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Predictive analytics in quality assurance for assembly processes: lessons learned from a case study at an industry 4.0 demonstration cell

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Abstract

Quality assurance (QA) is an important task in manufacturing to assess whether products meet their specifications. However, QA might be expensive, time-consuming, incomplete, or delayed. This paper presents a solution for predictive analytics in QA based on machine sensor values during production while employing machine-learning models based on logistic regression in a controlled environment. Furthermore, we present lessons learned while implementing this model, which helps to reduce complexity in further industrial applications. The paper's outcome proves that the developed model was able to predict product quality, as well as to identify the correlation between machine-status and faulty product occurrence.

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1. Introduction

For companies aiming at quality leadership, the final quality of any goods produced is vital for market success. That is why it is highly important for companies to ensure that every product meets the expected requirements. Throughout the years, diverse methods for quality control (QC) have been presented and implemented in production. Some of those methods prove to be highly effective, but costly, i.e. the inspection of every produced piece (100% control), either by automated or manual methods, by doing quality inspections based on a portion of the produced pieces and extend the results based on statistical methods, or by reducing the risk of mistakes by intentionally modifying the process to avoid human errors. This bears a considerable risk of not detecting faulty-parts (NOK) and sending them to customers [7, 17].

Whenever a QC method is selected, it is important to remark that compromises must be made in most cases. For example, traditional methods like controlling every produced piece might

affect have a considerable impact in the production, due to the (AP: review)

goals by delaying the production speed at the cost of lower rejection rates. On the other hand, higher production speeds normally requires statistical quality control methods. However, those methods do not provide one hundred percent certainty that the required product quality will be achieved [18, 13].

With the evolution of machine learning (ML) applications, we expect to enhance the QC by predicting the product quality at the initial stage of production. This will not only reduce cost in production, and strengthen the QC process, it will also be part of the predictive analytics tools found in production, which is currently widely used in diverse fields due to its accurate predictions [3, 11].

This paper is divided in 6 sections:

- **Introduction**, states the motivation of the project as well as the problem it intended to be addressed.
- **Related Works**, covers the methods used in quality check in production, as well as the bases of predictive analytics in production.

- **The case industry 4.0 demonstration cell**, describe the demonstration cell used on this project. It answer the question of where to test predictive analytics in a controlled environment and why our system is a valid platform for this implementation.
- **Machine learning Methods**, explains the three machine learning methods implemented on this work: Multilayer perceptrons, Support Vector Machines, Decision Tree.
- **Experiments**, describe the experiment process from the data acquisition and preprocessing, to the classifier optimization and testing.
- **Conclusion**, express the remarks and discoveries achieved after the finalization of this project phase, as well as presents a list of lessons learned during the implementation of the project, which might be helpful on further implementations.

2. Related Works

2.1. Quality control in production

The quality control of production processes and products is one fundamental part of general quality management. It contains the measures and activities needed to fulfill specific quality requirements. According to Illés, there are three established tools and methods of quality control [9]: The Statistical Process Control (SPC), Auditing and Total Quality Control (TQC). The SPC is normally used to monitor the production process using recorded data values for the quality characteristics, as well as to indicate any significant changes in the quality characteristics in the production process [18]. SPC methods can also take place before the actual manufacturing process, this is commonly known as "off-line SPC".

During the design phase of a process or product, off-line SPC procedures are deployed. Those procedures aim to increase the quality of the outcoming product by choosing controllable products and process parameter [15].

The biggest advantage of working with SPC is that large batches can be checked without major time impact on the QC process, however, this would be only possible if the variance of the process product parameters is small enough, to ensure process capability [10].

Another conservative technique to perform the quality check would be to check 100% of the produced parts. On this method, every product is controlled and binary sorted as an OK or Non-OK part. However, this has the disadvantage of high cost related to personal or specialized material and in certain cases, could lead to a delay in production.

Product and process auditing is the independent examination of product and process quality to provide information and it is considered the most fundamental quality control technique. This method is executed by an independent auditor, who based on sampling or checking records limits the finding on reporting incorrect processes procedures or products documentation. In a further step, the findings would be later corrected by another person rather than the auditor [7].

Statistical methods such as acceptance sampling or quality control charts represent a compromise between zero and the hundred percent control [18, 13].

While the SPC mostly optimizes the capability of the process, for example the acceptance plan prevents the nonconforming product to be pass and then delivered to the next process or the customer [13]. In the case of a hundred percent control, this is associated with higher costs and a higher requirement of time, compared to a quality control based on a machine learning model. Generally, statistical methods are faster than the hundred percent controls, however, their disadvantage is that those methods are based on assumptions. those assumptions might lead to errors if the variance of the product quality higher than expected.

The concept of TQC is to extend the scope of quality control to the whole company and product life cycle, by involving all departments of the organization [9]. The quality characteristics of a product can be classified as variables or attributes. Variables are measurable characteristics, which are shown as numbers. On the contrary, attributes are not measurable and can only take the binary values like "go" or "no-go" [15]. The advantage of variable measurements is that in the event of a defective intermediate or end product, precise measured values are available, which enable precise adjustment of the process parameters. This allows the desired quality to be restored. With that in mind, predictive quality control is a promising solution.

2.2. Predictive analytics in production

According to Delen and Damirkan, predictive analytics (PA) unravel the inherent relationships (if any) between input and output by using data and mathematical techniques [5]. PA offers a wide range of applications, and it can be implemented as long as the provided data are sufficiently available. By considering the industrial and production environment, PA would be a great asset due to the high flexibility and high amount of data available coming from processes, single machines or cells, products, and others. Some common industrial applications of PA in the industry are focused products (design and optimization), machines (predictive maintenance) and production (scheduling) [11].

Applications that combine PA with QC might improve the current QC processes. By employing machine learning (ML) techniques 4, together with traditional methods 2.1, it would be possible to upgrade the currents QC methods, and improve the cost-efficiency relationship in the QC process.

Based on an explorative literature review on this matter, the short outcome is that the findings that combine PA and QC are very scarce in the literature. This could be in great part, due to computer power limitations in early research and the recent increase of ML applications in this area. Related works, e.g from Krauß focused on automated machine learning for predictive quality in production [12] and product quality prediction in a process chain [11], Aumi focussed on the model development for predictive quality control of batch processes [2], and Ritter studied the ways of process modeling on quality prediction and assurance of chipboard [16].

By considering the lack of literature, our goal is to decrease this gap in the research area by implementing a functional predictive model in quality assurance for an assembly process, as well as describing the lesson learned during this implementation. To do so, we need to select the right testing platform. It has to have a clear production process, complete access to sensor data, and flexible enough to reprogram the process if necessary. In our work, we applied a case-based research approach [20] to answer the research question (AP: what research question?). One central motivation for a case-based research approach is to gain insights for real needs, rather than to develop theories without practical relevance [4].

3. The case industry 4.0 demonstration cell

Our case of study is an abstraction of an assembly process of the industry. The industry 4.0 demonstration cell is composed of three independent conveyor belts, a robotic assembly arm (UR3), a laser scanner used for quality control as well as a wide range of sensors, all orchestrated by a SIEMENS PLC S7-1200, see Figure 1. The executed abstracted assembly process consists of stacking two disks of different sizes on top of each other. These pseudo product quality are later determined by the laser scanner by evaluating the concentricity of both disks. If the disks' concentricity is within a tolerance of 1.5mm, the piece is classified as OK, if not, it is classified as NOK. By considering that malfunctions can occur during industrial production processes, our demonstration cell can simulate failures in diverse areas, such as:

- Assembly errors due to the robotic arm: incorrectly positioned disks.
- Bearing damage on the conveyor belts: vibration changes in the conveyor belt motors.
- Resistance on the conveyor belts: temperature changes in the conveyor belt motors.
- Malfunction of the gate door due to leakage in the compressed air system: cylinder stroke at the assembly barrier is slower.
- Faster operating point: disks shift position due to the high belt speeds.
- Missing material at the end of the warehouse: production stop due to lack of material.

Those simulated failures have an impact in the data collected by the sensors. Anomalies can be observed at the vibration sensors, temperature rise, fluctuations in the air pressure system, noticeable shifting on pieces' position as well as the stop of the process.

The continuous data collection and the clear correlation between the machine parameters is the ideal play-ground to implement a sandbox for machine learning implementations. With this in mind, our goal is to predict the quality of the product (concentricity of the assembled parts), prior to the actual quality check done by the laser scanner. We expect the findings gained with the demonstration cell to be transferred to various real as-

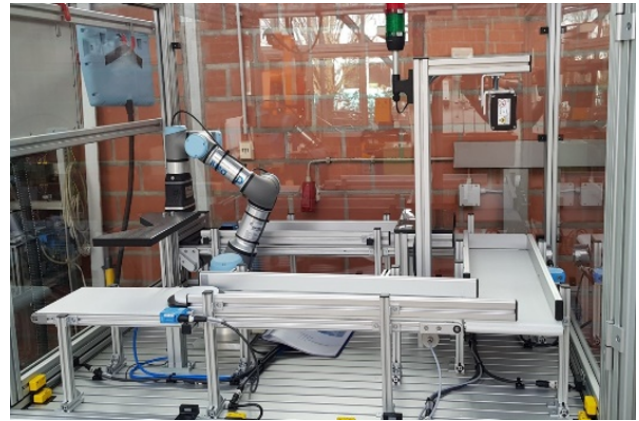


Fig. 1: The industry 4.0 demonstration cell at the University of Siegen

sembly processes and use cases, due to its manageable size and a high degree of scalability. This would be a step forwards for future implementations at the industry, where the quality predictions might determine early enough, the next steps for the assembled pieces.

4. Machine Learning Methods

To study which implementation would be more suitable for industrial application, we compare Support Vector Machines (SVM), Multilinear Perceptrons as well as random forests on the task of quality prediction. All three will be introduced next.

4.1. Support Vector Machines

Support Vector Machines (SVM) attempt to separate data along hyperplanes [1]. SVM offer a convex alternative to MLPs [19]. A convex classifier is guaranteed to converge to a global solution regardless of its initialization. Non-separable data can become separable if projected to a different possibly high dimensional space through a Kernel function. The Kernel trick allows SVM to solve some non-linear classification problems [19]. Radial basis functions (RBF) are commonly chosen as kernels [19], therefore, we choose to follow this practice as well.

4.2. Multilayer perceptrons

These feedforward neural networks typically combine multiple layers and activation functions [3]. A layer contains a large weight matrix and a bias vector. To evaluate the layer the input vector must be multiplied with the weight matrix before the bias vector is added. Each layer is typically followed by an activation function which adds non-linearity to the network graph. Rectified linear units (ReLU) are zero for negative inputs leave positive inputs unchanged. ReLUs are the recommended activation function for modern neural networks [8] we use these here as well. Since the linear parts of the ReLU and the linear matrix multiplication are differentiable we can employ gradient descent to train our classifier.

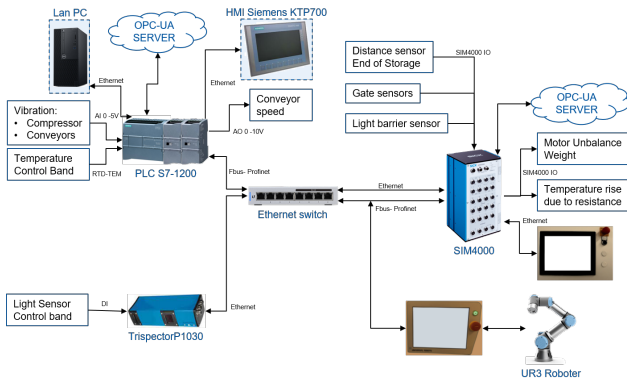


Fig. 2: Industry 4.0 demonstration cell: Connection diagram (simplified).

4.3. Decision Tree

Decision trees are essentially binary trees, which work with the input features at the roots, decisions are made by moving up the tree to top leaves. At every branch in the tree, a decision is made, until one arrives at the decision [14]. For numerical input features, each decision partitions the data [1]. For example by comparison to a threshold value. To construct the tree these cutoff values have to be chosen at every branch. The construction problem turns into an optimization problem when a split criterion is introduced. Common choices are cross-entropy of Gini-coefficient [1]. During construction, the chosen function must be minimized.

5. Experiments

5.1. Data acquisition

Industrial projects require to work with a variety of sensors and controllers. Thus, there is a risk of incompatibility between technologies. To avoid that problem, universal protocols are often implemented at industrial projects. This is the case for our industrial 4.0 demonstration cell, which shares data via protocol OPC-UA.

Figure 3 describes a simplified version of the real connection diagram of the demonstration cell. For our case, the data is shared independently from two OPC-UA servers. This represents the interaction between multiple servers in real production environments.

The first step to collect the data is to list all the variables of interest and to map their source. The second step is to determine the use cases of interest. This research focussed on the data described in Table. 1 and the six use cases described in Table. 2. The data was manually collected by using the software "UAExpert - v1.5.1". Approximately 15 hours of data were collected, while equally sampling each use case during the data acquisition time.

Data of interest	Server Source	Variable
Conveyor speed	Siemens PLC	Conveyor: Gate
		Conveyor: QC
		Conveyor: Store
UR3 Position	Siemens PLC	xyz Gripper position
Action Flags	Siemens PLC	UR3 gripper open/close
		Grab/drop disk based on disk type
Quality control	SICK SIM4000	OK-NOK label
		xy disk deviation from the center point
		Absolute disk deviation Position
Gate position	SICK SIM4000	Speed
		Safe to go
Store	SICK SIM4000	Disk Size

Table 1: Industry 4.0 demonstration cell: Relevant data linked with its reference source server.

Use Case	Description
Use Case 1	Conveyor speed: Slow
	Robot position: OK
Use Case 2	Conveyor speed: Slow
	Robot position: NOK
Use Case 3	Conveyor speed: Fast
	Robot position: OK
Use Case 4	Conveyor speed: Fast
	Robot position: NOK
Use Case 5	Conveyor speed: Too Fast
	Robot position: OK
Use Case 6	Conveyor speed: Too Fast
	Robot position: NOK

Table 2: Industrial 4.0 demonstration cell: Controlled Use-Cases. Use-Cases which the value *Robot position: NOK* and *Conveyor speed: Too Fast* will result in NOK pieces.

5.2. Data preprocessing

Once enough data is collected, the next step is to clean the raw data and organize it accordingly. For our case, that means to merge the data collected from the two OPC-UA servers, and synchronize the time-stamp. Since our systems are not completely synchronized, it was needed to calculate the delta-time between servers by referencing each server's base clock. Once the delta-time was determined, a time-stamp function was implemented to correct the time-shift between samples and be able to merge all the data without incompatibilities.

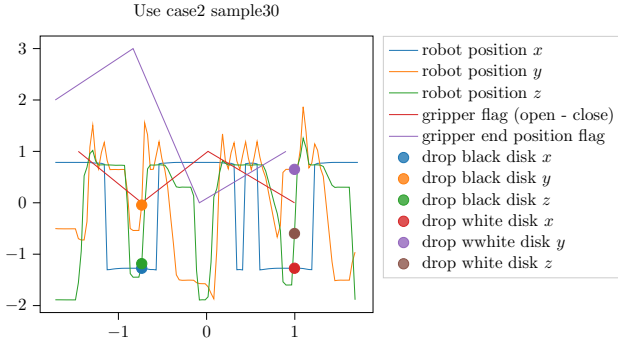


Fig. 3: Robot arm movement patterns. We show the movement of the cell's robot arm, its grippers, and the encoding of the overall position in the system. The changes in the grip flag are triggered, when the gripper opens or closes. Zero indicates an open, while one indicates a closed gripper. The position flags marks the state of the cell's arm. 0 means the black disk is in store, one that the black disk is at the gate, two that the white disk is in store and three that the white disk is located at the gate.

Data tags interpretation is an important step in the preprocessing process. The raw data collected from the sensors is sometimes tagged by an alphanumeric code predefined by the sensor manufacture. To work with the data, it was needed to implement diverse functions which have the task to clean the raw data in a more human-readable form. This means to remove samples out of clear boundaries and missing values, as well as to translate the sensor code tags based on a dictionary predefined by the authors. This last step, might be optional in other implementations, however, it proves to be a great addition for testing purposes.

Once the data is clean and compiled in one directory, our step was to split the data based on the assembly cycle. For our purpose, we split the dataset into individual data-samples with help of the action tags included in the dataset Table. 1. Subsequently, each data-sample is automatically checked for missing sensor values and discarded if so. At this point, we have a series of data-samples based on time series. However, we are not interested in a time series analysis, therefore it was needed to compress each time-series based data-sample in an atemporal data-sample. To eliminate time as a variable in our dataset, we defined a series of rules to be applied on each assembly cycle data-sample:

- Value of the robot position (xyz) while dropping the disk in the storage area
- Mean conveyor speed value per conveyor band
- Absolute deviation (xy) value at the quality control check
- Absolute quality control value: OK - NOK

Each time-series sample was evaluated based on the rules stated above, and the result of each evaluation was considered as our atemporal data-sample, which we used as the base for our classifier.

Approach	accuracy
Naïve-Baseline	64 %
Support Vector Machine	82 %
Multilayer Perceptron	88 %
Decision Tree	98 %

Table 3: Comparison of Support Vector Machine (SVM), Multilinear Perceptron and Random Forest classification on our anomaly detection task. The first row shows the performance of naively predicting a broken piece every time.

		True Values		Total
		OK	NOK	
Predicted Values	OK	18	0	18 + 0 = 18
	NOK	8	24	8 + 24 = 32
Total		18 + 8 = 26	0 + 24 = 24	50

(a) Support Vector Machine.

		True Values		Total
		OK	NOK	
Predicted Values	OK	18	0	18 + 0 = 18
	NOK	6	26	6 + 26 = 32
Total		18 + 6 = 24	0 + 26 = 26	50

(b) Multilayer Perceptron.

		True Values		Total
		OK	NOK	
Predicted Values	OK	17	1	17 + 1 = 18
	NOK	0	32	0 + 32 = 32
Total		17 + 0 = 17	1 + 32 = 33	50

(c) Decision Tree.

Table 4: Confusion matrices result of the prediction of 50 test data-points. We present the result of the predictions given by all three algorithms in detail based on the comparison between true values vs and predictions. The tables read from the upper left cell as: true-positive, false-positive, false-negative, true-negative.

5.3. Classifier optimization and testing

The robot's position at disk drop is marked in Figure 3. The quality prediction problem is framed as a classification task. The input vectors which we feed into our classifiers consist of the arm positions at the disk drops for both disks in three dimensions, as well as the largest recorded belt speed of all three belts. The interpretation of the quality measurement is used as the training target. It can be OK or NOK which we encode as zero and one.

We work with a total of 528 measurements. Each containing arm and belt data logs of individual cell run. 50 samples are set aside at random for testing purposes, leaving 478 training samples. The random number generator seed is set to one to ensure the train and test set splits are identical for all experiments.

We compare a total of three different classifier architectures on the data. A Support Vector Machine (SVM), a multilinear perceptron (MLP) and a Random Forest structure. All three methods are trained using standard hyperparameters.¹

Results are shown in table 3. For 32 of the total 50 test samples quality measurements indicate a problem. This sets the

¹ To allow exact reproduction of these results source code is available at <https://github.com/manubrain/Demo-Cell-Classification>

baseline over the entire data set, which would be obtained by simply labeling all samples as faulty. Over the test set, we require to classify more than 64% of the data correctly. We would therefore expect any naive classifier to produce at least 64% accuracy, which we have to surpass. In Table 3, we observe that this is indeed the case for all three approaches evaluated here.

Based on the MLP prediction results presented on Table. b shows that even though the prediction model is not 100% accurate, the percentage of false-positive predictions is 0%. The false-negative results represent the 12% of the test sample and the true predictions constitute 88% of the test data.

The outcome of the models shows that the random forest performed best followed by the multilinear perceptron and the support vector machine. However, by reviewing the confusion matrices presented in Table, 4, multilinear perceptron would be the preferred solution to be implemented at industrial applications due to the 0% ratio in false-positive results and high accuracy of 88%.

6. Conclusion

Based on the literature review, we observed that the hundred percent quality check method proves to be the most efficient method to guarantee the final product quality, however, the high implementation cost is its biggest draw-back. On the other hand, we have the statistical methods, which are known to be fast and efficient, but the lack of reviewing each product until the next batch review might imply a considerable loss whenever NOK products are found. This is based on the uncertainty of when did the error occurs and how many products are affected.

By implementing ML models capable to predict the quality of the product, just by the initial conditions of the process would be a great asset for the industrial processes. Within the limits of our work, we predict with 98% certainty the product quality by implementing a decision tree model with a 6-variables vector as input. However, our decision for industrial applications would be the MLP with 88% accuracy as to guarantee the QC and avoid labeling a NOK piece as OK. For further work, we expect to increase the certainty of the prediction model by collecting more data-samples and experimenting with other, more complex, ML models.

It is important to state that this prediction model is not yet ready to fully replace the statistical methods, not the hundred percent quality check method. However, a combination of SPC along prediction models could work well together, since the prediction model will evaluate each produced piece, and this will somehow compensate one disadvantage the statistical methods have.

It is worth to mention the most important points learned during the project implementation. This might help as building blocks for further research in the area.

6.1. Lesson Learned

Incompatibility between technologies; devices configured on the same network presented troubles to share data within

each other due to network restrictions, as well as the limitation to access and modify restricted program-code given by the machine manufacture. To overcome the situation stated above, it was necessary to reprogram big sections of the machine control system.

Data synchronization; two OPC-UA servers were used on this implementation. This lead to a series of data synchronization problems due to differences on the internal clock of both servers. In order to solve the issue, it was needed to write a time-stamp synchronization script that was deployed during the data preprocessing phase. Without harmonious time-stamps, determining the production cycle would have been impossible and the input data for the ML model would have been useless, and the model inaccurate.

Data interpretation; this process is considered complicate, time-consuming, and fundamental step on any ML applications. It is fundamental to understand the assembly process, the timing from the machine movements, the boundaries of the machine's sensors, as well a basic correlation within the presented data.

Missing values; to minimize the risk of false results delivered by the ML model, it would be compulsory to carefully review the ML input data. Missing values can have a great impact on the ML prediction, that is the reason why we deliberately review all the input data and validate it with the expected output from the diverse sensors. Whenever there was missing data, and as long as we did not fabricate data, we employed statistical methods to fill the data gap.

Adapting the industry 4.0 demonstration cell; the initial state of the demonstrator was very limited. Even though the process was well known, the lack of labels or flags whenever certain actions occurs, made complicated to have accurate data sampling from each assembly cycle. In order to overcome this uncertainty, we modify the machine program to raise specify flags whenever certain actions would be executed.

Machine Learning; careful measurement and meaningful preprocessing of our cell-date was key to the successful application of all three algorithms. Without the labels, the problem could not have been framed as a supervised classification problem.

Dataset size; as the starting point we collected as many data points as the ones found in the iris Dataset [6]. The next step was to collect batches of data of around 30 minutes per use case. This process was repeated until accumulate around 15 hours of data.

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