

Blended Intensive Program: Set-up of Smart Steam Engine Systems

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Keywords: OEE, MQTT communication, Artificial Intelligence, Data, Smart systems

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Abstract

An international program where technical topics are addressed requires careful attention. It is important to engage students with various topics in technology. Additionally, thorough preparation is necessary to ensure students are fully prepared for the program.

During the preparation phase, the technical objective of the week-long program must be clearly communicated. The technical goal of this program is to improve Overall Equipment Effectiveness (OEE) of a steam engine. The process begins with sending data via a Programmable Logic Controller (PLC) over MQTT communication to a broker. Using NodeRED, this data can be visualized, and with a Python script, it can be recorded into a dataset. With this dataset, an AI model can be selected and trained. The model is then to predict the trend of the chosen output as accurately as possible. The program spans one week, during which all steps are carried out to optimize the AI model and maximize the OEE.

1 Introduction

The technical department PXL Green & Tech will organise a Blended Intensive Program (BIP) for international students during the 2nd week of February 2025. A project should be developed for this BIP.

Nowadays, it is easy and popular to bring international students together to learn about a subject over a short period of time. Therefore, if students from different nationalities with different backgrounds from different countries want to take the same programme, they need to be well prepared for such a program. Therefore, they should be prepared beforehand to participate in the course as good as possible. Because of the language differences, the language of such preparation is English. Furthermore, the preparation should consider the content and educational background the participants have. In a technical context, it is therefore important for someone who knows a lot about subject A to learn something about subject B and vice versa. In preparation, it is therefore important to cover different topics so that each participant can learn. In the specific case of this program, participants are expected to extract data from a steam engine to determine the Overall Equipment Effectiveness

(OEE) using an Artificial Intelligence (AI) model. So, several topics are covered to bring this to a successful conclusion.

PXL University of Applied Sciences and Arts also tries to achieve Sustainable Development Goals or SDGs. These goals were designed by the United Nations as a shared blueprint for peace and prosperity for people and the planet now and in the future. The 7th goal ensures access to affordable, reliable and sustainable and modern energy for all.

2 Method

The project is about making a traditional miniature steam engine smart. This way, this project supports SDG 7.

Participants will be prepared to work with a Programmable Logic Controller (PLC), design 3D models to create mounts for the sensors, data communication with Message Queuing Telemetry Transport (MQTT), processing data in an AI model. So, this program covers various topics so there is something for every participant to learn.

For this, we start from a simple model. As this is just an ordinary machine, its OEE cannot yet be calculated, and it will not work optimally.

To make this machine smart, sensors are placed to monitor the parameters of the machine. These parameters are boiler pressure, boiler temperature, generator voltage and two valve positions. There is a valve on the boiler and there is a valve on the pipe to the flywheel. It will be necessary to determine which sensors can measure these parameters.

This sensor data is then sent via MQTT and processed by a machine learning model. Thus, values can be predicted about the OEE, and the machine can be optimised. However, a communication protocol will have to be established to enable this.

For some students all these topics are new. So, keeping the students engaged in the virtual components leading up to the in-person sessions might be challenging. This can especially happen if the material is too complex.

The first goal of the project is to create a functional setup. To do this, a parts list is drawn up containing the necessary sensors, wiring, resistors and PLC components. Custom sensor mounts are then designed to hold the sensors in place. The steam engine will then be mounted on a case, along with the sensor(s) and the PLC, thus ensuring a complete setup is assembled once. This process will be repeated six times to ensure sufficient setups are ready for the BIP. Finally, a feedback system using a servo will be created on just one of the setups.

The second goal of the project is creating virtual content of the project using SCORM to prepare the BIP-students maximally. This content contains following topics: steam engine, OEE, TwinCAT and Node-Red.

The third goal of the project is to collect data for machine learning. This data will be used to create a model by the expert who will handle the topic of machine learning during the BIP.

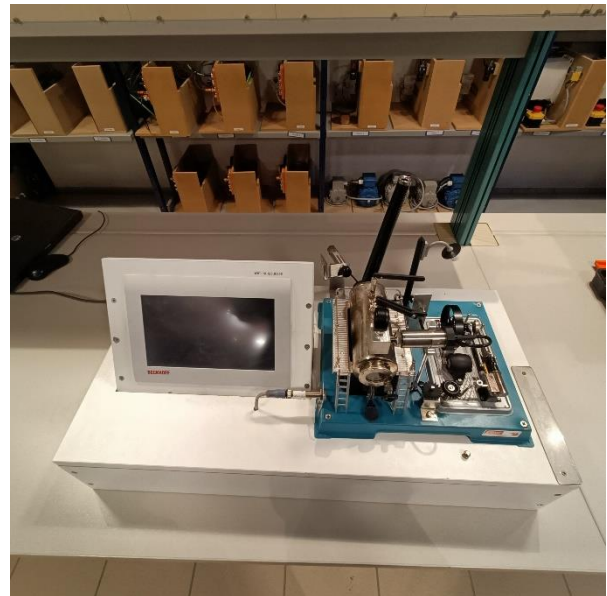
The fourth goal of the project is to conduct the Blended Intensive Program and provide guidance to all participants, ensuring that by the end of the week each team had developed a setup capable of calculating the Overall Equipment Effectiveness (OEE) of the steam engine. In this way it is possible to play the steam engine game and win the competition by achieving the highest OEE score among all the participating groups.

3 Results

The goals set are not solved one by one. They have progressively resulted over the course of the project.

Working principle of the steam engine

A steam engine is a heat engine that performs mechanical work using steam as its working fluid. The steam engine uses the force produced by steam pressure to push a piston back and forth inside a cylinder [1]. This pushing force can be transformed by a connecting rod and crank into rotational force for work. To stabilise the energy, a flywheel is placed on the rotating shaft. In Wilescos steam engines, this shaft is connected by a belt transmission to a generator, which converts this mechanical energy back into electrical energy.



Picture 1: The steam engine with PLC

The steam engine game

To play the game, one must prepare the machine: first, the machine is cleaned, i.e. the condensation tank emptied, the tank drained, and possible oil leaks wiped up. Then the tank is filled with 200 ml of water, the pipes are topped up with oil and one makes sure the heat element is ready to switch on. When this is done, the game starts, and the heat element is switched on. The water in the tank will start to heat up and the temperature will begin to rise.

From the moment the game is started, a timer starts running. Over time, when the game has been running for 10 to 12 minutes, a message will

appear indicating that it is time for maintenance. Depending on the maintenance (minor or major), the condensation tank will have to be emptied, the water refilled, and the valves checked. The output of the generator provides the best quality when it is within the limits of 4 to 6 volts. After 20 minutes of play, the program calculates and displays the OEE. The aim of this game is to ultimately achieve the highest possible OEE.

OEE on a steam engine

Overall Equipment Efficiency, or OEE, is a parameter that can determine the efficiency of a machine [2]. OEE is calculated from the product of three factors namely availability, performance and quality.

Availability is the effective runtime, and it is calculated by subtracting the planned production time from the time the machine is not producing. Lost time can be due to breakdowns or unexpected times when production is stopped.

Performance is maximum if the machine runs continuously at its ideal speed during runtime. However, this is also often not the case. Sometimes a cycle takes just a little longer or there is a short wait before continuing or the machine runs at a lower speed for a while. The performance is therefore known as the actual output, and it is the difference of the theoretical output minus the performance losses.

Quality is the last factor affecting OEE. This factor, as its name suggests, indicates the qualitative output of a machine. It happens that the first product does not meet the requirements and is therefore rejected. Even during production, there will sometimes be products whose quality is not high enough and these are therefore also to be rejected.

For some machines and applications, it is quite easy to determine OEE. However, for a steam engine, this is not so simple. There is no discrete output, and it will first be necessary to determine which of the three factors that determine OEE has the most influence on the steam engine's OEE. For this, an area has to be defined. In this study, it was chosen to start the planned production time from the moment the heating starts. Then, the water will heat up and evaporate before powering the generator. The time this takes is considered planned downtime. This is because it is known that the steam engine has to warm up before it can drive

the generator. Qualitatively, research has shown that the ideal output of the generator is 5 volts and anything within the limits of 4 to 6 volts is of sufficient quality. The closer to 5, the greater the quality. Thus, quality is the biggest determining factor affecting the OEE of the steam engine. It can be monitored by reading the output of the generator.

To calculate the OEE of machines, it is therefore very important to have the right data available. In the case of the steam engine, the temperature and pressure of the boiler, the position of the whistle on the tank and the position of the valve towards the drive mechanism and the output of the generator are all monitored. This is possible using sensors that measure these values and transmit them to the PLC. Thus, these parameters can be accurately monitored.

The sensors

The temperature in the boiler rises to around 125 degrees Celsius. It is also a closed tank and so a non-invasive measurement technique was chosen. The temperature sensor Optris RSCSLT15SFCB1K has a range of -20 to 350 degrees Celsius and works by UV radiation. The output signal of this sensor is a voltage between 0 and 10 volts.

The pressure in the boiler rises to 1.7 bar during normal operation and the maximum pressure is 3 bar. However, pressure cannot be measured non-invasively and therefore it will have to be mounted on the tank. The industrial pressure transmitter 716-262 has a range of 0 to 4 bar and an output signal between 0 and 10 volts.

The position of the valve on the tank is measured by coupling it with a potentiometer. As it can only do a small displacement, a potentiometer with a range of one revolution is sufficient. The Bourns 91A1A-B28-B10L was chosen for this purpose.

The position of the throttle valve is also measured by a potentiometer. For this, the Bourns 1kΩ Rotary Potentiometer 3590S-2-102L was used, since that the valve can rotate 2880°, potentiometer has a range of 3600° (10 revolutions). The supplied energy is monitored and controlled via a NOUS A1T Presa Smart Tasmota Smart Socket. This is connected to the power cable to the electric heating elements.

Beckhoff parts

If a sensor is properly connected, the sensors will detect a change as soon as there is a change in the system. This then translates into a voltage difference for the sensors whose output signal is a voltage and a current difference for the sensors whose output signal is a current difference. The sensors are connected to Beckhoff etherCAT terminals. Depending on the terminal, these can receive a voltage or current signal and digitise it. The resolution depends on the type of terminal, but for the EL3074 it is 12 bits. The digital value is transmitted via the terminal by the bus coupler (EK1100) to the PLC where it can be read in. Before this value has any meaningful meaning, it must be converted to a readable value. For this, the sensor datasheet is advisable. It shows the operating range and thus the information on how to scale it.

The material list

The aim is to repeat this setup six times: one demo built in advance and five built during the BIP. For this purpose, a bill of materials (see Table 1) has been created with the components needed to build such a setup. The top five rows of the bill of materials consist of the sensors. Since there is a 24V distribution and the potentiometers only have a range of up to 10 volts, two resistors are also listed (see row 6). They are placed in series, one for each potentiometer, and serve to reduce the input voltage of the potentiometer to 10 volts.

Also listed are two Beckhoff etherCAT terminals, EL3074, which are needed to capture the output signals from the sensors. Finally, a smart socket has also been added, since the steam engine bought is powered by a heating element. This socket also sends its data to the PLC and can also be controlled.

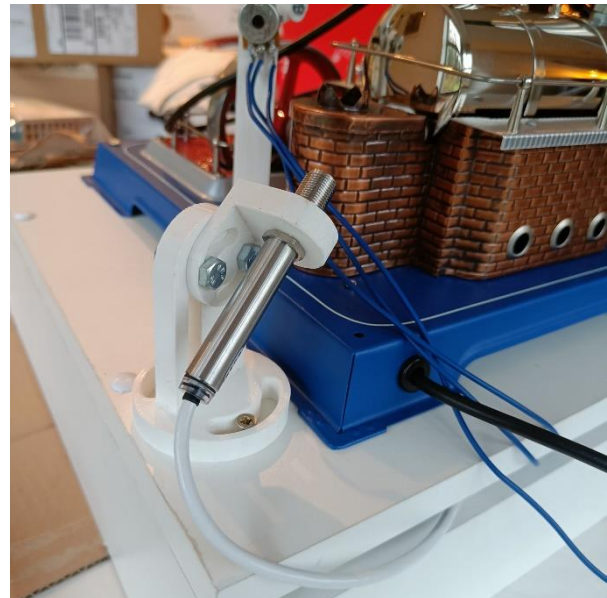
Table 1 – material list for one setup

Parts	Additional info	amount
Thermal sensor	0-10V	1
Pressure sensor	0-10V / 0-4bar	1
Potmeter Throttle	0-10V	1
Potmeter Whistle	0-10V	1
Smart Socket	/	1
Generator M66	0-10V	1
Resistor	1500Ω + <=0.25W	2
Power Cable	/	1
Steam Engine	/	1
240-24V transfo	2.5A	1

DIN Rail	35x7.5x200mm	1
EL9185	24V distribution	1
EL3074	0-10V	2
EK1100	Bus coupler	1
C9900-P927	Connector	1
CP6600-0001-0020	PLC touchscreen	1

Design of the mounts

The sensors are attached to the machine using mounts. For the temperature sensor, a mount is designed in the CAD program Onshape. Onshape is used because it is an easy-to-use, free CAD software. This design is then 3D printed in plastics. The pressure sensor has to be mounted on the tank. For this, an aluminium spacer is made so that the pressure sensor can be screwed airtight to the tank. The mounts for the potentiometers are also going to be made. No special CAD drawings are provided for these mounts. Furthermore, a gear and connector are also designed to adjust the position of the throttle and the whistle valve respectively. For this, a CAD drawing is also provided with a design of this piece, which is then laser cut.



Picture 2: Mount with temperature sensor

Production process of the mounts

Two mounts for the potentiometers are needed. The base of these mounts is an aluminium plate with thickness 2 millimetres. First, the piece is cut out of the plate. After this, holes are drilled into the piece using a column drill. These holes serve to fix

the mount to the base plate and fix the sensors. Finally, the mount is folded to the correct dimensions.

The pressure sensor mount is made from an aluminium rod with a diameter of 30 millimetres. This is first sawn to the right length, then drilled into the top and bottom. Sharp edges are then removed by giving the sides a chamfer with the lathe. The hole at the top is then tapped so that the sensor can be screwed on. By first wrapping Teflon around the sensor thread, an airtight seal is achieved. A hollow screw is then screwed into the bottom of the mount, again with Teflon. This screw sticks out for a part, making the connection with the tank.



Picture 3: Mount for pressure sensor

Design of the case

For the case, the first choice was a thick plate with cable ducts mounted on it along the steam engine to route the cabling. The PLC could also be mounted on the plate in an MDF glazed holder. After discussion, it turned out that another case had to be provided after all. A case was therefore designed in SolidWorks for this purpose. The technical drawings were sent to Modest, a sawmill from which a quotation was requested. This request proved to be unprofitable from a price perspective. Therefore, a second design was created, which could be realized more cheaply at a friendly sawmill.

Connecting to the Beckhoff PLC

A programmable logic controller (PLC) or programmable controller is an industrial computer that has been ruggedized and adapted for the control of manufacturing processes, such as assembly lines, machines, robotic devices, or any activity that requires high reliability, ease of programming, and process fault diagnosis [3].

Sending data

The sensor values are read by the PLC; this was easy by linking these inputs to a variable within TwinCAT. The variables are then put into a JSON string. This program sends the values to the broker every second. It turned out that there was a problem with a capture of JSON files. Because the message could not exceed 255 characters, not all messages were sent properly. This was because the variables in the TwinCAT program were stored as REAL types. As a result, the transmitted value sometimes consisted of unnecessarily many digits (too precise and too many digits after 0). This was solved by converting the values, where this would not negatively affect accuracy, to an integer. For example, the temperature was sent as an integer as 120.0 instead of 119.984257526. This saved space in the JSON files and allowed all messages to be sent properly.

PLC program

The PLC program is written in TwinCAT and composed of one Programmable Organisation Unit or POU in addition to the MAIN (in which this program is called). This means that the logic of the steam machine game is contained in one program. However, multiple visualisations are used. These show the different screens on the PLC.

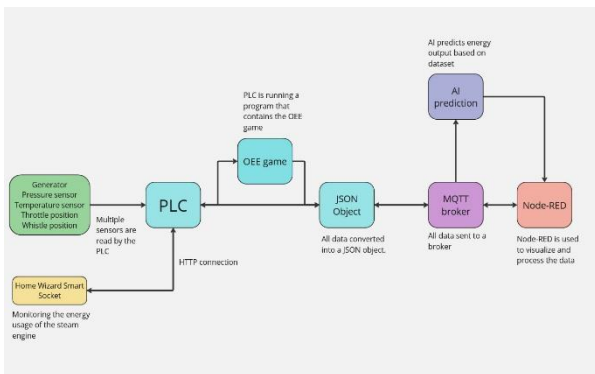
MQTT communication

MQTT, originally an initialism of MQ Telemetry Transport, is a lightweight, publish-subscribe, machine to machine network protocol for message queue/message queuing service. It is designed for connections with remote locations that have devices with resource constraints or limited network bandwidth, such as in the Internet of Things (IoT) [4]. It must run over a transport protocol that provides ordered, lossless, bi-directional connections—typically, TCP/IP.

In this case, the broker is the central spot of the dataflow. It receives the Json messages sent from the PLC. At first, a python program was subscribed

to the broker and received these Json files as well. This allows a dataset to be constructed from the sent data. This dataset could serve as training data to do machine learning. It can then re-expose its output to the broker. Secondly, the data was sent to influxDB, a docker container where the data is automatically stored in a dataset and which third parties also have access to.

All this information is also exchanged with Node-RED, where a visualisation dashboard provides an overview of data and the output of the AI model. Node-RED is a flow-based, low-code development tool for visual programming, originally developed by IBM for wiring together hardware devices, APIs and online services as part of the Internet of things [5]. The smart plug also provides its information via the Tuya smart app and Tuya developer platform to Node-RED. Via Node-RED, the smart plug can also be controlled. The communication model is shown in picture 5.



Picture 5: Dataflow

The Feedback system

The feedback system consists of an ESP32 and an MG996R servo motor, with a 360-rotation angle, which can control the throttle valve with a gear connection. The ESP32 is subscribed to the topic, receives the data and therefore, it can react to almost real time information of the steam engine. The program works as follows: if the generator output value is higher than 5, it sends a signal to turn the servomotor clockwise, which causes the throttle to close slightly. If the output falls below 4, the ESP turns the servomotor slightly in the opposite direction, which opens the throttle slightly. The generator output is compared every two seconds, allowing the valve to be gradually opened or closed. This feedback system was made on just one setup.

The virtual component

For the technical part explained above, participants should be prepared. Therefore, after the introduction, the preparation consists of four major parts: OEE measurements, Onshape, a basic PLC lesson and Node-RED. The preparation is written in English and available to participating students via the platform review 360 online from about two months before the BIP takes place. This gives them enough time to find moments to do this preparation.

The OEE measurement part consists of an explanation OEE, as mentioned here earlier in the text above. It also includes practical exercises and asks students to think about how to determine OEE of more complex systems.

The Onshape section in the preparation includes a guide to help setup this open-source free software and a tutorial to get acquainted with the program. This is followed by four small exercises to model basic objects and, finally, this section contains another challenging exercise. This part of the preparation focuses on the mechanical part of the BIP.

The basic PLC lesson includes an explanation of a PLC. This is followed by the link to TwinCAT and again an installation guide is provided to properly install this software. This is followed by general programming rules used when writing a program in TwinCAT. Next are instructional videos detailing an example exercise. In the exercise, topics such as adding a global variable list and function block are included. Finally, pieces of code from the TwinCAT program used for the application with the steam engine follow. This is explained and added as a filling-in exercise.

The final section follows the basic PLC lesson. In it, variables from the example programme are sent to a broker via MQTT. Again, a video tutorial explains how to install Node-RED. From NodeRed, the variables are subscribed to the broker and visualised. This part is more about data communication.

Machine learning

After the dataset is created, the process for machine learning can start. In machine learning, the raw data is first cleaned up. This means that missing data is completed, duplicates are removed, erroneous data is removed, outliers are handled, and units are unified. This way, a good, clean dataset created and is ready for preprocessing. In preprocessing, all data points are scaled to the

same scale using the Z-score method. This is called data normalisation, and this will allow some Machine Learning algorithms to work more accurately.

A suitable model is then chosen and trained for the steam engine dataset. It is expected that a linear model will be suitable, because the outcome will be a continuous variable.

The next step is to evaluate performance of the model. This ensures the reliability and efficiency of a model. In this step, features are selected. In application to the steam engine, these are features that affect the OEE of the system. These are the temperature, pressure, output of the steam engine because they hold information about the status of the machine.

The model is then improved and optimised.

Finally, the model is commissioned. New data comes in and output follows.

This was all done in Orange, an open-source data visualization, machine learning and data mining toolkit. It features a visual programming front-end for exploratory qualitative data analysis and interactive data visualization [6].

Since no Orange model can be added to the PLC within the PXL, it was no longer used in this project. An expert in machine learning will provide the machine learning and lessons on this during the BIP.

Blended Intensive Program

At the end of the 5-day Blended Intensive Program, all six mixed international teams successfully created a setup to calculate the OEE of their steam engine.

At the start of the week each team was provided with a teams environment that provided access to documentation, and a premade kit including the wired sensors, the steam engine, a programmable logic controller, I/O cards, the case and other miscellaneous items.

The program was structured to guide the students toward the goal of the Blended Intensive Program. On Monday, the students were introduced to the concept of Overall Equipment Effectiveness (OEE) and began designing mounts for the sensors. On Tuesday, these mounts were produced and installed on the setups. On Wednesday, the students transmitted sensor data to a broker, visualised it in Node-RED, connected the smart

plugs, and collected data for use in machine learning. On Thursday, they used the collected data to develop a machine learning model. Finally, on Friday, the students refined their setups in preparation for the final OEE measurement and delivered preparations on their setups, explaining their machine learning approach and OEE calculation. The week concluded with all teams competing for the highest OEE score, after which the following grades shown in picture 6 were awarded.

	Weight	The Innovators	Group 2	Volt&Vapor	Team Nexus	Choo choo crew	Tech Titans
Team game	6	0	2	3	0	2	1
OEE pitch	15	12	12	12	15	12	12
Daily standup	10	6	5	8	8	6	10
Video	20	20	10	20	18	18	15
presentation	20	20	15	20	20	18	15
OEE	30	19,5	18	19,3	19,2	19,23	19,6
FINAL RESULT		77,5	62	82,3	80,2	75,23	72,6

Picture 6: Results per Team

Conclusions

The aim of this project is to prepare and conduct a Blended Intensive Program (BIP) in which students collaborate on improving the Overall Equipment Effectiveness (OEE) of a steam engine by using modern technologies. Although not every technical aspect could be implemented by the researchers in full detail, all necessary preparations were completed and the BIP itself was successfully carried out. These goals will now be discussed.

The first goal was to create a functional setup for the steam engine. This was achieved by carefully selecting, wiring, and mounting the required sensors, including temperature, pressure, voltage, and potentiometers for the valves. Custom mounts were designed and manufactured to securely attach these sensors to the setup. One complete setup was fully assembled, with a Beckhoff control panel with integrated PLC connected to EtherCAT I/O terminals to capture sensor signals and convert them into digital values. A feedback loop was integrated on this setup using an ESP32 with a servo motor to control the throttle valve, creating real-time optimisation based on generator output.

The second goal was to create virtual content to prepare the participants. Lessons were created on OEE, Onshape, PLC programming in TwinCAT, and data communication via Node-RED. These materials were made available in English through Review360, giving students sufficient time to

prepare themselves for the program. This goal was therefore met.

The third goal was to collect data and provide the foundation for machine learning. A dataset was generated using MQTT communication, Node-RED visualization, and InfluxDB data storage. This dataset will be used during the BIP by the machine learning expert, fulfilling the third goal.

Finally, the fourth goal was to conduct the BIP itself. By the end of the week, each team had successfully assembled its steam engine setup, transmitted and visualized sensor data, and calculated the OEE. The competitive aspect of achieving the highest OEE ensured engagement, while the interdisciplinary teamwork allowed knowledge exchange across backgrounds. This completes the final goal.

Acknowledgements

A special thanks to Mrs. Deckers, Mr. Pilat and Mr. Vanheusden for the technical support, help and fine cooperation on the project. Furthermore, we would like to thank Mr. Willekens, who also helped us. Finally, we would like to thank Mr Camps for the weekly appointments.

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