of a Smart City

Cities are a human invention, born from the human need for security, the convenience of living together, easier management of resources, better quality of life, and smaller mobility distances. With smart cities, people can reinforce their role and their proximity inside the city space (Zubizarreta et al., 2016). Despite considerable research in the field, debates remain concerning the definition of a smart city. In a study by Albino, Berardi, and Dangelico (2015), the authors refer to a smart city as a fuzzy concept used in ways that are not always consistent. There is neither a single template for framing a smart city nor a one-size-fits-all definition. First used in the 1990s, the term smart city focused on the significance of new information and communications technology (ICT) regarding modern infrastructures within cities. Smart-city researchers Batty et al. (2012) stated:

> The concept of the smart city emerged during the last decade of the 20th century as a fusion of ideas about how information and communications technologies might improve the functioning of cities, enhancing their efficiency, improving their competitiveness, and providing new ways of addressing problems of poverty, social deprivation, and poor environment. (p. 483)

More people are electing to live in cities more than ever, which poses unprecedented challenges for stakeholders to address city inhabitants' quality of life. Smart-city initiatives have emerged as an alternative for tackling sustainable city development challenges. Due to smart-city objectives being highly local and even regional, different cities require different "smart" solutions. Some studies suggest that the smart moniker is used to rationalize institutionalizing technology as a means of municipal power, shifting the discourse away from politics and citizen-centric policy to a technologically driven focus controlled by consultants and private industry (Osborne & Rose, 1999; Vanolo, 2014). Regardless, with no shared definition, cities are self-defining as smart without a consensus. Although various definitions abound, a smart city ultimately represents a complex system of systems that leverages innovative ICT to benefit a community, integrated with complex subsystems to fulfill its operational objectives.

Challenges for Managing Smart Cities

There are numerous challenges and opportunities for managing smart cities. Monzon's (2015) brilliant research on urban challenges in the Mediterranean provides excellent insight. Although his research focused on the Mediterranean region, the insights represent a global perspective. Monzon's research categorized the challenges into six key areas—governance, economy, mobility environment, people, and living. Monzon subdivides those key areas into several categories of specific global challenges, such as shrinking cities, unemployment, urban sprawl, affordable housing, problems of urban youth, and climate change effects. Growing populations in urban areas demand more resources and better services to meet the challenges ahead. As various challenges exist in managing smart cities, opportunities for improvement are born out of smart-city implementation to solve problems.

Prior Solutions to the Management of Smart Cities

In the smart cities' space, contributions are growing toward the body of work concerning unique solutions in the management of smart cities. First, Strohbach, Ziekow, Gazis, and Akiva (2015) established that an increasing amount of valuable data sources, advances in IoT, and big-data technologies offer new potential for delivering valuable analytical services to citizens and urban decision-makers. However, a gap remains in combining the current state-of-the-art in an integrated framework that would help reduce development costs and enable new services. In a study by Strohbach et al. (2015), the authors showed how such an integrated big data analytical framework for IoT and smart-city applications would work. Second, China is a fast-growing innovator of smart-city solutions and ideas. In a study by Chen, Wang, and Guo (2016), the authors noted that to build sustainable, livable, and safe cities, the Chinese government began experimenting with its first smart-city project in 90 cities in late 2012. The project aimed to transform digital cities into smart cities; and, as of 2016, over 290 cities were involved. China emphasizes the data from smart cities and the data from lifecycle perspectives (data collection, data analysis, and data-driven smart services).

Chen et al. further highlighted three unique challenges in China's smart-city efforts and presented three promising future directions to characterize a potential road map for smart-city development: 1) overwhelming amounts of data not being open for broader analysis; 2) structural deficiency in operating through centralized, top-down approaches; and, 3) reactive responses to significant events. Finally, in a study by Mohammadi and Taylor (2017), the authors addressed rapid urbanization challenges in which cities are determined to implement advanced socio-technological changes and transform themselves into more intelligent cities. However, the success of such a transformation relies on a thorough understanding of the city's states of spatio-temporal flux. Understanding such fluctuations in context and interdependencies among various entities across time and space is crucial, if cities are to maintain their smart growth. Mohammadi and Taylor also introduced a Smart City Digital Twin paradigm enabling increased visibility into cities' human-infrastructure technology interactions in which spatiotemporal fluctuations of the city integrate into an analytic framework.

The concept of a digital twin as a monitoring and analytical tool for tracking systems or operations of enterprises was the focus of this current research on developing an architecture that can monitor a smart city with a digital twin as its backbone. The primary research question was, how can a city implement smart concepts in its operations and management using a digital twin? The digital twin concept is increasingly popular with researchers and professionals seeking to visualize, model, and work with complex urban systems. Implementation occurs by coupling physical systems with comprehensive digital representations that can automatically update to match their physical counterparts' state (Dawkins, 2018). In the early 2000s, Michael Grieves developed the current framing of the digital twin concept, putting forward the embodiment of physical world items in a digital representation. Software clones physical objects and embodies Marc Andreessen's famous 2011 Wall Street Journal quote in which he stated that society is rapidly advancing to a point where "software is eating the world" (Andreessen, 2011). The digital twin concept follows the continuum advanced by the fourth industrial revolution, bringing forth the age of cyber-physical systems (CPS).

CPS is the core foundation of Industry 4.0, deeply intertwining physical and software components, with each operating on different spatial and temporal scales and interacting in myriad ways that change with context (Xu, Xu & Li, 2020). Within the construct of the digital twin in smart cities, there is no widely accepted standard architecture. Production engineering provided the foundational base for Michael Grieves' expertise in product design in the digital twin concept. In recent years, the idea broadened in its application to characterize various digital simulation models that run alongside real-time processes on social, economic, and physical systems (Batty, 2018). The smart health space is one area to draw lessons for more general applications.

ISO/IEEE 11073 (X73) Personal Health Device standards emerged in 2008 to facilitate communication between personal health devices (such as computer systems and smartphones) and healthcare managers. The standards promote health data exchange facilitation, while providing plug-and-play, real-time interoperability. Adherence to the X73 communication model establishes the minimum requirement for personal health devices and managers to be X73 compliant. The X73 standards ensure that a health device and a compliant manager can complete the data transfer successfully. The overall requirements include: 1) data collection using sensory devices; 2) standardization of data communication; 3) data analytics to detect patterns; and, 4) real twin and health caregiver feedback using hard and soft actuation.

Expanding the digital twin push for some measure of standards, industry titans joined the conversation. Microsoft (2021) developed Azure Digital Twins leveraging its Azure cloud computing service. Established by a platform as a service (PaaS) offering, Azure Digital Twins enables the creation of digital models of entire environments. These environments include buildings, factories, farms, energy networks, railways, stadiums, and entire cities. Also, IBM developed a digital twin exchange for uncomplicated access to digital twin data for equipment, facilities, and IoT; it uses real-time data to enable understanding, learning, and reasoning—applications such as the Duke Energy renewables wind turbine fleet and Europe's largest shipping port–Port of Rotterdam.

A Smart-city Architectural Framework

City services and infrastructures are being stretched to their limits in scalability, environment, and security, as they adapt to support this population growth. Thus, visionaries and planners seek a sustainable, post-carbon economy to improve energy efficiency and minimize carbon-emission levels. Along with city growth, innovative solutions are crucial for improving productivity (increasing operational efficiencies) and reducing management costs. The development of a broad-based, solution-focused architecture helps manage the complexity. In smart cities, technological advancement offers new potential for delivering analytical services to citizens and urban decision-makers. However, a gap exists between combining the current state-of-the-art in an integrated framework that would help reduce development costs and the enabling of new services. Research undertaken by Mohammadi and Taylor (2017) and Dawkins (2018) yields insight into the establishment of models relaying the shift to a digital-twin/smart-city paradigm.

The research by Mohammadi and Taylor (2017) constituted a pragmatic perspective in developing a model to capture data from an actual city (Atlanta, GA) and account for spatiotemporal fluctuations at the intersection of reality and virtuality. In a study by Dawkins (2018), the author investigated this paradigm shift through the lens of a solution in visualizing, modeling, and working with complex urban systems across the Atlantic at London's Queen Elizabeth Park. Building on the efforts of Mohammadi and Taylor (2017) and Dawkins (2018), Figure 1 shows the proposed framework from this current study on digital-twin/smart-city architecture. Regarding an overview of the framework, the starting point was a representative smart city digitized via the Microsoft Azure platform (Microsoft, 2021) then optimized.

First, the monitoring tier senses components associated with resource consumption. The framework's approach starts with the IoT element connecting the sensors necessary to feed the data required to inform the development of the digital twin. IoT sensors are the digital foundation of a smart-city framework. This section of the framework includes the application of edge computing, where the sensors in a subsystem of the smart city tie to the larger, more extensive system with distributed sensors in the field, where computation may occur at a distant location or near the device. Second, a middle layer analyzes data to detect real-time anomalies or patterns. Storage encompasses this aspect as a component of the big-data framework. This is also where data can reveal patterns and trends unseen in previously constructed operational frameworks. The third layer of the proposed framework involves machine learning to discover the classification of the type of usage for relevant resources, predictive models, and other aspects of discovery feeding into the recommender subnetwork to assess trends and consumption valuations. The architecture connects to the recommender system's interdiscipli-

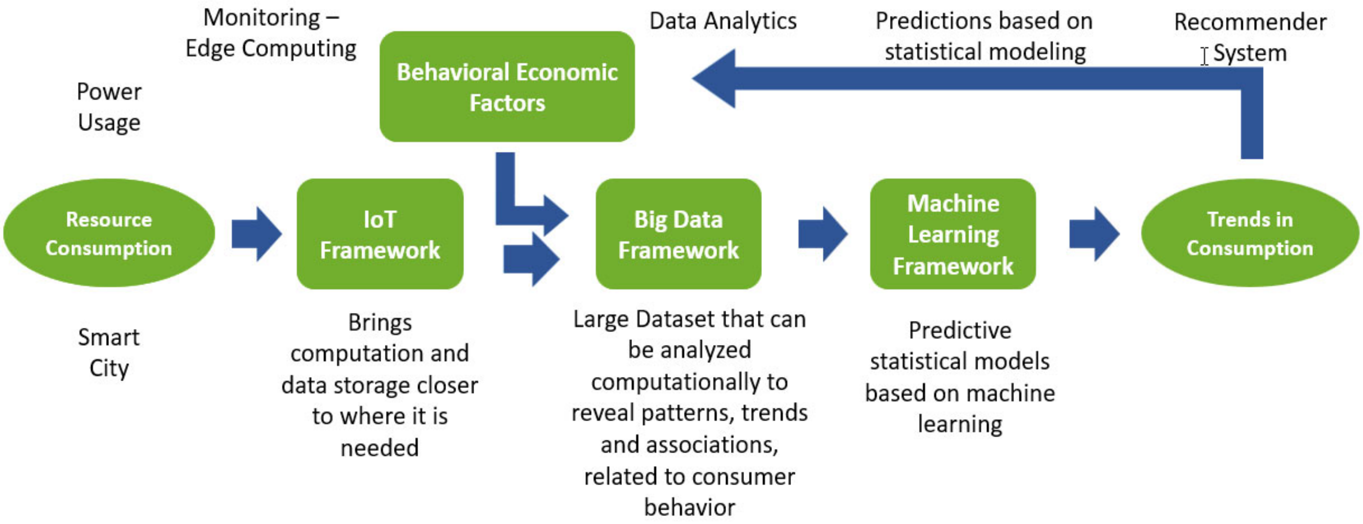


Figure 1. Research architecture.

nary component associated with behavioral economic factors. Those factors additionally serve as input to the big-data framework. The behavioral economic factors are important, because they inject the conceptual measure of uncertainty and irrationality into the framework related to human decision-making. In expanding the accessibility of smart city component implementation, this research proposes a structure within which the construction industry provides the point of entry (Jones, 2021). Figure 2 presents the engagement of smart city implementation across varying levels. These five levels of development allow for implementation to be as simple or as complex as resources are available for a city.

- Level 1 is the Descriptive Twin level. It is a live, editable design version—a visual replica of a built asset. Users specify what information they want to be included and what data they want to extract. It conveys the most basic level, essentially converting analog data to digital format, and acts as the base for all of the upper levels.
- Level 2 denotes the Informative Twin level, with an added operational and sensory data layer. The twin captures and aggregates specific data, then verifies it to ensure that systems work together.
- Level 3 is the Predictive Twin level. This twin can use operational data to acquire insights. At this level, insights from the data answer questions about why certain things or situations occur, and data analysis becomes a common component at this stage.
- Level 4 is the Comprehensive Twin level, and simulates future scenarios and considers "what-if" questions. At this level, systems can respond to future scenarios and decide accordingly; artificial intelligence algorithms are also prevalent.
- Level 5 is the Autonomous Twin level. This twin can learn and act on behalf of users; the machine recommends the ideal solution and takes action. This level of implementation represents the ultimate sophistication of the proposed architecture.

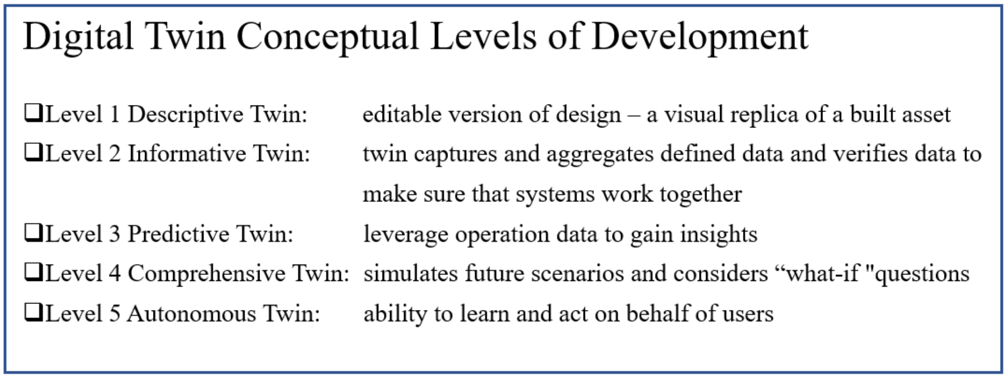
Case Study

A case demonstrating the implementation of the digital twin framework is the next step in this research's development. For validation, the model explores a smart-energy case from a sample of residential electric utility customers from the Pecan Street Research dataset. From the digital twin perspective, residential home automated metering infrastructure (AMI) sensors express the sampled customer energy data. Energy data analysis focuses on optimizing the system via increased efficiency and lower overall costs. Microsofts's Digital Twins Definition Language (DTDL) provides the platform for modeling the noted sensors. DTDL uses a variation of the JavaScript Object Notation (JSON) format, namely JavaScript Object Notation for Linked Data (JSON-LD). JSON-LD is a lightweight Linked Data format and provides a way to help JSON data interoperate at Web-scale. Microsoft developed DTDL for describing models that include IoT devices (such as AMI meters), device Digital Twins, and asset Digital Twins (Nath & van Schalkwyk, 2021). Figure 3 provide an example of the DTDL code.

```
{
    "@id": "dtmi:digitaltwins:rec_3_3:device:ElectricalEnergySensor;1",
    "@type": "Interface",
    "displayName": {
      "en":  "Electrical energy sensor"
    },
    "extends":  "dtmi:digitaltwins:rec  3  3:device:EnergySensor;1",
    "@context":  "dtmi:dtdl:context;2"
}
```

Figure 3. DTDL code for AMI sensor.

Next, sampled AMI meters are aggregated via the Microsoft Digital Twin platform. Then, assessment of relevant patterns occurs via the Azure Auto Machine Learning (ML) module for further insights regarding energy efficiency and potential cost savings.



Digital Twin Conceptual Levels of Development

❑Level 1 Descriptive Twin:	editable version of design – a visual replica of a built asset
❑Level 2 Informative Twin:	twin captures and aggregates defined data and verifies data to make sure that systems work together
❑Level 3 Predictive Twin:	leverage operation data to gain insights
❑Level 4 Comprehensive Twin:	simulates future scenarios and considers "what-if "questions
❑Level 5 Autonomous Twin:	ability to learn and act on behalf of users

Figure 2. Conceptual levels of development.

Conclusions

Although researchers have not firmly settled upon the authoritative definition of a smart city, the authors of this current study define it as the integrated framework of services, operational, and human-technology interactions that allow for the efficient and beneficial needs of the citizenry in a densely populated urban setting. Notably, the literature has more of a consensus in defining the digital twin as the computer-generated representation of an actual process or entity, which was suitable for this current research application in the implementation of a smart-city framework. In constituting the digital twin in the smart-city framework, this focus of this current study was on the smart-energy domain employing three quintessential technologies of the Industrial 4.0 era: 1) IoT as analogous to the "eyes and ears" within the context of necessary sensors in the smart-city framework, represented by AMI inputs in the smart-energy domain; 2) big data in the smart-energy space tied to the enormous datasets previously not available in the analog-based energy billing meters; and, 3) machine learning capabilities to leverage tools, algorithms, and data analytics yielding insights for the digital twin implementation in the smart-city framework.

Integrating these components leads to the research aim of developing an architecture that can monitor a smart city with a digital twin as the backbone of the implementation. The digital twin concept is becoming increasingly popular with researchers and professionals in various industries to visualize, model, and work with complex urban systems. This current research contributes to the development of an architecture that can monitor a smart city with a digital twin as the backbone of the implementation. Future work will focus on the development and testing of this model using a fully developed digital twin case study of the smart-energy sub-domain.

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Biographies

WESLEY CONWELL is a PhD candidate in interdisciplinary engineering at the University of Alabama at Birmingham. He earned his BS in electrical engineering from the University of Alabama, MBA from the University of Alabama at Birmingham, and MS in electrical engineering from the University of Alabama at Birmingham. Mr. Conwell's research interests include smart cities, data analytics, big data, the Internet of Things, and machine learning. Mr. Conwell may be reached at wlconwel@uab.edu

LEON JOLOLIAN is Interim Chair, Professor, and Undergraduate & Graduate Program Director at the University of Alabama at Birmingham. He earned his BS in electrical engineering from Manhattan College, MS in electrical engineering from Georgia Institute of Technology, MS in computer science from Polytechnic University, and PhD in computer science from the New Jersey Institute of Technology. Dr. Jololian's research interests include component-based software architecture, mobile and cloud computing, the Internet of Things, and machine learning. Dr. Jololian may be reached at leon@uab.edu

UNDERSTANDING BARRIERS OF INSTRUCTOR ADOPTION OF BLENDED LEARNING IN AN INTERNATIONAL SETTING

Shweta Chopra, Central Michigan University; Christine M. Witt, Central Michigan University

Abstract

Worldwide, the education system has witnessed an enormous transformation, especially in this last decade. Innovations in information and communication technology are rapidly evolving and improving in this field. As a result of these developments and the COVID-19 protocols of the past, today's education system is no longer limited to a traditional classroom. The use of internet and communication technologies (ICTs) to assist pedagogy has a vast impact, particularly on the higher education sector. ICTs have changed the way higher education is delivered, assessed, and managed. This global study involved a U.S.-based university providing instructors at African universities course materials to teach in a blended learning (BL) format. Participants were significantly more positive about the quality of the content and their comfort level in carrying out the course discussions due to the BL platform. Most participants observed improved student interaction and communication. This study has implications for the encouragement of faculty adoption of BL platforms.

Introduction

The technological revolution in education has caused a rapid development of E-learning, online learning, and blended learning (BL). These terminologies are often used inconsistently by users and researchers in the education field and have conflicting definitions in various articles (Moore, Dickson-Deane & Galyen, 2011). Distance learning refers to a learning system that allows students to access an instructor's course materials from a geographically distant area (Moore et al., 2011). The invention of the computer and the subsequent explosion of digital technologies played a vital role in the introduction of this delivery system. The term distance learning evolved and gave rise to other forms of learning systems, namely E-learning, online learning, and blended learning (Conrad, 2006). E-learning can be defined as learning supported by ICT devices such as computers, laptops, tablets, smartphones, and CDs (Ellis, 2004). E-learning can be broadly classified into synchronous and asynchronous. Synchronous E-learning uses a learning model in which information and communication technologies enable students to access live classroom sessions or meetings.

Asynchronous E-learning is typically offered via the internet and allows students to control their learning schedules and pace (Takalani, 2008). The terms E-learning and online learning originated in the 1980s and are often used synonymously (Moore et al., 2011). For this discussion, E-learning and online learning refer to the same learning method. Course content in online learning is delivered completely online; that is, internet-based (Oblinger, Oblinger & Lippincott, 2005). Online learning offers students convenience and flexibility with respect to the study location, time, and course duration (Jacob & Radhai, 2016).

Online Learning Advantages

Students can now take a variety of quality online learning classes globally. Classes are offered with renowned experts from different parts of the world and students have access to quality information never before possible. Online programs are often cost-efficient compared to attending the courses physically at a university (Bartley & Golek, 2004). Studying online can save commuting costs as well as the infrastructure fees charged by schools or universities. Online learning is less affected by campus shutdowns for pandemics, natural disasters, or political upheaval (Witt, Trivedi & Aminalroayae, 2021).

As the cost of education is rising, students often need to work to support their education. Online learning enables students to apply knowledge gained through these courses at work without a lag. Online learning helps professionals continue their education without leaving their job to improve their technical skills and advance their careers. Online programs also help to avoid any discontinuity or gap in the person's résumé. Online programs often offer a wide variety of courses from which professionals choose appropriate courses based on their career path (Benson, 2002; Larreamendy-Joerns & Leinhardt, 2006.

Online students can benefit from video lectures that are included with course materials. Recorded lectures ensure that important class topics are covered. Students can replay video lectures for their various needs, including loss of concentration or reinforcement of a topic. The video lecture will always be available for access when students revisit the topic. This may not be possible in a traditional classroom, particularly if the student is shy and hesitant about asking the instructor to repeat the topic. It can also affect a student's understanding of the rest of the topics discussed in the class. These web-based lectures have a positive effect on student learning outcomes and enhance student satisfaction (Zhang, Zhou, Briggs & Nunamaker, 2006). Online discussion forums in online learning platforms help students who have inhibitions in participating actively in traditional classrooms.

Limitations of Online Learning

Even though online learning has numerous advantages, it has some limitations. One of the main limitations of online learning is the lack of social interaction. Limited interaction between the students and teachers can adversely affect student learning. A study conducted by Laine (2003) concluded that asynchronous online learning may not be as effective in higher-level studies in areas such as information technology. When a significant amount of learning occurs using software and solving problems in the presence of an instructor, online learning can be deficient. The value of having an instructor providing support and instruction in a traditional classroom is difficult to duplicate in online learning. Other aspects of the student experience may not be present in online learning. Some online students may feel lost or isolated in an online learning environment (El Mansour & Mupinga, 2007).

Students may feel overwhelmed, if they don't receive proper directions on where to find the resources in the online platform. This can lead to students feeling frustrated, anxious, and confused (Noriko & Kling, 2003; Piccoli, Ahmad & Ives, 2001). This may not be an issue in the traditional classroom, where students make a physical connection with their peers and instructors compared to online learning. Online learning programs demand more discipline, self-motivation, and time commitment from students (Golladay, Prybutok & Huff, 2000; Serwatka, 2003). Student inquiries are handled differently in an online environment. In a traditional course, students can ask questions when they are confused.

However, in an online learning setting, students typically have to wait for an email response or assignment feedback. Traditional classrooms offer a conducive environment for students to learn from their peers' experiences, group discussions, and social interactions. Such components can completely lag in an online learning environment or are not built into the course (Paechter & Maier, 2010). In a traditional classroom, instructors can understand the mood or emotions of the class and appropriately choose the content for the class. They can also control the pace of their instructions better when they are in a traditional classroom. This is not possible in an online environment and can be considered another limitation. Conrad (2002) found that instructors feel a "bit in the dark" in an online learning environment, as they are not able to observe the students for cues.

Blended Learning

The limitations of online learning have led to a different delivery system termed blended learning (BL) (Davis, 2000; Koohang & Durante, 2003). BL is defined as an introspective integration of face-to-face traditional classroom learning and online learning experiences (Garrison & Vaughan, 2008). BL involves instructors utilizing online learning elements prior to or after their course meets in a traditional classroom. This delivery system utilizes the best features of online learning and face-to-face learning (Garrison & Kanuka, 2004).

In certain situations, students may be asked to complete online content before attending the classroom session. This allows instructors to go into greater depth on a topic during the face-to-face meeting time. This type of BL environment is called a flipped classroom. A component of flipped instruction requires students to view online lectures before the face-to-face session with the instructor. Many of the learning activities will be performed in face-to-face sessions in the presence of the instructor. This allows the instructors to give immediate feedback on student learning activities and the students will have a better understanding of the lecture (Gilboy, Heinerichs & Pazzaglia, 2015; Roach, 2014). A flipped classroom is student-centered. Students are responsible for working through the course materials and having a basic understanding of the materials. This allows for more student participation in class discussions or activities, which can lead to a deeper understanding.

In some situations, students may be asked to use the online content after the classroom session through discussion forums or quizzes to revise the topic covered in the classroom session (Smart & Cappel, 2006). Deperlioglu and Kose (2013) and Suda, Sterling, Guirguis, and Mathur (2014) studied the impact on students and found that BL had a positive impact on the learning process among the student population. Further, other studies demonstrated that students enrolled in BL achieved higher academic performance compared to students pursuing face-to-face or online courses (Bernard, Borokhovski, Schmid, Tamim & Abrami, 2014; Suda et al., 2014; Vernadakis, Giannousi, Derri, Michalopoulo & Kioumourtzoglou, 2012). Table 1 presents each learning system and definition used for this study, based on seminal research. Although BL has become popular across the globe, there are some challenges with respect to its implementation, delivery, and quality assurance.

Challenges with Blended Learning Systems

The implementation of BL has been smooth in developed and most developing countries. However, BL has been a challenge in less-developed countries such as African countries. The challenges can be classified into three levels: 1) technological; 2) university management; and, 3) academic. Tarus, Gichoya, and Muumbo (2015) and Aminu and Rahaman (2014) studied challenges faced by BL systems in Kenya and Nigeria, respectively. Both studies reported similar results with technological challenges. When attempting to adopt BL, the authors identified poor ICT infrastructures at the universities. Participants identified internet bandwidth and lack of technology related to the online platforms.

Table 1. Definitions of learning systems.

Learning Types	Definition	Research Paper
Face-to-face learning	Traditional learning in a classroom setting that may not use online study resources	
Distance learning	Delivery system where the students are located in a geographically distant area from the instructor.	(Conrad, 2006)
E-learning	Includes course contents and instructional methods delivered via Internet, audio tapes, videotapes, satellite broadcasting, interactive television	(Ellis, 2004)
Online learning	Delivery system which is wholly online or internet based.	(Oblinger et al., 2005)
Blended learning (BL)	Introspective integration of face-to- face traditional classroom learning and online learning experience	(Garrison & Vaughan, 2008)
Flipped classroom	Students attend an online lecture and/or complete assessments before the classroom session, students perform the learning activities in classroom in the presence of the instructor	(Gilboy et al., 2015; Roach, 2014)

Inadequate or lack of ICT, such as laptops or computers for accommodating the students enrolled in a BL program, were reported. The standard of other ICT infrastructures—such as Wi-Fi, routers, and wired connections for setting up quality internet connections—was poor at these universities (Aminu & Rahaman, 2014; Tarus et al., 2015). University management-level challenges included insufficient budget allocations by the university administration for implementing or enhancing the ICT infrastructures. Another challenge was that universities had inadequate online learning policies. The root cause of these challenges was the lack of funding available to the universities (Tarus et al., 2015). Faculty participating in BL programs face several challenges. Developing the online learning content for a BL classroom demands a major time investment. This time is in addition to the faculty's regular classroom teaching hours and is often uncompensated. Islam, Beer, and Slack (2015) identified that instructors face difficulties when managing their time while implementing BL in their classrooms and do so without any additional pay. Lack of technical support for academics while accessing the online content of a BL system is another challenge. Instructors are often not capable of solving a myriad of technical issues they face when using BL.

Significance of the Study

The focus of this current study was to investigate BL and compare it to other learning types. Technological challenges faced during the adoption of BL programs in professional courses at universities were identified. Another aim of this study was to investigate and recommend the best technological practices to smoothly implement BL systems. The results of this study can be applied in higher education and other educational institutions that are planning to incorporate BL programs into their educational systems. A BL curriculum developed by a midwestern university in the U.S. for an e-curriculum master's program at three universities located in South Africa, Uganda, and Ghana was studied. The e-curriculum master's program was focused on plant breeding E-learning in Africa (PBEA) and genetics. The course content for this program was designed and prepared by faculty in agronomy, statistics, research methods, and engineering departments at the U.S. university. The course teaching materials were uploaded to the BL platform for the instructors at these African universities. Students enrolled in the program also had access to these online materials for their reference and learning.

The authors of this study aimed to investigate the technological challenges experienced by instructors at African universities while adopting BL programs. While there are previous studies that address the challenges associated with the implementation and management of BL systems, this is a first-of-its-kind study, where the focus was on the instructors at African universities and their use of course materials prepared and provided by a university located on a different continent. This seminal research is unique in that the online content was developed by the instructors themselves. Previous studies that evaluated BL technologies focused on the quality of ICT infrastructure in different countries and identified challenges faced at the universities while adopting a BL learning program. This current study focused on the experience of the instructors at these African universities.

Research Methodology

A mixed-method research design was selected and applied to this study. Mixed method involves the collection of both quantitative and qualitative data. A questionnaire-based survey was conducted to collect the quantitative data. Qualitative data was collected from focus group participants. Qualitative data helps to corroborate the quantitative data collected through the questionnaire-based survey (Bazeley, 2006). A mixed-method research design allows for a comprehensive and complete understanding of the various aspects of the BL platform under investigation.

Participants of the survey included seven faculty from three African universities associated with the BL platform. The seven faculty members had an average of 8.5 years of experience at their respective universities. Participants also averaged two years of experience working in the BL platform developed by a U.S. university. Prior to conducting the survey of the focus group, the questions were validated with the help of three academicians and researchers, who had experience in BL education and technology acceptance models. The survey questions were refined using their expert feedback.

The feedback involved readability enhancement, change in question sequencing, and additional question suggestions. Prior to data collection, a brief presentation was made by one of the authors to participants discussing the research background. Participants were briefed about the Internal Review Board protocol. Before data collection, participants were informed of the volunteer nature of their participation and the ability to discontinue at any time. No personal identification information was collected.

Survey Design

Survey and focus group questionnaires were prepared by referencing a literature review on BL and previously validated questionnaires. Through previous studies, existing challenges with respect to BL adoption and management in various countries were identified. Survey questions were designed to inspect if these challenges were applicable to the current study. A literature review was completed to understand the factors leading to the acceptance of BL technologies. The survey questions were divided into two categories: 1) individual demographic questions (university, gender, and years of experience of the academics, age, and course/courses taught by the academic), and 2) Likert-scale questions were aimed at understanding the level of agreement of faculty on the current learning type and various factors identified of technology acceptance in a BL environment.

A five-point Likert scale, ranging from strongly disagree (1) to strongly agree (5), was used to measure the level of agreement of faculty on the survey questions. Likert-scale questions were prepared by referring to previous studies on BL and technology acceptance models (Islam et al., 2015; Dečman, 2015; Farzin & Dahlan, 2016; Ramayasa, 2015; Bradford & Wyatt, 2010). Survey questions assessed the following features of the current study platform.

- Comfort level of faculty with the use of ICT
- Challenges and advantages associated with the BL platform for faculty and students
- Level of expertise and efforts needed in blended mode teaching
- Evaluation of the impact of university ICT infrastructure, technical assistance, training, ease of use, and the faculty workload on the teaching and learning process in BL

Survey Dissemination

The survey was conducted among seven faculty from African universities when they were visiting the Midwestern university for a boot camp in August of 2017. These faculty members have been part of the identified BL program for more than two years at the time of the focus group. They had all received training on BL and ICT. A paper-based survey questionnaire was used. A cover letter and a consent form that explained the details of the research and participant rights were included along with the questionnaire. This study complied with the university's Internal Review Board requirement.

Focus Group

Focus groups are selected by researchers to discuss the subject of the research, from their personal experience. This allows researchers to quickly recognize the full range of perspectives held by the participants (Powell & Single, 1996). Focus groups allow the participants to interact with each other, ask questions, and comment on each other's experiences and opinions (Kitzinger, 1995). Due to the preliminary nature of the study and the limited number of participants, a focus group was an ideal data collection technique. It allowed for the collection of attitudinal data and perspectives of the faculty members. Furthermore, a focus group design accommodated the rare nature of this study with faculty from three separate universities located in different parts of the world to meet and discuss their individual experiences with BL. The questions for the focus group were identified through the literature review and based on the prior experience of the researcher in the field. Table 2 shows the guiding questions used in the focus group.

Qualitative and quantitative data were collected on the same day. In this study, the questionnaire-based survey information was used for further validating focus group information. The objective of the focus group was to obtain detailed information about personal or group feelings, perceptions, and opinions of faculty on the various aspects of the BL platform. The focus group offered an opportunity for the participants to seek clarification on the questions asked in the survey. A set of open-ended questions were posed to the participants in the focus group and were of a similar theme to the survey. Discussions of the open-ended questions were recorded with the permission of the participants, and the responses were later transcribed for data analysis. Data triangulation was completed with the help of expert academicians that had observed instructors and students participating in the BL curriculum at African universities.

Results and Discussion

The data collected through the survey questionnaires and focus group were analyzed separately. Five of the seven participants agreed that the students enjoyed the BL environment. Four of the seven participants believed that the students learned better with the BL platform compared to the traditional classroom. Instructors valued that, “students can use reference materials at the time they want. They have more flexibility in learning process because of the platform.”

Table 2. Focus group guiding questions.

Question Number	Question focus group was asked
1	Why do you use Plant Breeding E-learning in Africa (PBEA)? Is it mandatory to use PBEA for the program you are part of?
2	How were you introduced to PBEA?
3	Do you feel that the use of PBEA platform has helped to deliver the courses better than the traditional classroom teaching? Why?
4	Do you have any suggestions to improve the PBEA platform?
5	What suggestion do you have to improve the student engagement in the PBEA platform?
6	What are your suggestions on implementing any new technologies (that you know of) on the PBEA platform to improve the delivery of the courses?
7	What are your suggestions on improving the infrastructure at the university to improve the course delivery?
8	Do you feel the need for any additional support, technology, or training that could help you in using the PBEA platform better? Please explain.
9	How does the student assessment in the PBEA platform differ from traditional classroom teaching?
10	What are the most positive aspects of teaching a course using the PBEA platform?
11	What are the least positive aspects of teaching a course using the PBEA platform?
12	What advice would you give to a faculty member considering a blended learning course (like PBEA platform) for the first time?
13	What are the challenges you face while accessing PBEA platform?
14	What sets you apart in your organization is if you have decided to use PBEA that others have not?

Six of the seven participants felt that the predesigned BL platform was easy to use. The faculty didn’t receive any training in accessing or using the BL platform. Even though the faculty found it difficult initially to use the BL platform, they were quickly able to get acquainted with the environment and use the platform with ease. Although initial struggles and challenges existed, due to a lack of training, there were no significant problems using the BL platform. This is supported by a participant’s response, “Initially it was difficult using the platform, now it is not.” Six of the seven faculty stated they were not able to solve the technical problems associated with the computers while accessing the program by themselves. Four of the seven participants said that they had received assistance in resolving the technical problems related to BL, whereas the rest of the participants disagreed. An instructor stated that “there is technical support for the students and faculty from the IT department of the universities.”

Although there was a support team to provide technical assistance for faculty and students, they were not fully satisfied with the support they received from the IT department. All seven of the participants found the information and technology infrastructure good at the university level. The literature review identified the main challenges with respect to the usage of BL platforms as the lack of quality ICT infrastructures. Many universities lacked enough computers for their students and internet connectivity. In the case of this BL program, ICT infrastructure was not an issue. The faculty involved with this study referenced quality libraries and computer labs during the focus group through this statement, “Libraries and computer labs work 24 hours which the students can access.”

Even though the universities had quality ICT infrastructures like computer labs, laptops, and Wi-Fi, the important thing for BL programs to consider is ensuring students and faculty can use these infrastructures for accessing BL courses. Participants of the survey and focus group raised concerns that internet connectivity and electricity were not available to them all the time, which hindered their use of the ICT infrastructures for learning and teaching activities. Three of the participants reported issues with high-speed internet—it was unavailable. Poor internet connectivity and electricity were previously identified by other studies, particularly those in African countries. This challenge was faced during this BL study and supported by a participant’s statement, “When there is no internet or electricity, the faculty is out of work.”

Six of the seven participants agreed the BL course content was high quality. One participant neither agreed nor disagreed. All participants agreed that they were comfortable carrying out the BL course discussions. A participant praised the BL system with the statement, “The quality of BL course content is better than the one we have been using earlier for traditional classroom teaching.” However, the survey results indicated that the BL platform was not being utilized by all the faculty. Even though five of the faculty used the BL platform three to four times a week, two faculty reported they seldom used the BL platform for teaching. Two faculty reported ICT infrastructure issues as the main reason for seldomly using the BL platform. These faculty only used ICT for the courses that were connected to the program in this study.

Six of the seven participants felt that the additional effort required to teach the BL courses was high compared to traditional classroom teaching. This aligns with previous studies that identified additional effort without any extra pay as one of the major concerns or dissatisfaction for the academics about BL. Six of the seven BL faculty that participated in this study said that they were still satisfied with the BL platform despite the additional effort. Four of the faculty agreed that the BL platform had improved the interaction between them and the students. Two of the participants neither agreed nor disagreed on the improvement of faculty-student interaction due to the BL platform. One participant disagreed and did not believe that the BL improved their interaction with students. Most of the faculty reported that the BL platform presented students with a better structure for the learning activities and enabled better communication between faculty and students.

The findings that better student engagement is a feature identified as an advantage of BL systems compared to traditional classroom learning were consistent with the literature review. Three of the seven participants strongly agreed that they were happy with student engagement on the BL platform; three participants neither agreed nor disagreed on whether they were happy with BL systems. One participant stated they were not happy with the student engagement aspects of a BL system. Three of the seven faculty felt they were more respected at the university because they were teaching a BL course, while four of the seven participants disagreed on any positive influence at their institution based on their usage of a BL platform.

Implications and Conclusions

The responses and data collected from this study of three universities in South Africa, Uganda, and Ghana verified that similar challenges and benefits exist across all countries, when faculty adopt blended learning platforms. The results can inform the practice of designing and supporting BL e-curricula, especially at the university and professional levels. An implication of this study is that satisfaction with BL platforms may encourage faculty usage. Many of the survey respondents were significantly more positive about the quality of the content and their comfort levels in carrying out course discussions due to the BL platform. Several faculty judged the course content to be superior to the traditional classroom materials used for the course. Most of the participants observed improved student interaction and communication.

A survey of the literature published on BL revealed some universal problems that need to be addressed when implementing E-learning and BL platforms. In this study, all respondents were positive and satisfied with the information and technology infrastructure of their respective ICT departments. Six of the seven participants encountered difficulties initially navigating the BL platform. Only four of the seven participants received the needed assistance to resolve their problems. In addition to needing better assistance, faculty also reported issues with electrical outages and internet connectivity.

This study has similar implications for future studies conducted on BL. Quality IT infrastructure and support are essential aspects of successfully implementing BL platforms. Work sessions designed to offer collaborative sessions and IT problem-solving support should be held. Ideally, these sessions should be compensated or fulfill department commitments to motivate faculty in adopting all aspects of the BL experience. Follow-up sessions could also help faculty to identify any areas of the BL platform they want to improve. Such sessions could also help instructors to recommit to the BL platform and continue to improve their skills. Surveys of both students and faculty need to be conducted to determine problem areas and improve the quality of the BL platform for each course.

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Biographies

SHWETA CHOPRA is a faculty member in the Department of Business Information Systems at Central Michigan University. She was previously an assistant professor in the Engineering Technology and Management Department at Ohio University. She holds a PhD in Industrial Technology from Purdue University, and MS and BS degrees in polymer engineering from Pune University. Her research interests include lean manufacturing for small and medium organizations, healthcare, and the use of information and communication technology for food distribution and measuring student learning outcomes with industry engagement. Dr. Chopra may be reached at chopr1s@cmich.edu

CHRISTINE WITT is an associate professor in the Business Information Systems Department at Central Michigan University. Dr. Witt holds a PhD in Technology from Purdue University and a Masters of Educational Technology from Central Michigan University. Her research interests include blended learning, flipped instruction, student learning of Enterprise Resource Planning systems, scaffolding simulations to support student learning, and lean business process improvement. Dr. Witt may be reached at witt1cm@cmich.edu

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Bowling Green State University-Firelands
One University Drive
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Office: (419) 372-0628
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