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Retrofitting of legacy machines in the context of Industrial Internet of Things (IIoT)

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Abstract

In the context of Industry 4.0 (I 4.0), one of the most important aspects is data, followed by the capital required to deploy advanced technologies. However, most Small and Medium Enterprises (SMEs) are neither data ready nor have the capital to upgrade their existing machinery. In SMEs, most of the legacy machines do not have data gathering capabilities. In this scenario, the concept of retrofitting the existing machinery with sensors and building an Industrial Internet of Things (IIoT) is more beneficial than upgrading the equipment to newer machinery. The current research paper proposes a simple architecture on retrofitting a legacy machine with external sensors for data collection and feeding the cloud-based databases for analysis/monitoring purposes. The design and functional aspects of the architecture are then tested in a laboratory environment on a drilling machine with no embedded sensors. Data related to the speed of the drill head and the bore depth are collected using newly retrofitted sensors to validate the proposed architecture.

Keywords: Retrofitting ; IIoT ; Industry 4.0 ; Digitalization ; SMEs

1. Introduction

Industry 4.0 (I 4.0), also known as the fourth industrial revolution, requires the combination of advanced technologies to bridge the physical shop-floor machines with cyber systems to enable cyber-physical interactions. One such technology is the Industrial Internet of Things (IIoT), which combines different disciplines, e.g., sensor technology,

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retrofitting technology, and data analytics. Research claims that companies can benefit from increased production efficiency and profits with the potential usage of IIoT [4]. However, implementation of IIoT comes with inherent challenges for the manufacturing industries, especially for Small and Medium Size Enterprises (SMEs). Most SMEs still work with age-old legacy machines with no data exchange capacities. This brings the first challenge that the SMEs are not data ready to get the benefits of IIoT such as predictive maintenance [22], real-time monitoring [16], etc. SMEs also lack a deep understanding of IIoT concerning the benefits and challenges associated with it. The lack of awareness of SMEs related to advanced manufacturing technologies and employee skills [12] are other hurdles for implementing IIoT.

The main idea behind IIoT is to have better control over what is happening in the plant. This is achieved by gathering data or information and making it available in a helpful form to everyone needing it, be it the workshop worker or the company's top management. This information could be about how fast a machine is working, how much stock of a particular part is available, how many workers are ill, and most importantly, the status of machinery and production overview. This is already possible in some ways. However, IIoT implementation would make it more uniform, easier to do, and take it further than the simple data gathering. Most factories are built over the years, and additions to it are made over time, which means that the companies can have machines, sensors, Programmable Logic Controllers (PLCs), and other devices that have different ages, interfaces, and are from different manufacturers in the same factory. This combined with the fact that manufacturers have their proprietary software, interfaces, etc. makes it extremely difficult to unify data and information.

Furthermore, another hurdle in the digital transformation of an SME is the lack of investment needed to replace legacy machines with advanced machinery. Moreover, it is unclear either from research or real-world examples which path to take for a plant to be IIoT ready. The current research presents retrofitting as a starting point for SMEs with legacy machines towards the digital transformation journey. Retrofitting deals with the idea of upgrading the existing legacy machines without compromising their functionality in preparation for IIoT. As per Lins et al. [13], retrofitting is directly linked to the longer life of the old machines (sustainability), productivity, and increasing the technology level (I 4.0). Moreover, the concept of "smart" retrofitting is gaining popularity as well, where virtual counterparts such as smart glasses are added to physical items to gain control of the manufacturing process [1]. Nonetheless, this paper takes the traditional retrofitting approach of upgrading the physical entities of the shop floor rather than adding the virtual counterparts to develop a cheaper retrofitting alternative for SMEs.

To achieve the first steps in the direction of IIoT at a reduced cost, one needs to see if the existing machinery can be made intelligent by retrofitting external sensors to measure different critical variables associated with the process. These variables are vital to measuring the functioning/status of the machines, such as temperature, speed, the machine's vibration, tension, etc. The current research focuses on the feasibility and validation of retrofitting old machinery with sensors and collecting, storing, and processing data using open source tools. This research will present a generic architecture on retrofitting old machines and showing a possible implementation of it in a laboratory environment. By basing the architecture on open source and easily accessible tools, we achieved a cheaper and flexible alternative to retrofitting legacy machines. Moreover, the architecture can be applied to most retrofitting scenarios, if not all, with slighter modifications.

The rest of the paper is structured as follows: Section 2 covers the state of the art of IIoT, retrofitting technology, and security aspects of IIoT. In section 3, a general architecture for IIoT in the context of retrofitting is explained and the laboratory implementation of the retrofitting is covered in section 4. Discussion and conclusion are presented in section 5 and in section 6 respectively.

Nomenclature

I 4.0	Industry 4.0
SME	Small and Medium Enterprise
IIoT	Industrial Internet of Things
PLC	Programmable Logic Controllers
OEM	Original Equipment Manufacturer
GPIO	General Purpose Input Output

2. Literature study

Over the last few years, with the emergence of I 4.0, the notion of IIoT has become an increasingly important topic of discussion in both research institutions and the industry. In [18], the authors reflected on the available literature relevant to I 4.0 applications and concluded that the implementation of I 4.0 required a holistic approach and interdisciplinary knowledge. For example, to successfully implement IIoT in an industrial setting requires integration of production processes with digital technologies [16]. Integrating physical and cyber systems of the modern manufacturing landscape allows industries to enable predictive maintenance and OEMs to offer data-based services. However, most of the legacy machines in SMEs do not have the infrastructure to generate data; in other words, they aren't data ready. Therefore the first step in the direction of I 4.0 is to upgrade the existing machinery in SMEs using retrofitting technology.

The existing literature presents the retrofitting of machines in two different categories [23]: "industry 4.0 push" and "need-based pull." In the first category, the research aims to develop and retrofit all the equipment to provide connectivity and data collection capability for legacy machines, which is a prerequisite for transition to I 4.0. The second category focuses on specific equipment and improving its efficiency, productivity, predictive maintenance capability, etc. Nevertheless, the basic needs across both categories stay the same: external sensors, data connectivity, databases to store the data, data processing, data analytics for predictive maintenance, and security. The authors in [22] employed retrofitting and demonstrated the development of a predictive maintenance model from the data collected using low-cost embedded systems and sensor technology. The case study was focused on a robotic cell for the detection of abnormalities and forthcoming failures. The researchers in [5] highlighted the importance of retrofitting and its role in predictive maintenance in a process industry. They performed retrofitting in a two-phase process plant and developed a framework to guide the transition process from a classical process plant to an Industry 4.0 ready process plant. They showed that the retrofitted system allowed efficient maintenance and operator safety management using the proposed anomaly detection and simulation platform.

Jeschke et al. [9] talks about the start of IIoT and defines some of the focus points of it which could be adapted in the context of retrofitting. Preuveneers and Ilie-Zudor [18] goes into details about the state of development of different subjects that are included in the IIoT umbrella. However, it keeps it still at a superficial level of details. The last survey paper review and the more recent one is Zambetti et al. [23] is specifically a research paper about state of the art about retrofitting legacy machinery. However, it focuses on why it would be interesting for OEMs to sell and enable the servitization of machines by retrofitting them.

Two publications focused on the security aspects of IIoT. These papers are relevant for retrofitting scenario as in SMEs, retrofitting can be seen as the first step towards IIoT. The first one being Sadeghi and Yuen [19] in which they look at the whole I 4.0 and identify potential risk factors. They do not detail any specific security problem but show where in each part of the development of I 4.0 there could be problems. The second one is Tedeschi et al. [21] they focus on the development of an architecture that enables secure communication between sensors and the rest of the communication system of a company.

We identified eight research papers that focus on the methodologies or architectures to enable retrofitting of machines. Guerreiro et al. [7], and Lins et al. [14] published a series of papers and introduced the concepts of smart retrofitting and retrofitting of the entire plant, respectively. Burresi et al. [4] adapted the methodology of [7] and applied it to develop an architecture to retrofit a specific section of a steel plant. Fan and Chang [6] developed a general architecture to be able to retrofit machines. However, they did not include cloud connectivity, which is considered essential when transitioning to I 4.0. Bosi et al. [3] made a detailed architecture of the communication layers in an IIoT setting. Orellana and Torres [17] developed an architecture that enables SMEs to transition to I 4.0 at a reduced cost. However, the central focus is not on the retrofitting in and out itself but on how to do it. Mayer et al. [16] took a pedagogic approach to IIoT and developed an architecture that allowed them to teach university students how to use some of the IoT tools and gave them a practical initiation into IoT.

Retrofitting of CNC machines was the focus of two papers. Jónasdóttir et al.[10] developed a device called BAUTA, which enables them to get remote access to CNC machines with no connection to the internet. This device allows them to remote control the machine. It is a method specifically designed for use with CNC machines. Kim et al. [11] developed a system with the help of a camera to monitor CNC machines from a distance. This is, however, only possible if the machine already has some human-machine interface. This is not a retrofit in the same sense as defined at the beginning of this section, as no sensor is added to upgrade the machine.

We found several papers focused on tackling specific needs in companies concerning retrofitting. In [2], Bakir et al. proposed Industry_Integrator, which can be used to retrofit machines in SMEs. Some researchers [8] [22] combined machine learning and aspects of retrofitting for predictive maintenance applications. Luke et al. [15] developed a system MIALinx, a software that allows unskilled workers to easily input some rules based on sensor information with a focus on maintenance. With a goal of real-time monitoring of machines, Strauß et al. [20] retrofitted some machines in a plant and added sensors to them. In their data flow from the physical layer to the cyber layer, they used proprietary software already used in the specific plant. However, the current research focuses on developing the data flow with open source software at a cheaper cost.

We found that the existing literature related to retrofitting leaves several research gaps. The majority of the papers did not present the practical implementation of the proposed methodology. Moreover, the focus on SMEs is clearly missing except in [1] [17] [2]. The final research gap, evident in all the papers, is that open-source software and cheaper hardware reduce the cost of retrofitting initiatives in SMEs. The current research aims to address these research gaps with a laboratory implementation of the proposed general architecture.

3. Proposed Architecture

The general methodology applied in this research is as follows. At first, we defined the problem statement from our experience with SMEs [12] that they are not data ready and hence they are not ready for digital transformation to I 4.0. After a structured literature survey, we figured out that the retrofitting technology is a starting step for enabling data gathering capacity for legacy machines in SMEs. We made an exhaustive analysis on how and where the variables could be measured on the machine. This included types of sensors, manufacturers, and communication interfaces of the sensor and the position and mounting points for the sensors. We made sure to use most of the already available electronics of the machine so that the cost of retrofitting could be kept to a minimum and to simplify the communication with the machine. After this choice was made, the mounting and fixing points of the sensors were designed, and 3D printed. The third and last step of the methodology used in this work was to establish a general architecture that can be used to retrofit most, if not all, machines in a company.

The architecture presents a general perspective of IIoT, which can be applied to any legacy machine in the context of retrofitting. The integration of legacy machines (physical layer) with reporting and analytical systems (cyber layer) involves several steps. These steps must be executed sequentially for successful retrofitting, data gathering, and building databases for legacy machines. Furthermore, the database is linked to monitoring and analytical instruments to make it possible for a company to enter the I 4.0 territory truly. Each step in the integration process involves the usage of specific hardware/software.

The first step in the integration process is to upgrade the infrastructure of the legacy machines by retrofitting. At the beginning of retrofitting, the only infrastructure available is the machine itself. However, in I 4.0, the machine must be connected to the digital world. Hence, retrofitting smart sensors, actuators, and IoT devices to the machine can establish a starting point for integrating physical and cyber worlds. Moreover, retrofitting the above infrastructure does not guarantee data extraction from machines. Therefore, controllers such as microcontrollers, PLCs, or computers are introduced in this step, and they are referred to as IoT nodes. The introduction of IoT nodes ensures the data extraction from the sensors and connects the machine to the internet to facilitate the next steps. The second step is to establish a secure gateway between the physical and cyber layer by introducing a middle layer called IIoT gateway, which is further connected to IIoT middleware. For this purpose, a standardized communication protocol is required. This protocol ensures accurate and swift data transfer between the machine and the IIoT middleware. In the final step, the collected data is stored in databases and sent for analytical purposes using a web-based software or local edge-computing device. Fig. 1. shows the general architecture of retrofitting a legacy machine to introduce it to the I 4.0 regime.

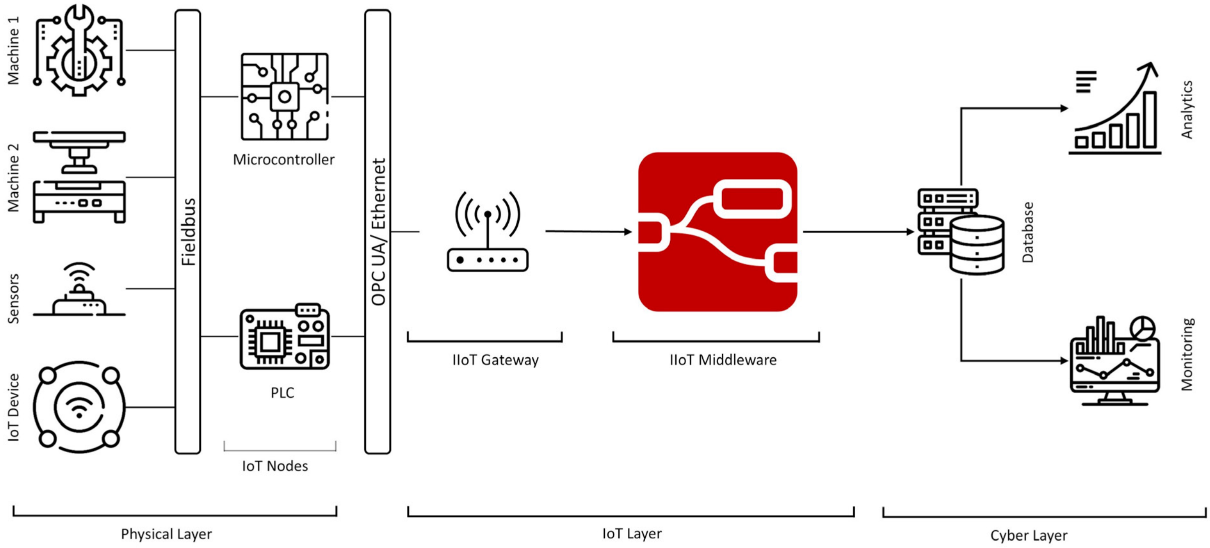

Fig. 1. General architecture of IIoT in the context of retrofitting.

4. Laboratory implementation

This section aims to present a concrete implementation of the architecture mentioned in section 3 in a laboratory setting. Starting with the physical layer, the legacy machine used in the case study was a Contimac TB20, a column-drilling machine (Fig. 2). This drilling machine has no sensors or any information-gathering capabilities. These machines are a classic example of legacy machines seen in SMEs and an ideal legacy machine to retrofit. The machine can offer a wide range of variables to measure. However, a decision was made to collect the critical variables such as drill speed and drill depth. A speed sensor in the form of a hall sensor that sits inside the top cover of the machine is added. For the functioning of the hall sensor, a small magnet is fixed to one of the disks that spins the drill. To measure the depth of the drill, an infrared distance sensor is retrofitted and placed on the stationary part of the column. In order to extract the data from the machines, Raspberry Pi is chosen as a controller, and the sensors are connected to it with cables. The inclusion of a Raspberry Pi ensures extraction of the data and connects the machine to the internet via Ethernet protocol using LAN technology. Internet connectivity is the most critical feature for collecting and forwarding the data from machines to other software tools in the subsequent steps. Retrofitting of legacy machines is complex for many reasons, one of which deals with the type of output from the sensors. In this case study, the hall sensor provides digital output directly connected to the General Purpose Input Output (GPIO) of the Raspberry Pi. However, the infrared sensor gives an analog output; due to this, an analog to digital converter was added to the Raspberry Pi in the form of a Pi Hat and then connected to GPIO. This completes the hardware setup for retrofitting.

The gateway between the physical and cyber layer is achieved by installing an IIoT middleware software called Node-Red on the Raspberry Pi. Node-Red is a browser-based editor that has the benefit of being open-source and well documented, having a library of freely accessible nodes needed for the use of databases, and the reading of sensor data from multiple sources. Node-Red serves as an easy-to-use programming software that can combine various software and hardware interfaces, being it simple voltage readings or complex communication protocols used in industry. With an already existing node to access the GPIO Pins of the Raspberry Pi, one can quickly get the status of the pins on which the Hall sensor was connected. For the distance sensor, the manufacturer developed nodes for the use of Node-Red; this makes it easy to handle the signal that comes from the A/D converter connected to the pins of the Raspberry Pi. Both signals needed to be modified so that the needed information can be correctly displayed. The speed sensor, which simply switches from 1 to 0 each time the magnet passes in front of it, was connected in Node-Red to a node

Fig. 2. Legacy machine (Contimac TB20).

that calculates the frequency of a signal when it changes from 1 to 0. Then the frequency is multiplied by 60 to get the drill speed in RPM. The infrared sensor outputs a voltage from 0V to 3V and ranges from 10cm to 80cm. To convert this voltage into understandable distance units, the output voltage for distances ranging from 10cm to 80cm was manually measured and curve fitted using MATLAB©. The output of a MATLAB curve fitting is a 3^{rd}-degree differential equation that can be easily programmed in Node-Red to get the distance in metric units.

To process the data received in Node-Red, two software tools are required. One is to store the data, and another one to do real-time reporting and analytics. We can use different software based on the amount of data collected and the needs of the company. However, in this case study, we used InfluxDB as a choice of database because the software provides an in-built node in Node-Red, which reduces extensive interface development. In InfluxDB, the values are saved with a timestamp and the name given to those in Node-Red, such as speed, depth, and so on. For real-time reporting and analysis of the data, another software tool Grafana was used. Grafana is a powerful tool to create live dashboards of the data directly fed from InfluxDB. These live dashboards can be adjusted to the specific requirements of the company making Grafana an ideal option to monitor the real-time status of the machine. The laboratory implementation of the retrofitting technology based on the architecture in the previous section is shown in Fig. 3 and the retrofitted column drilling machine is shown in Fig. 4.

5. Discussion

IIoT is a relatively new concept, and there is no one fits all solution that exists for adaptation. Especially in SMEs, where there is considerable resistance to change [12], introducing a new concept or technology can face many challenges. When it comes to retrofitting, it is probably challenging to develop a solution that can be applied to a wide range of machines and for various industries. This research created a more generic architecture for legacy machines with no data exchange capabilities. Moreover, the architecture with some modifications can be applied to different machines because the hardware & software used in the research is open source and can be used under many different circumstances. When it comes to SMEs concerning IIoT or retrofitting, the willingness to know what and know-how is essential to adopt these concepts. Often, state-of-the-art research focuses on creating a methodology or architecture used in specific scenarios and tackles the problem at hand. The current research achieved a more general approach to retrofitting legacy machines and making them cheaper and more accessible for companies. After a successful laboratory validation, we approached a few SMEs in the Luxembourg region and are currently conducting the field test on the actual shop floor. In this particular field test, we have retrofitted five sensors to a semi-automated labeling machine

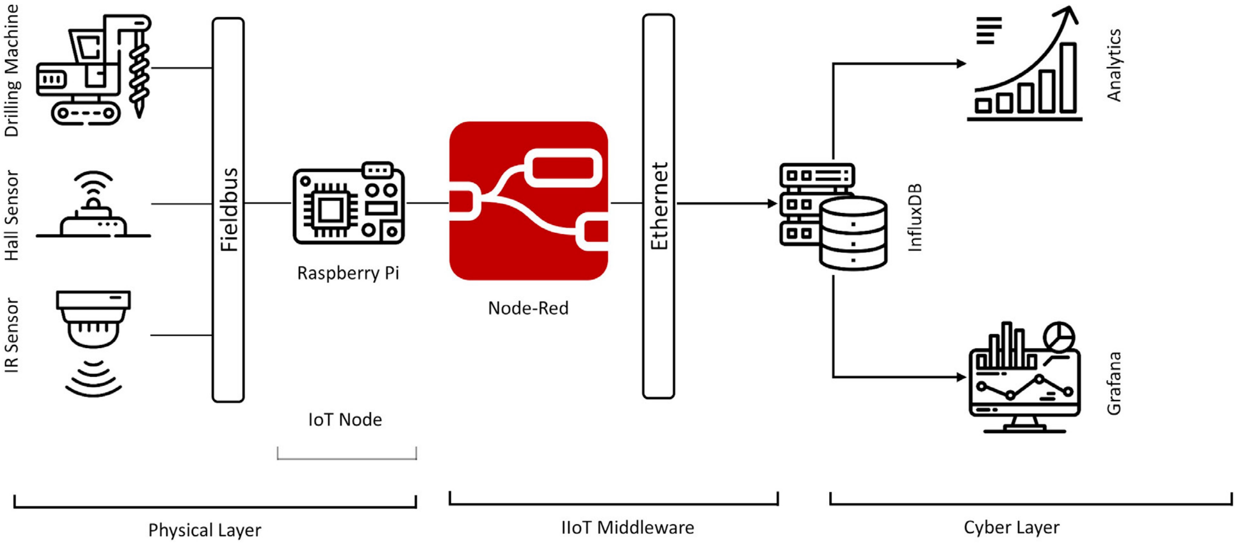

Fig. 3. Adapted architecture for laboratory implementation.

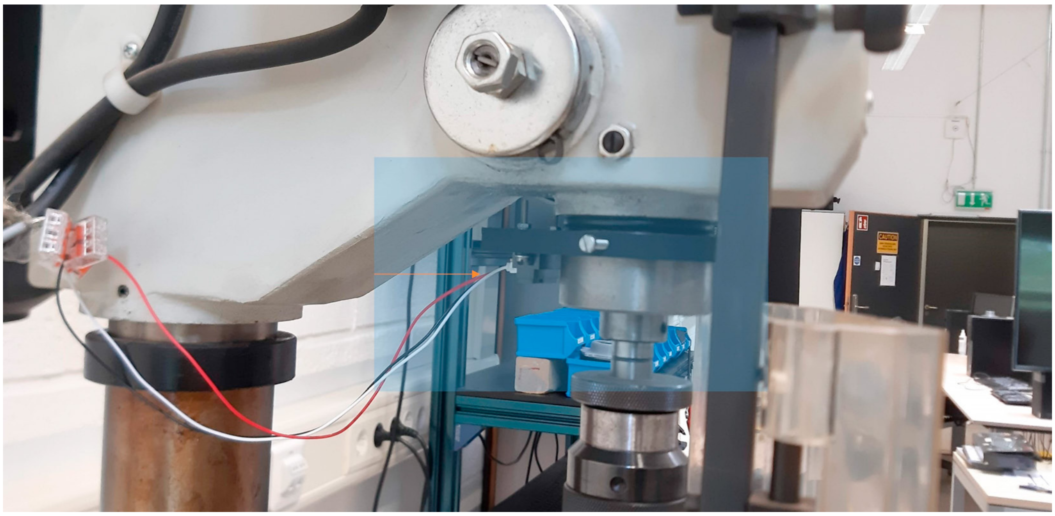

Fig. 4. Drilling machine with the retrofitted IR sensor.

using the generic IIoT architecture shown in Fig 1. As the machine in the company was already using Siemen's PLC system, we adapted the architecture without any significant changes. In a global picture, the Original Equipment Manufacturers (OEMs), who by nature have the complete know-how of the legacy machines, could utilize this enormous opportunity to retrofit old machines and provide comprehensive services in the context of I 4.0 [23]. However, this area requires extensive research due to the uncertainty of potential concerning such initiatives from OEMs. Moreover, several field tests from this research project can also help to see the potential opportunities of extended services to SMEs in the context of retrofitting and IIoT.

6. Conclusion

This paper presented a general architecture of IIoT in the context of retrofitting with which SMEs can retrofit legacy machines at a low cost. This was possible thanks to the low-cost sensors, inexpensive single-board computer in a Raspberry Pi, and open-source software. These tools can help companies upgrade machines with no data gathering capabilities and enter the era of I 4.0. The software and hardware were chosen based on the general architecture. The same is possible to be implemented by workers and companies with limited IT know-how. It was also one of the goals set at the beginning of this research, as it allows for more diverse types of companies to implement it. However, during the implementation of the general architecture in the laboratory, we had faced challenges in selecting the hardware that can speak to single-board computers such as Raspberry Pi. In some cases, we had to build additional boards to support the sensors' digital and analog outputs. When the focus is more specifically on the retrofitting aspect, one major problem is that there is no one-fits-all concept or solution until now. Moreover, it will probably be challenging to develop such a concept as the applications differ so much from one company, plant, and machine to another that every retrofit is almost a unique solution by the nature of the concept. This research tries to reduce the variety of architectures and to create a more generally applicable system. That is why the used software is capable of being used in so many different circumstances. SMEs look for simple architectures with minimal cost when adapting I 4.0. Expanding the system in the analytics, cloud connectivity, and clustering of machines departments will be the goal of future research.The general architecture developed in this research is straightforward and currently being implemented in an SME based in Luxembourg with slight modifications to the proposed architecture to enhance the security of the retrofitting set-up.

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