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# A process plant retrofitting framework in Industry 4.0 perspective ⋆

**Fabio Di Carlo** * **Giovanni Mazzuto** * **Maurizio Bevilacqua** *
**Filippo Emanuele Ciarapica** * **Marco Ortenzi** *
**Luciano Di Donato** ** **Alessandra Ferraro** ** **Marco Pirozzi** **

* *Department of Industrial Engineering and Mathematical Science, Polytechnic University of Marche, 60131 Ancona, Italy; m.bevilacqua@univpm.it (M.B.); f.ciarapica@univpm.it (F.E.C); fabio_dicarlo@outlook.it (F.D.C); g.mazzuto@univpm.it (G.M.); marcoorte0@gmail.com (M.O.).*
** *Dipartimento Innovazioni Tecnologiche e Sicurezza degli Impianti, Prodotti ed Insediamenti Antropici, INAIL, 00143 Roma, Italy; l.didonato@inail.it (L.D.D.); ale.ferraro@inail.it (A.F.); m.pirozzi@inail.it (M.P.)*

**Abstract:** Retrofitting old plants is an excellent alternative to their replacement to prepare them for industry 4.0. Many papers are related to retrofitting, but few studies concerned the process industries.
A framework to retrofit a process plant is presented and applied to a two-phase mixing plant providing a guide starting from the plant study and ending with the I4.0 paradigm implementation. The approach allowed to improve plant safety and maintainability conditions. The several issues arising during the retrofitting can be related to its multidisciplinarity aspects, the recursion in the definition of new variables to be monitored, and the information flow management.



*Keywords:* Retrofitting; Industry 4.0; Old process plants; Framework development; Safety and Maintenance; Diagnostic Systems; Performance Evaluation; Design of Safe Controllers.

## 1. INTRODUCTION

Industry 4.0 has been at the heart of the modern industry economic and social transformation for several years. Its concept was born in Germany in 2011 thanks to a political initiative to strengthen the German industry position on the world scene Rojko (2017). Thus, it is among the hottest topics discussed by the scientific and industrial communities Zhou et al. (2015). Generally, Industry 4.0 aims to transform digitally manufacturing companies and value creation processes. Revolutionary technological innovations characterize this transformation. These innovations eliminate the barriers between the virtual world and the physical world by integrating smart products, smart machines, machines, workers, production systems, and processes. Some of the technologies needed for Industry 4.0 implementation are: Autonomous Robots, Simulation, Big Data and Analytics, System Integration: Horizontal and Vertical System Integration, Cybersecurity and Cyber-Physical Systems (CPS), The Industrial Internet of Things, Additive Manufacturing, The Cloud, Augmented Reality. These pillars define the technology needed for its implementation Vaidya et al. (2018).

The benefits generated from the introduction of Industry 4.0 raised the interest of many companies. Different problems are connected to the implementation of the Industry 4.0 solutions, particularly for SMEs where research and development budgets are limited and where technological competencies are dedicated. In many cases, it is more efficient to adopt a retrofit process rather than replace plants Ciarapica et al. (2008). Therefore, it is necessary an approach to retrofit a process plant with an Industry 4.0 prespective, usable also by SMEs.

In this work, we aim at carrying out a smart retrofitting, so it involves the implementation of all necessary tools and technology provided by Industry 4.0 in addition to the classical retrofitting features. In particular, the present work aims to develop a general framework to retrofit an old process plant to make it ready for industry 4.0.

There are many retrofitting models in an Industry 4.0 perspective in literature, most of which relate to manufacturing environments such as production lines or CNC machines. The retrofitting in the manufacturing environments usually involves one unit at once; through retrofitting the unit became industry 4.0 ready. Instead, in a process plants, to retrofit an old plant into a smart

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plant, it is necessary an overall vision.Christofides et al. (2007).

Although the existing research is valuable, to the best of the authors' knowledge, regarding the development of a framework for retrofitting process plants from an Industry 4.0 perspective, there are not many relevant cases in the literature. The framework includes a preliminary analysis, in which a general overview of the current state is carried out, and the main criticalities are identified; analysis of the objectives, in which the strategic objectives are defined; retrofitting process through which the old plant is transformed into a plant ready for industry 4.0, development of applications for industry 4.0, development of the user interface to allow use by interested operators. Finally, a case study is proposed. For this reason, the framework presented in this work aims to create general guidelines for retrofitting an old process plant to bring it into line with the new industry 4.0 paradigms. The paper is organized as follows. Section 2 presents a literature review that analyzes the most relevant retrofitting studies from an industry 4.0 perspective in industrial and process plants. Section 3 introduces the general framework developed to retrofit process plants. Section 4 describes the application of the proposed framework to an old two-phase mixture process plant. Finally, section 5 presents a discussion and conclusion setting out the problems encountered in applying the general framework and the managerial implications.

## 2. LITERATURE REVIEW

A systematic approach has been used for the literature review to analyze previous works connected to Smart Retrofit implementation. The protocol used for this analysis is as follows: Scopus has been used as a research database, both journal and conference papers have been selected, only documents in English have been considered, the keywords used for research and the number of documents found are given in table 1, documents not related to the industrial sector (e.g., related to construction) haven't been considered. Some of the papers found appeared in more than one search. The documents found were 56 in all of which 30 were relevant.

Table 1. Contribution to literature review

| **Keywords** | **# of papers** | **# of relevant papers** |
|---|---|---|
| ”Industry 4.0” AND ”Retrofit” | 24 | 15 |
| ”Industry 4.0” AND ”Retrofitting” | 30 | 23 |
| ”Industry 4.0” AND ”Revamping” | 1 | - |
| ”Smart retrofit” | 5 | - |
| ”Smart retrofitting” | 7 | 4 |

Several works deal with retrofitting for Industry 4.0 implementation. Fig.1 shows how the majority of the analysed papers refer to manufacturing processes to the best of the authors' knowledge. The documents that refer to retrofitting for the implementation of industry 4.0 in process plants are few, as shown Fig.1 Windisch and Doppelreiter (2019) introduce an approach for oilfield digitization with an eye towards Industry 4.0 and big data. Lins et al. (2018) present a retrofitting method from an industry 4.0 perspective and a case study with a didactic process plant.

Some authors have presented some useful tools for the retrofitting process. For instance, Nsiah et al. (2018) propose a toolkit for evaluating the application of Industry 4.0. Lucke et al. (2019) suggest a MIALinx application, a useful tool in retrofitting operations to simplify IT integration, focusing more on the importance of a user-friendly interface. Niemeyer et al. (2020) present a mobile sensors kit and an IoT platform through which SMEs can quickly evaluate the potential benefits drawn from industry 4.0. Panda et al. (2020) propose a Plug&Play platform for retrofitting to integrate the sensor system with a cloud platform and the analysis and monitoring system.

The” others” category includes all relevant documents that do not refer to specific applications. For example, Tuptuk and Hailes (2018) analyze the importance of cyber security in smart systems, essential during the retrofitting phase, to avoid underestimating IT security aspects. Alexandru and Pupăză (2020) present a smart retrofitting case study to predict heat transfer characteristics using machine learning algorithms. Birtel et al. (2019) address the problem of retrofitting when human resources are a backbone of the production process, proposing a method for the connection between Asset Administration Shell and human resources. Bevilacqua et al. (2020) developed a Digital Twin reference model to define conceptual guidelines to support the implementation of Digital Twin for risk prediction and prevention.

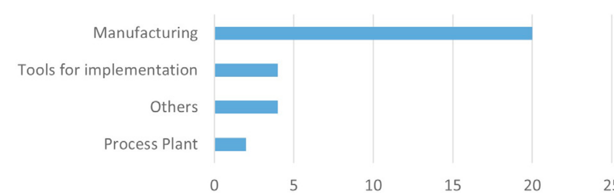


Fig. 1. Topic distribution

From the research, the documents found relating to retrofitting process plants for the implementation of industry 4.0 are very few. Therefore, the search has been expanded with the keywords: ”retrofitting” AND” process plant”. However, this new research did not present relevant documents.

The literature review shows how, through retrofitting operations for the industry 4.0 adoption, many SMEs companies can approach the world of industry 4.0 in a sustainable, economic, and environmental way. Through smart retrofitting, companies can profit by minimizing time and investment compared to a replacement. Most of the cases discussed in the literature refer to manufacturing processes, while regarding process plants, it is still an unexplored topic. Therefore, in this paper, the authors propose a general framework for the retrofitting of process plants and the framework application in a case study on a two-phase mixing plant.

## 3. THE GENERAL FRAMEWORK

The general approach proposed to transform an old processes plant into a plant ready for Industry 4.0 is represented in Fig.2. The transformation process is divided into five macro areas. Initially, it is necessary to define the objectives to be achieved with retrofitting. A preliminary

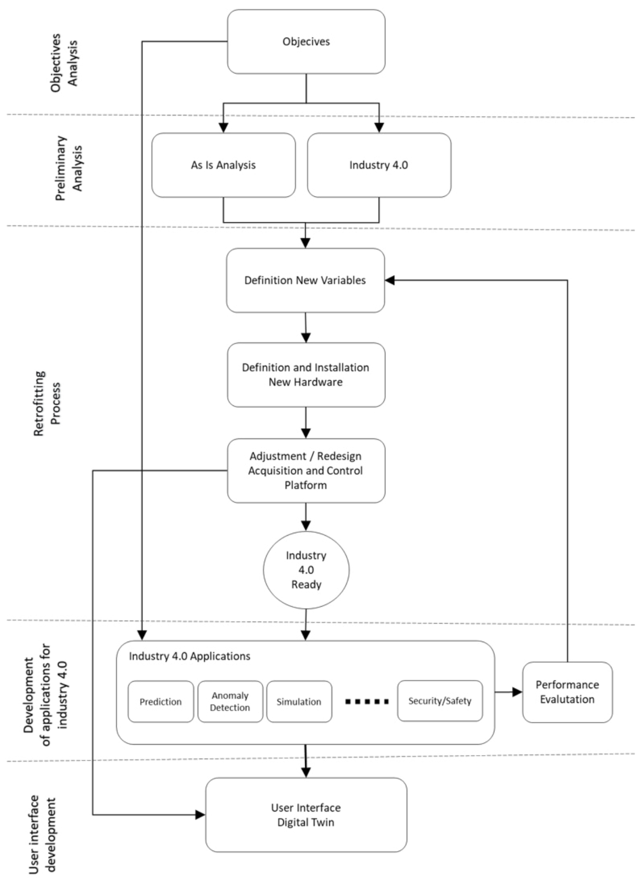


Fig. 2. General Framework

analysis is then carried out in which the plant current state and the opportunities that the implementation of industry 4.0 can provide are evaluated. Thus, it will be possible to define the applications of Industry 4.0 necessary for the intended purpose. At the same time, it will be possible to define the operating procedure for retrofitting the old process plant into a process plant industry 4.0 ready. Finally, a user interface must be developed to make the developed applications easy to use for the operators. Subsequently, each area will be described in detail.

### *3.1 Define the strategic objectives*

The adoption of industry 4.0 paradigms makes it possible to achieve targets such as: improving working conditions, better quality processes, better communication and collaboration, improve productivity, efficiency, flexibility and agility, reduces costs. It is not necessary for companies aim to achieve all of these. At this stage, it is crucial to understand which of these potential targets is best to seek. For-profits already in the short term, it is better to aim to achieve the objectives that managers find as most strategic. Once the strategic objectives are defined, it will be possible to identify the applications necessary to achieve them. In the future, the system could be ready for other Industry 4.0 application.

### *3.2 Preliminary analysis*

In the first step, a careful evaluation of the current state of the old plant is essential. A detailed description of the plant and process is required; it is necessary to identify the plant's main functions, which is the finished product, which are the variables that come into play in the process, which variables must be monitored once controlled. It could be interesting to analyze the historical data collected in the past and carry out interviews with the operators who used the plant to identify the potential criticalities of the plant. Through an iterative process, the preliminary analysis and knowledge of industry 4.0 paradigms can change or add previously defined objectives.

### *3.3 Retrofitting process*

This phase can be divided into three sub-phases:

*Definition of new variables:* Considering that the idea is to create a digital mapping of a process, a careful technical evaluation must define the possible additional variables to be monitored and controlled to achieve the required targets. As shown Fig.2, variables definition is an iterative process.

*Definition and installation of new hardware:* The sensors and actuators acting on the variables must communicate with the acquisition platform to be developed. It is essential to pay attention to the sensors and actuators already present on the plant since some of them could not communicate with third-party systems, consequently requiring their replacement or adjustment.

*Adjustment / Redesign Acquisition and Control Platform:* In this step, the necessary tools are defined to ensure adequate process control and data collection. Moreover, as required by industry 4.0 paradigms, a real-time system for the data analysis has to be developed because continuous data collection implies a considerable volume of data, sometimes unuseful. The collected data will be stored in specific databases and used in real-time by the applications developed subsequently. Appropriate communication protocols will have to be defined and implemented to guarantee the required performance in terms of speed and security. For a small amount of data and a moderate number of connected users it is possible to use classic database managers such as MySql, instead, for rapid and frequent access by many users, a solution based on Cloud Storage can be adopted using database systems such as NoSQL. However, some plants could be already equipped with acquisition and control systems, so it is necessary to evaluate their compatibility with the new platform. Conversely, it is mandatory to replace or modify the old system. At this point the system is ready to Industry 4.0.

### *3.4 Development application for industry 4.0*

Although the retroffited plant is ready to Industry 4.0 , it is necessary to develope specific application such as, anomaly detection tools, predictive maintenance tools, control quality tools, remote control applications and digital twin to benefit from it. Develop one or more of these applications it is a complex process and it could take a lot of resources and time. For these reasons, to achieve results in the short term, it may be advantageous to develop the necessary applications to fulfill the strategic objectives defined above. Once defined the required applications, problems related to lack of information can arise during development.

The performance evaluation of the applications follows the development phase, and it is one of the most critical step. Indeed, the defined objectives could not be achieved. For instance, this problem could be related to a lack of information, requiring at this point, the re-evaluation of the variables necessary for monitoring and control.

### 3.5 Development of the user interface

The adopted technologies improve both Human-Machine and Machine-Machine interactions by developing a user-friendly interface such as a web application, a portable device application, a VR application, or an augmented reality application.

## 4. APPLICATION OF THE FRAMEWORK

The proposed framework has been applied to a two-phase mixture process plant located inside the Laboratory of the Department of Industrial Engineering and Mathematical Science (DIISM) of the Polytechnic University of Marche (Ancona, Italy). The steps described were carried out to make it ready for industry 4.0 and improving its maintainability and safety conditions.

### 4.1 Define the strategic objectives

The main objective of the retrofitting process con be summarized as follows:

- Create a virtual process parallel to the physical one for both static and dynamic analysis;
- Propagate information to all interconnected and achievable digital objects to increase the safety of the operators that work in the plant;
- Intercept anomalies at the beginning to minimize the damage from breakage or support preventive/predictive maintenance.

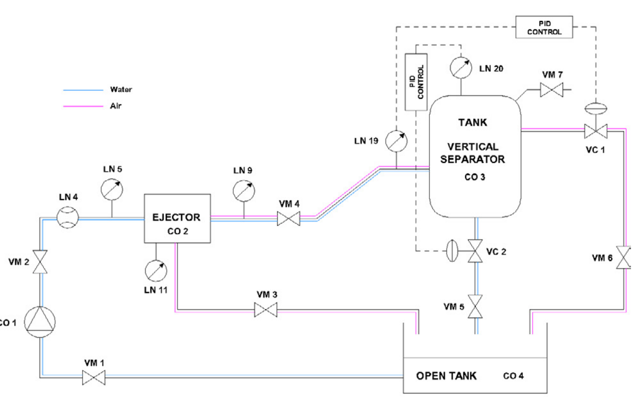


Fig. 3. Old plant scheme

### 4.2 Preliminary analysis

The first analysis consists of all physical resources to be controlled, such as personnel, equipment, material and process. The plant is originally equipped with a series of sensors (pressure, flow, level) for the process monitoring. Fig.3 and table 2 show the analysis results.

Table 2. Sensors installed in the old plant

| Variables | Ref | Sensor | Type |
|---|---|---|---|
| Pressure before ejector | LN5 | Brannan | Pressure gauge |
| Pressure on the ejector case | LN11 | Brannan | Pressure gauge |
| Pressure after ejector | LN9 | Brannan | Pressure gauge |
| Pressure in the tank | LN19 | Foxboro 841GM-CI1 | Relative pressure sensor |
| Liquid level in the tank | LN20 | Foxboro IDP-10 | Differential pressure sensor |
| Flow before the ejector | LN4 | Foxboro Magnetic Flowtransmitter | Flow sensor |

### 4.3 Retrofitting process

As described above, this phase can be divided into three sub-phases:

*Definition of the new variables:* according to the retrofit objectives, new variables are required and they are explained in table 3.

Table 3. Sensors installed in the new plant

| Variables | Ref | Sensor | Type |
|---|---|---|---|
| Pressure before ejector | LN5 | Setra 280E | Absolute pressure sensor |
| Pressure on the ejector case | LN11 | Setra280E | Absolute pressure sensor |
| Pressure after ejector | LN9 | Setra280E | Absolute pressure sensor |
| Pressure in the tank | LN19 | Foxboro 841GM-CI1 | Relative pressure sensor |
| Liquid level in the tank | LN20 | Foxboro IDP-10 | Differential pressure sensor |
| Flow before the ejector | LN4 | Foxboro Magnetic Flowtransmitter | Flow sensor |
| Air inlet flow | LN8 | Foxboro Vortex DN 50 | Volumetric flow sensor |

*Definition and installation of new hardware:* The acquisition and control board used in this case is an Arduino Mega 2560 accepting an input voltage for analog signals from 0 to 5 volts. Fig.4 shows the layout of the system with the new equipment, while table 3 shows the sensors associated with the variables. The sensors SETRA280E are voltage sensors working between 0 to 5 volts and have been connect directly to Arduino. The other sensors are current sensors working between 4 - 20 mA; for the acquisition Arduino has been connected to a 250 Ω resistor placed in series in the sensor circuit, in this way it has been possible to measure the voltage difference between 0 to 5 V.

*Adjustment / Redesign Acquisition and Control Platform:* The Acquisition and Control Platform is dedicated to transferring data or information between Digital Twin and plant elements. In a Cloud server, real-time data from the field are stored. The platform is designed for data acquisition, sorting and visualization.

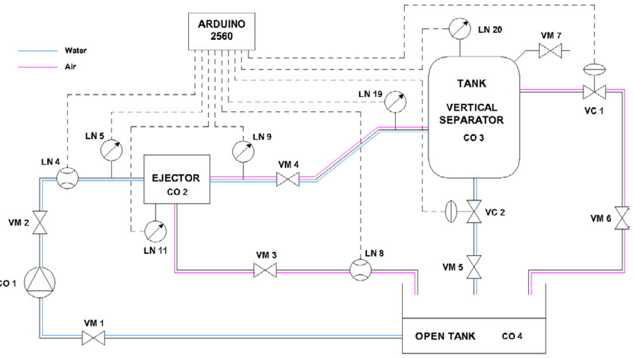


Fig. 4. New plant scheme

### *4.4 Development application for industry 4.0*

According to the retrofitting objectives, a Digital Twin of the plant has been developed to create a virtual process parallel to the physical one. For developing the plant Digital Twin of different solutions can be used:

- Modeled all components of the plant through mathematical equations;
- Use Computational Fluid Dynamics (CFD) Simulation software;
- Use a supervised algorithms.

It is decided to use a supervised approach, taking into consideration the complexity of the analysed plant. Moreover, as it is a laboratory plant, it is possible to make data acquisition campaigns. In particular, Machine Learning and Swarm Intelligence (SI) algorithms have been evaluated. As an example, we show in Fig.7 a screenshot of the Digital Twin tool. In this article,for reasons of space, has been described only the Machine Learning algorithm developed for the anomaly detection.

The Anomaly Detection and Prediction Tool has been developed to predict why faults are occurring, the causes, and how long the system can go on before it breaks down or goes out of the correct plant operating parameters. A supervised approach has been used. A testing campaign

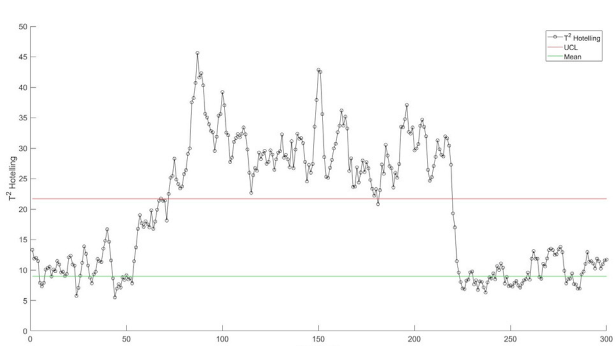


Fig. 5. Example of anomaly analyzed with Hotelling $T^2$

was carried out, identifying through Hotelling $T^2$ statistics the acceptable threshold values before having out of control working conditions (see figure 5). The faults have been reproduced intentionally using some valves simulating anomalies in a short time. Repeat the tests several times and train the simulation and machine learning algorithms based on these tests.

Several Neural Network structures have been implemented and evaluated in terms of accuracy. On the best combinations (see Fig.6), a k-fold cross-validation with K=7 was performed. Besides, the network trained to each iteration of the k-fold was used to evaluate the accuracy, the recovery (fraction of classifications erroneously assigned to the negative class), and the F1 indicator Shanmuganathan and Samarasinghe (2016).

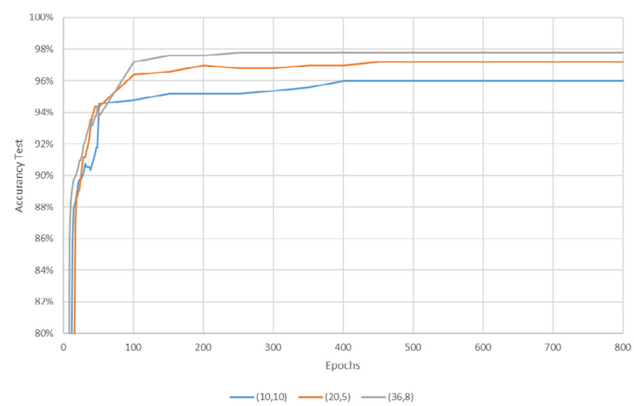


Fig. 6. Accurancy test on the best combinations MLP for anomaly detection

The external dataset was produced by generating the anomalies under different working conditions (i.e. opening angles of the shut-off valves).

### *4.5 Development of the user interface*

The sensors gather data to activate warning signals if the discrepancy between the two values exceeds defined thresholds. Through wearable systems, it has been possible to monitor, for example, the distance of the operator from the plant and send alerts in case of risk situations (a burst, an over pressure, etc.).

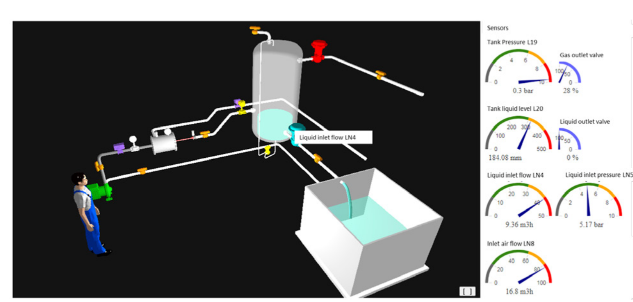


Fig. 7. Screenshot of Digital Twin user interface

## 5. DISCUSSION AND CONCLUSIONS

The introduction of industry 4.0 is revolutionizing the modern industry. This article proposes a general framework to guide the transition process. The proposed method consists of 4 macro phases: preliminary analysis, objectives analysis, retrofitting process, development of applications for industry 4.0, and development of the user interface. The adoption of industry 4.0 paradigms can lead to various benefits to companies, but this is not a simple process, especially for companies already equipped with old systems. There are no official protocols to guide companies with old process plants to the transition process towards industry 4.0. In this work, a general framework is proposed to retrofit an old process plant; subsequently, the proposed method is applied to a case study relating to a two-phase mixing plant. Even if the experimental plant is still in test phase, thanks to the retrofitting process it was possible to notice a significant improvement in terms of process control, product quality, quantity and time of maintenance.

The proposed process presented some challenges in its application. One of the most complex issues is the multidisciplinarity aspects connected to a retrofitting process. From the early stages to the last of the retrofitting, the professionals involved are different. In the early stages, it was necessary to include experts who knew the process to identify both the variables to be monitored to have complete control of the process and the potential critical issues that could occur. Subsequently, in the instrumentation phase and the development phase of the acquisition and storage platform, it was necessary to involve electronics and IT experts. Finally, for the development of the specific applications characterizing industry 4.0, such as the digital twin or the anomaly detection tool, data analysts were involved. Another problem encountered is related to recursion in the definition of new variables. As shown in Fig.2, a negative result in the application performance evaluation process involves a verification of the variables taken into consideration and possible integration of different variables. This recursive process will undoubtedly lead to a satisfactory result, but at the same time, it can lead to excessive completion time. The tool developed for anomaly detection uses a supervised machine learning algorithm that needs labels and a trained dataset. In the case in question, it was possible to collect data relating to anomalies as it is an experimental plant, but this may not be possible in other cases. The transition to industry 4.0 by its nature involves that a lot of control and monitoring information is exchanged between different devices. This intense flow of information is usually not present in old plants, highlighting a new and relevant problem linked to security information. Indeed, these data must be protected both for privacy and plants and operators' safety. Due to the identified advantages of the proposed approach, it can be implemented also on manufacturing plants.

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