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Retrofitting-Based Development of Brownfield Industry 4.0 and Industry 5.0 Solutions

TUAN-ANH TRAN[1,2,3], TAMÁS RUPPERT[1], (Member, IEEE), GYÖRGY EIGNER[2], (Senior Member, IEEE), AND JÁNOS ABONYI[1], (Member, IEEE)
[1]MTA-PE 'Lendulet' Complex Systems Monitoring Research Group, Department of Process Engineering, University of Pannonia, 8200 Veszprém, Hungary
[2]Physiological Controls Research Center, John von Neumann Faculty of Informatics, Biomatics and Applied Artificial Intelligence Institution, Óbuda University, 1034 Budapest, Hungary
[3]Department of Mechanical Engineering, School of Mechanical Engineering, Vietnam Maritime University, Haiphong 180000, Vietnam

Corresponding author: Tamás Ruppert (ruppert@abonyilab.com)

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ABSTRACT The ongoing Industry 4.0 is characterized by the connectivity between components in the manufacturing system. For modern machines, the Internet of Things is a built-in function. In contrast, there are legacy machines in deployment functioning without digital communication. The need to connect them became popular to improve overall production efficiency. As building a new smart factory as a greenfield investment is a capital-intensive choice, retrofitting the existing infrastructure with IoT capability is more reasonable than replacing them. However, this so-called brownfield development, or retrofitting, requires specific prerequisites, e.g., digitization status assessment, technical and connectivity development, management requirement, and operational need, representing a significant disadvantage: lack of scalability. In the meantime, Industry 5.0 is under human-centric priority, which poses new challenges to the retrofitted system. Aware of the challenge, this paper provides a systematic overview of brownfield development regarding technical difficulties, supporting technologies, and possible applications for the legacy system. The research scope focuses on available Industry 4.0 advancements but considers preparing for the forthcoming Industry 5.0. The proposed retrofitting project approach can be a guideline for manufacturers to transform their factories into intelligent spaces with minimal cost and effort but still gain the most applicable solution for management needs. The future direction for other research in brownfield development for Industry 5.0 is also discussed.

INDEX TERMS Brownfield development, legacy system, Industry 4.0, Industry 5.0, retrofitting, automation.

I. INTRODUCTION

In the context of Industry 4.0 (I4.0), the connectivity of equipment, machines, and various supporting devices to the Industrial Internet of Things (IIoT) within a manufacturing facility is a critical function [1]. Thanks to this comprehensive integration that enables the communication between humans and machines, insight and data-driven solutions for complicated operation problems are available [2]. As a result, the so-called intelligent manufacturing system can be monitored in such an efficient way [3], with optimized resources regarding human labor [4], production time [5], energy [6], and operational cost [7]. With these useful applications, modern machines nowadays come with various ways of transmitting data and communicating with each other as well as to the system [8], creating a connected Cyber-Physical Production System (CPPS) [9]. That is the fundamental concept of data-driven smart and digital manufacturing [10], which is a foundation for every management principle that can be applied automatically upon [11].

Nevertheless, not all companies invest in newly released and modern machinery. Much older generation devices lack connectivity but still perform good operations on duty, even though the operational collaboration, power consumption, and carbon emission are not as good as the new ones. Without high investment in new equipment and technologies, companies can retrofit these existing equipment to adopt the I4.0 [12]. Equipping them with the Internet of Things (IoT)

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capability is the first step towards any more intelligent system with higher process quality and power consumption efficiency, which has considered the environmental effect [13]. The integration of new devices and technology into the traditional processes in the digitization journey can offer great opportunities for companies to re-design business and expand service activities, which facilitate data-driven business strategy making [14]. The need for retrofitting solutions emerges in Small and Medium-sized Enterprises (SMEs) [15], which is the most vulnerable object of being left behind in the I4.0 development [16]. The IoT upgrade for better utilization of existing infrastructure with legacy equipment and legacy software is named brownfield development [17], also known as retrofitting [18]. According to some resources, these two definitions can be used interchangeably.

In a simple explanation, retrofitting means equipping the legacy systems with IoT connectivity, helping them get started with IoT technologies, and can be labeled "*IoTization*" [19]. The objects in retrofitting include the hardware of machinery and the production method, operator, and management as stated in Ref. [20]. The most challenging obstacle of a retrofitting project is that in a legacy system, there are machine tools from different manufactured times, thus having different communication protocols [21]. Due to the lack of sensors and actuators, process control needs to be conducted manually by observing, sensing, estimating, and adjusting the machine parameters [22]. Together they formed a system with minimal connectivity that is not suitable for IoT and data-driven management approaches, which need data collection and analysis as prerequisites [23]. On the other hand, other complex considerations need to be taken before starting a retrofitting project with a specific system. Some of them are the digital maturity of the current system, machinery condition, the operational need that determines the connectivity type, intended management purposes, and the financial decision on investment.

In the advent of Industry 5.0 (I5.0) as a sustainable, a human-centric, and resilient initiative proposed by the European Union (EU) [24], manufacturers should take into consideration enhancing workforce empowerment as a way to support their workers during production tasks [25]. This integration of human employees should be built upon the achievement of I4.0 technology-driven orientation as a way toward a digitized production of the future [26]. It means retrofitting approach should take a step toward the involved human by adopting concepts such as Operator 4.0 [27]–[30], Operator 5.0 [31]. Consequently, the retrofitted system with the data analyzing and monitoring capability can gradually benefit its operator. Besides, continuous improvement in process monitoring, quality management, and energy utilization are criteria that need to be considered sustainable metrics.

There are lessons from the previous implementation of I4.0 that the fragmented approach of single technical development in a specific domain can lead to more challenges from the management perspective [32]. Consequently, management roles such as decision-makers and executives can face difficulties in comprehending the overall picture before the decision to implement I4.0 concepts in their facilities [33]. Several studies in the I4.0 maturity models aim to assist comprehensive guidance over this problem. However, most of them show a gap for a holistic, structured, organizational alignment approach [34]. Due to this reason, organizational aspects have been included in the maturity model proposed in Ref. [35], which assesses the I4.0 readiness of the firm by measurable items that are suitable for the production environment. However, I5.0 brings its relevant concerns. In its threshold, the ambiguity of digital transforming legacy manufacturing systems remains untouched, with a lack of updated guidance that fulfills the previous gap of I4.0.

Understood this conundrum of industrial manufacturing managers, we want to take a step ahead in helping them with a more updated, comprehensive, systematic, organizational-aligned approach to adapting their facilities to keep up with the subsequent development. According to this aim, the main contributions of this work are as follows:

- After conducting a systematic overview of the existing I4.0 solutions to upgrade the old-fashioned system into a connected one, we followed the IoT reference models to categorize them into targeted layers for digitization.
- Advanced management philosophies are discussed, with validated evidence of advantages from retrofitting projects. Then a project approach is proposed, based on a well-known and adopted maturity model and kept in mind the sustainability goals of I5.0, with specific steps and respective consideration criteria, deliverables. The proposed guideline can provide managers and decision-makers with a holistic picture of how to conduct their brownfield development, organize their development activities, permeate the digitization spirit into their team, and prepare for the possible obstacles.

We hope this research encourages managers to invest effort in retrofitting projects, strengthening their advantages in the next industrial revolution. In the following sections, section II provides the key research questions and the search strategy that have been used for skimming the databases for related materials. Section III is devoted to describing the enabling I4.0 technologies that have been deployed for the retrofitting purpose of brownfield development. Its subsections described the layers in which the works have been done and specific manufacturing operation management applications on the table. Section IV revealed several developments which prepared for the I5.0 application. In Section V we recommend a possible framework for a retrofitting project from a management aspect. Then comes the recommendation in Section VI for future researchers and entrepreneurs in the fields. The conclusion is drawn in Section VII.

II. RESEARCH METHOD

In this section, the motivation of this research is discussed, and the research objectives are mentioned. Based on that, corresponding keywords and search terms are developed, with a search strategy deployed for the database search. A search flowchart diagram illustrating the research process is given, indicating sources of materials for further synthesis.

A. BACKGROUND AND OBJECTIVES

Several literature review papers about retrofitting in specific domains, such as smart cities or buildings and construction sites, but only a few mentioned retrofitting in manufacturing. A systematic literature review about smart retrofitting of legacy manufacturing systems is done in Ref. [36], providing a comprehensive conceptualization of smart retrofitting definition and drivers, challengers. Brownfield development with retrofitting approach sometimes is arguably debated over greenfield investment, as they go through a similar framework in carbon area as a means for productivity improvement in the aluminum industry [37]. However, there is a lack of technical concerns due to the non-scalability of solutions between different manufacturing systems. Besides, previous retrofitting research does not discuss the system management possibilities or the aimed goals in detail. Thus a bigger picture is needed for further support and encouragement of the assessment and consideration upon investment in brownfield development. For that purpose, this paper addressed the following objectives:

- **Objective 1**: Identify and describe the case studies of retrofitting the existing machinery with IoT capabilities in the manufacturing industries.
- **Objective 2**: Figure out the technical enablers for these kinds of retrofitting and what management purposes can be deployed upon them.
- **Objective 3**: Sketch the framework for the forthcoming I5.0 retrofitting solution.

B. SEARCH STRATEGY AND PROCESS

In this literature research, we followed the preferred Reported Item for Systematic review and Meta-Analysis (PRISMA) [38]. Scopus, Web of Science (WoS), and Google Scholar are the main databases used. The relevant keywords are defined within the desired scope as "retrofit*", "brownfield", "legacy", "Industry 4.0", "Industry 5.0", "maturity", "strateg*", "implement*". The asterisk signs are deployed to capture all forms of interesting words. By searching for title, abstract, and keywords sections with the search terms elaborated from predefined keywords, the search is limited to press and articles in scientific journals or conference proceedings. Thus, we believe that all successful case studies in brownfield development are comprehended. Report and conference abstracts were excluded. Table 1 detailed the search terms being used and the corresponding number of search results. We separated the keywords "Industry 4.0" and "Industry 5.0" to see how the current awareness of academic society on Industry 5.0 is. The search was done by the authors independently.

Scopus database provided a result of primarily high relevant papers. At the same time, Google Scholar shows a wide range of hits, in which there are only a few papers related to the interest questions. The network visualization in Figure 1 depicts the relevance of the keywords that the authors suggest. It can be seen that the emergence of retrofitting solutions and the concern for legacy systems are still being loosely connected and less emphasized in the search-resulted papers. The most prominent keyword mentioned is Industry 4.0, while Industry 5.0 is not shown in the network as there are too few documents that mention this concept.

TABLE 1. Search terms and results.

Keyword combinations	Scopus	WoS	Google Scholar
"Industry 4.0" AND ("retrofit*" OR "brownfield" OR "legacy")	245	68	826
"Industry 4.0" AND "retrofit*" AND ("maturity" OR "strateg*" OR "implement*")	44	0	842
"Industry 5.0" AND ("retrofit*" OR "brownfield" OR "legacy")	1	1	11
"Industry 5.0" AND "retrofit*" AND ("maturity" OR "strateg*" OR "implement*")	1	0	21
Total	291	69	1700
Total hits	**2291**		

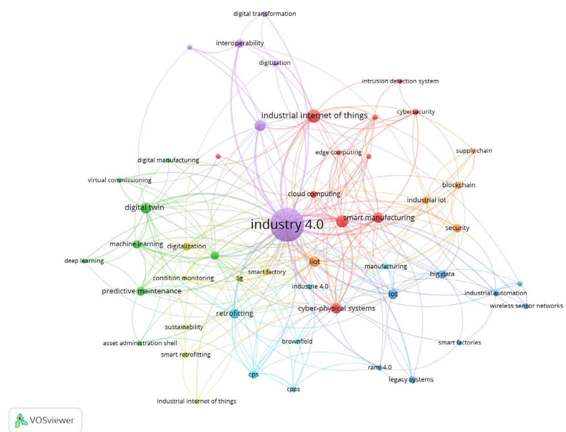

FIGURE 1. Keywords network visualization.

The following steps of the search process are described in Figure 2. After removing the duplicates on Mendeley reference management software [39], there are 2245 papers left. Then each paper has been under two general screening steps: firstly with its title, and secondly with its abstract, to define the relevant research outcomes. The number of relevant papers after two screening steps is 91. These papers are classified by level of relevance by the authors independently. If there is ambiguity for a specific paper during the classification, at least two authors may discuss and assign the class. If their discussion cannot resolve the ambiguity, another author may decide on the discrepancy. The levels of relevance are:

- No relevance: The research approach is not related to retrofitting activities or brownfield development in industrial manufacturing.
- Low relevance: The research approach is loosely related or does not consider the I4.0 connectivity. However, it is associated with an important aspect of a retrofitted system.

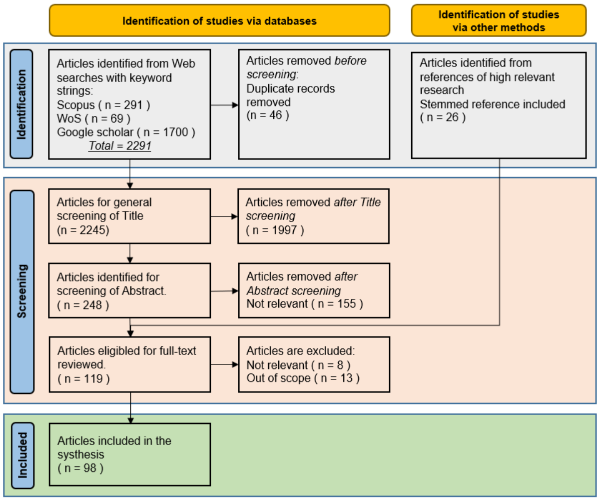

FIGURE 2. The PRISMA-based flowchart diagram of the selection process of the reviewed papers.

- Medium relevance: The research result is partly aligned with the retrofitting or brownfield development approach for I4.0, but the scale of the case study is not the full scope of a project, and the goal of brownfield development is not stated explicitly.
- High relevance: The approach is fully aligned to the retrofitting practice and explicitly states the brownfield development goal. The case study is described in detail, and the suggestion is helpful in shaping the future research direction.

Then the papers with high relevance are scanned further for their reference list to seek the related stemmed references. By adding 26 stemmed reference papers, the aggregated number of papers eligible for full-text review is 117. Some research is defined as "out of scope" and thus not included in the synthesis. The following criterion distinguishes such items:

- Did not describe the use case and deployed technologies explicitly [40], [41]
- Conduct the retrofitting work without I4.0 orientation [42]
- Performed the validation in a fragmented way, not related to any industrial machinery [43]–[45]. Only for the cyber-security aspect, we accept research papers in this section that have the experiments conducted without specific machinery but simulation scenarios, considering the special characteristics of this aspect and its scarcity of research work.
- Review the industrial application without any specific proposal in the field [46]–[49].

Since these papers are excluded, thus the total number of papers collected for the synthesis is 98. For these remaining papers, there are research questions to be addressed as the guiding light for data collecting:

- What type of industrial context has the improvement been done?
- What are IoT-based technologies that have been used? And what are the layers in which the technologies were deployed?
- What manufacturing operation improvement can be applied given that the I4.0 technologies are ready?
- What are the recommendations and future trends of brownfield development that should be concerned?

Only some of the four questions mentioned above apply to papers with low and medium relevance. These papers were resolved in the same way as the relevance classification step. The authors collected the data and noted its use cases for citing in the suitable section accordingly. The following section will be the synthesis of enabling technologies that have been used for retrofitting projects from the collected papers.

III. ENABLING TECHNOLOGIES - EXISTING SOLUTIONS FOR RETROFITTING

This section categorized the enabling technologies deployed in previous retrofitting projects, considering that the current I4.0 is on the market. Based on the reference model for IoT with seven layers [50], the approach of retrofitting projects is modified accordingly based on the layer that is re-configured. Several authors suggested different retrofitting models, but somehow they share the typical scope in several aspects. Lins *et al.* in Ref. [18] defined the technologies for I4.0 retrofitting as four levels of IoT sensors, Software-Defined-Network (SDN) architecture, Open Platform Communications (OPC) communication, and cloud computing. In Ref. [36], the author mentioned that a common retrofitting approach might conduct their work on three levels: sensor, connectivity, and data. In Ref. [51], another classification is adopted with three levels: hardware, communication, and cloud. A similar three-level classification with devices, connectivity, and infrastructure levels is proposed in Ref. [15], while [52] categorized them into physical resources, network, and data application layers. This paper reviews enabling technologies and solutions for retrofitting projects in four groups of activities: sensor and actuator deployment, connectivity enhancement, data management, and operational application. The relative connection of the activities performed over the IoT level in the reference model is depicted in Table 2. For each layer, the technologies are considered due to their scope accordingly.

The first step in brownfield development is enhancing the data acquisition from dated equipment that often has varying degrees of instrumentation and automation and can be categorized by deploying the additional sensors in the first level of the IoT reference model. Legacy machines lack ways to monitor their processing parameters [22]; fortunately, sensor technologies nowadays are well-advanced for that purpose [53]. In many cases, additional actuators are added to enhance the automation at the field level and replace the human manipulation [54]. A network with sensors and actuators can contribute significantly to the migration of legacy manufacturing systems towards the I4.0 [55].

TABLE 2. Retrofitting activities upon levels of IoT reference model.

IoT reference model	Interested subjects within layer	Retrofitting activities
Level 7: Collaboration & Processes	Business process.	Operational application: Performing data-driven decision for managerial purposes.
Level 6: Application	Data manipulation by softwares.	
Level 5: Data abstraction	Aggregation and access the data for application.	Data management: Integrate data handling, visualization tools or management platforms.
Level 4: Data accumulation	Store acquired data for query-based consumption.	
Level 3: Edge computing	Convert network data flows into information for storage.	Connectivity enhancement: Establish connectivity of physical assets, M2M communication. Integrating field-level control or automation of existing PLCs.
Level 2: Connectivity	Communication and connectivity between devices & network (gateways, communication controller)	
Level 1: Physical devices & Controller	Physical devices.	Sensor & Actuator deployment: Integrating external sensors to record physical values, and additional actuator to assist automation.

Then the next step covers the subsequent two IoT layers, providing the connectivity that mediates the data flow. With a different level of connectivity in a dated manufacturing system, it is problematic to connect the machines, and the legacy system is usually controlled locally through its Human-Machine Interface (HMI) [19]. Machine-to-machine communication is established as the data from additional sensors, existing Programmable Logic Controller (PLC), or add-in micro-controllers of the machine can be integrated [56]. Integrating the data of existing legacy PLCs into a connected system is a special interest in retrofitting projects [57]. The system can be coherent if the old machines are linked with the new ones [58].

The fourth and fifth layers in the IoT model are covered by the use of a data storage and management system [59]. An integrated Information Technology (IT) infrastructure is required to cast the administration upon the system [60]. This foundation is the prerequisite condition for enterprises to foresee their business at the strategic level: Business planning and logistics, defined by the fourth retrofitting layer [61]. Retrofitting focuses not only on the physical asset but also on the broader picture of the business operation itself. In the sixth and seventh IoT levels, data-driven management decisions can be taken within the frame of Manufacturing Execution System (MES), Enterprise Resources Planning (ERP), and other software tools [62]. There are possible applications for managers, as well as management philosophies, that can be deployed with the aid of available data [63].

The ultimate goal of a retrofitting project is the comprehensive digital transformation of legacy systems [14]. This successful transformation requires the development of cost-effective and reliable measurement, along with data collection and manipulation solutions that can ensure condition monitoring [64]. The establishment of vertical and horizontal integration of the entire production is needed [65], to allow the autonomous operation of the equipment without significant modification [66]. This goal should be achieved by a long-term strategy as the company moves forward in its digitization journey [16]. The following subsection explored the brownfield development across industries, with the technologies utilized in the activities mentioned above.

A. SENSORS AND ACTUATORS DEPLOYMENT

Several retrofitting projects perform the sensors and actuators deployment at the initial phase of the implementation as the first step to integrating the physical and virtual world [12]. Sensors and actuators usually go in pair with an interested process parameter [67], thus their simultaneous consideration and selection ensure that a functional Digital Twin can be developed from low-level [68]. In this layer, sensors and actuators play a vital role in process automation in general and the IoT approach in particular. This section is devoted to synthesizing the most frequent sensors and actuators deployed in retrofitting.

1) SENSORS DEPLOYMENT

Existing legacy equipment lacks sensors to indicate their operating status [69], thus additional sensors should be integrated. Several researchers stated the difference between a general-purpose sensor and an IoT-specific purpose sensor [70]. Though there is a significant difference between on- and off-the-shelf sensors in the market, in this review paper, we took an overview of which were deployed in previous successful retrofitting projects without digging into that difference. The types of deployed sensors can be categorized as listed in Table 3.

The sensors can be divided into measuring the parameters of the production environment (e.g., temperature and humidity) or measuring the machine parameters (e.g., vibration, energy consumption, tension) [15]. The use of sensor types is closely related to the process parameters and quality, mentioned later at the end of this section. Energy retrofitting is still an underdeveloped concept [83]; thus, the use of energy sensors in past projects is scarce. A system of high-frequency sensors is deployed in Ref. [95] to track the energy utilization of various equipment in the food processing system to enhance energy efficiency. Meanwhile, accelerometers and temperature sensors are among the most frequently used, and on-the-shelf products are preferred in many studies.

Along with the usage of the commercial sensor, there are types of sensors that are especially suitable for retrofitting purposes, such as the ultra-thin silicon chips proposed in retrofitting project in Ref. [96]. There is an evaluation of alternative manufacturing methods for 3D Mechatronics Integrated Devices (MID) sensors for retrofitting purposes mentioned in Ref. [53]. With this ongoing interest, retrofitting-purpose sensors will be available on the shelf in the close future.

It can be seen that the type of chosen sensors is different from industries such as textile [97], food processing [51], and car assembly [75]. On the other hand, within the same industry, different sensors are chosen due to the different machine status and various operational needs of the managers, such as in the case of metal cutting [53], [72], [83], [87], [92]. This

TABLE 3. Most frequent used sensors to retrofit legacy system.

Type of sensors	Description	Specific type	Industries & Use cases
Tempera-ture sensor	Measure the temperature of the subject.	General type	Textile [15], [22], [71], Metal cutting [72], Food processing [73]
		Thermal couple	Metal forming [58]
		LM35	Didactic plant [18]
		DHT11	Flexible Manufacturing System (FMS) [74]
		Sensorkits	Car assembly [75]
		Thermocouples perfluoroalkoxy K-type	Electronic manufacturing [76]
Pressure sensor	Measure the pressure within a pipe or a furnace, or any close space.	General type	Food processing [73], Didactic plant [18]
		Honeywell High-accuracy Silicon Ceramic gauge-type	Electronic manufacturing [76]
		Absolute pressure sensor Setra 280E & Relative pressure sensor Foxboro 841GM-CI1 & Differential pressure sensor Foxboro IDP-10	Oil extraction [54]
Flow sensor	Measure the flow of the substances.	Foxboro Magnetic Flowtransmitter	Oil extraction [54]
		Volumetric flow sensor Foxboro Vortez DN 50	Oil extraction [54]
		General type	Didactic plant [18]
Position sensor	Define the position of the interest object in a defined space.	Festo cylinder position sensor	Assembly line [77]
		Radio-frequency Identification (RFID) chip	Fabric knitting [78]
		Baumer Ident RFID tag	FMS system [79]
		Laser displacement sensor (LDS)	Aluminium casting [80]
Acoustic sensor	Measure parameters such as object distance, liquid level by using acoustic waves	Self-built sensor	Oilfield [81]
Current sensor	Measure the amplitude of current inside a wire.	Inductive current clamp sensor Sensorkits	Car assembly [75]
		Non-invasive current sensor SCT-013	Didactic plant [18], Industrial robot [82]
		Non-invasive current transformer	Didactic plant [18]
CO2 sensor	Measure the part per million (ppm) of CO2 in the atmosphere.	General type	Metal cutting [72]
Energy sensor	Measure the amount of consumed energy by machine operation.	Schneider Electric Power Tag	Metal cutting [83]
Motion sensor	Detect the movement of objects in a defined space, e.g. in a furnace.	Camera motion sensor	Iron & Steel production [84]
Magnetic sensor	Sense the magnetic field generated by a magnet or current caused by the machinery movement.	Hall-effect sensors	Industrial motor-driven system [85], Textile [15]
Metal sensor	Detect metal material appearance.	MSPA13 NPN transistor	Industrial robot [82]
Color sensor	Recognise/detect the colour of a material or passing part.	TSC230 RGB	FMS system [74]
Accelero-meter	Measure the vibration, or acceleration of the machine structure	General use accelerometers without specific type	Industrial equipment [86], Textile [71], Metal cutting [87]
		Bosch BMX160	Metal cutting [53]
		Bosch BMA280	Computer Numerical Control (CNC) machining [88], Industrial robot [89]
		ADXL345	Limestone processing [90], [91]
		Bruel & Kjaer 4535-B-001	Metal cutting [92]
		Sensorkits	Car assembly [75]
		Raspberry-Pi accelerometer	Metal cutting [93]
		MMA7361	Aluminium casting [80]
Visual sensor	Capture the object movement, position or characteristics.	Raspberry Pi 1.3 camera	High-bay shelf warehouse [94]
		USB camera	Industrial robot [82]
		Yarn breakage sensor	Textile [15]
		Knot sensor	Textile [15]

fact reflected the realistic heterogeneity of the legacy system and the un-scalability of the retrofitting solution.

TABLE 4. Most frequent used actuators to retrofit legacy system.

Method of deploying actuators	Retrofitting usage	Specific type	Industries & Use cases
Integrate existing actuators to control the process variables	Adjust and control the state of liquid inlet/outlet flows.	General control and binary valves	Oil & Gas processing [98]
		Level switch	Water processing [102]
	Control the weld tool path.	ABB6640 robot controller	Metal de-burring and grinding [103]
	Control the direction and speed of a conveyor.	Siemens three phase asynchronous motor	Material handling [104]
	Detect the status of a mechanism.	Limit switch	Assembly line [77]
	Control the steam pressure of the metal pressing machines.	Hydraulic pressure recuperators, Steam valves	Metal forming [58]
	Control the velocity of the conveyor.	Motor control switch	Material handling [105]
	Control the process of gassing and ventilation. Control conveyors and fixtures.	Pneumatic and hydraulic valves	Sand core [68]
Employ new actuators to control the process variables	Adjust and control the state of the gas/liquid inlet/outlet flows.	Pneumatic solenoid valve ECKARDT MB6713	Oil extraction [54]
		Solenoid valve	Didactic plant [18]
	Control the on/off and emergency states	Self-built switch and controller	Metal machining [64]
	Control machine tools spindle speed.	Speed drive & Spindle descent meter	Metal machining [64]
Employ new actuators to extend the capability of existing hardware	Serve as end actuator to an robotic arm.	Self-built gripper.	Industrial robot [82]
	Transport a sensor to the interested location for measurement.	Linear motor and encoders, general type	Aluminium casting [80]
	Transport the machined part to the interested location.	Pneumatic linear actuator	Aluminium casting [80]
	Prevent injuries from spindle rotation during machining process.	Self-built movable protection screen	Metal machining [64]
	Providing clamping force for the welding fixture	Pneumatic clamps	Metal forming [97]
	Clean the cutting tool after machining	Self-built mechanism.	CNC machining [106]
	Close the protective door and vice of the CNC machine.	FESTO pneumatic cylinders with solenoid valves	Experimental plant [21]

2) ACTUATORS DEPLOYMENT

Legacy systems usually require human manipulation with adjusting and controlling tasks. For brownfield development, these manual tasks can be performed by actuators to ease the attentive presence of human workers. On the one hand, the existing legacy actuators can be incorporated with automation capability to facilitate the manufacturing process control [98]. On the other hand, an additional actuator or end-effector can be deployed to extend the system capability for performing the related process [80], [99]. An IT-based integration of additional sensors and actuators with the existing legacy system can be established with a self-built invasive unit [100], thus providing a digital retrofit solution for operational purposes such as process automation, production control, or quality assurance. An industrial wireless sensor and actuator network can perform distributed sensing, data fusion, and collaboratively decision-making with human workers [101]. In this section, several actuators and their usage in retrofitting development are mentioned in Table 4, to sketch an overview of how they can be deployed in a certain condition and working environment.

In most retrofitting scenarios, the existing legacy actuators can be integrated into the system control, thanks to the newly established system connectivity [58]. The application of integrated control, control algorithm, and process simulation help to manipulate the actuators effectively, with predefined control sequences [98]. Process and quality control functions can be incorporated into the local automation, in pair with respective sensors [77].

In other cases, retrofitting effort is done with new sensors and actuators deployed [100]. Additional actuators can perform controlling on process variables automatically in a real-time manner [64], with the signal being monitored by respective sensor readings, or governed by an embedded board that can receive user command, or automated by a retrofitting platform [18]. The search for the suitable sensor and matching actuator can adopt the static or dynamic model creation in [67]. Noticeably, besides existing variables, the retrofitting attempt may introduce new variables which share an impact on the process [54]. In addition, new actuator deployment can extend the capability of the existing hardware, thus incorporating new aspects into the system [80], such as safety [21], [64].

The actuator types can be self-built or commercial, depending on the specific need of the retrofitting purpose. Self-built actuators opened a wider range of applications as they can adapt to the design of existing mechanism and structure [82] or provide a unique function [106]. The safety aspect can be integrated into the intrinsic design of the actuator [82].

B. CONNECTIVITY ENHANCEMENT

The weak point of a legacy system is that there are homogeneous IT systems and machines with different interfaces and protocols [67]. This connectivity enhancement came into the retrofitting projects after the sensors were deployed, as communication is a crucial characteristic of I4.0 [18]. Once the connectivity is established, new options for operation monitoring, forecasting, and controlling can be available on the shop floor [80]. PLCs already have taken place in legacy systems. They will continue to exist for a long life-cycle time, thus urges a reasonable need to integrate them into IIoT infrastructure [107]. The first subsection of this section is devoted to the development of retrofitting the manufacturing systems with PLCs. In the second subsection, the IoT components deployed to retrofit the connectivity of legacy systems are described.

1) I4.0 PLCs RETROFITTING

Many retrofitting projects involved the use of a PLC. This subsection is mainly devoted to describing the retrofitting works done upon the legacy plants with existing or new PLCs, considering the different approaches and integration methods that aim to develop an I4.0 connected manufacturing system.

In legacy manufacturing systems, PLCs are still in charge of controlling the production processes with relatively long life cycles, with their natural characteristics of hardware-based and mission-critical. However, due to their limited processing and communication capabilities, plant monitoring and data analysis cannot be incorporated into I4.0 architecture [57]. In this scenario, I4.0 retrofitting attempts were made to access these data of PLCs and forward them into new interconnected environments. In other cases, the deployment of new PLCs is also considered a way to automate processes and enhance field-level control of the legacy manufacturing system. The type of existing PLCs and their new role in a connected system, as well as new deployed PLCs with their retrofitting roles, are described in Table 5. Noticeably, there are cases in which the reliability concerns, vendor restrictions, and outdated programming environments make the PLC irreplaceable, obstructing the retrofitting attempts [57].

TABLE 5. Most frequent improvement on PLCs to retrofit legacy system.

Existing role of PLCs	Specific type	Improvement after retrofitted	Industries & Use cases
Low-level control of system components	Siemens S7 300 & S7 400	Integrating OPC-UA interface with Azure cloud	Metal cutting [72]
	PLC Siemens S7-1200 & Siemens ET200s	Virtual PROFINET	Lab experiment [108]
Perform logic control on system modules	Siemens PLC S7-1200	Provide LoRaWAN Class A connectivity to Siemens IOT2040 device with Node-RED platform	FMS system [79]
	Siemens S7	Data collection and exchange with visualization dashboard and the DT (Digital Twin)	Metal casting [109]
	Beckhoff PLC	Hilscher Raspberry Pi IIoT Gateway/MQTT broker with Node-RED platform	Lab experiment [57]
	Siemens S7-1500	Hardware Gateway with PLC4X and S7 Protocol via MQTT and Eclip Paho API	Lab experiment [57]
	B & R Power Panel 400	Commercial Data Adapter: Softing DataFeed OPC suite with INA2000 protocol	Lab experiment [57]
Data acquisition from sensors	General legacy PLCs not supporting IoT protocols	Modbus TCP network with MQTT	Metal cutting [72], Metal forming [58]
New PLCs	Siemens S7 ET200SP	PROFINET via OPC-UA server	Phone assembly experimental plant [110]
	FESTO PLCs	CoDeSys software via OPC-UA server	Phone assembly experimental plant [110]
	Siemens S7-313C-2DP	Form a middle layer to link fieldbus with SCADA system to enhance communication.	FMS system [55]

With existing PLCs in a legacy system, retrofitting activities aim at broadening their capability or accessing and integrating their data [58]. Several retrofitting concepts for interfacing legacy PLCs in I4.0 scenarios are proposed in [57], which consider the case of factories containing PLCs from different manufacturers. The LoRaWAN connectivity is integrated into a PLC in [111], which enhances the field device connection. To retrofit an old system, new PLCs can be deployed to perform logic control on system modules such as conveyors [110]. Generally speaking, to integrate legacy PLCs with limited connectivity into an IoT system, several components such as communication protocols, programming language, and execution environment should be taken. A middle layer can be formed based on the features of the existing PLCs to enhance the connectivity that makes the system fully I4.0-compliant [55]. This connectivity enhancement will be discussed in the following subsection.

2) I4.0 CONNECTIVITY RETROFITTING

Regarding establishing the shared communication and connectivity between devices and networks, hardware such as micro-controllers, micro-computers and gateways are added, protocols such as communication, messaging, and platforms should be defined [72]. These connectivity-related technologies are categorized in the Table 6.

Embedded controllers and micro-controllers (e.g., NodeMCU and Arduino) can be implemented for embedded control, and process automation, especially with continuous production type [90], [91]. Micro-computers such

TABLE 6. Most frequent used technology to retrofit connectivity of legacy system.

Type of technology	Description	Specific type	Industries & Use cases
Micro-controller	Compact integrated circuit for embedded control.	NodeMCU ESP8266	Limestone processing [90], [91], Material handling [19]
		Arduino Mega 2560	Oil extraction [54]
		Arduino Uno	Experimental plant [21], FMS system [74], Water industry [112]
Micro-computer	A low-cost computer for data collection, acquisition and embedded control.	Raspberry Pi	Textile [97], Metal forming [97], Food processing [73], Material handling [105], FMS system [65], Lab experiment [108], [113]
		Raspberry Pi Zero and Raspberry Pi 4	Plastic injection [114]
		Raspberry Pi Zero W	CNC machining [12]
		Raspberry Pi 3	Experimental plant [21], Olive oil processing [95], Limestone processing [91]
		Raspberry Pi 3B+	High-bay shelf warehouse [94], Limestone processing [90], Industrial robot [89], CNC machining [115]
Embedded controller	Data-logging, embedded monitoring, and control.	cRIO 9040	Textile [71]
Sensor network protocol	Provide existing sensor and actuator network with wireless communication	OCARI	Lab experiment [113]
Wifi shield module	Allow an Arduino board to connect to Wifi.	ESP8266	FMS system [74]
IoT Gateway	Enable IoT communication for device-to-device or device-to-cloud.	IoT gateway SECO C23	Steel Mill [20]
		Siemens IoT 2040	Metal cutting [83]
		Raspberry Pi 3B	Industrial robot [17]
		Laird RG186	Lab experiment [116]
		Self-elaborated SmartBoxes	Textile [97], Metal forming [97]
		dataFEED OPC suite gateway software	FMS system [79]
		UAGate gateway software	Modular Production System [56]
Network architecture	Network configuration for the connected system.	SDN	Didactic plant [18], Industrial robot [82]
		Asset Administration Shell (AAS)	FMS system [12], [16]
Wireless communication technology	The chosen data transmission protocols.	LoRaWAN	Lab experiment [111], [116], [57]
		LPWAN	Oilfield [81]
Communication protocol	The chosen communication protocol for the system.	OPC Unified Architecture (OPC UA)	Textile [15], [71], [97], Phone assembly experimental plant [110], Food processing [51], [73], FMS system [12], [16], [65], Sand core [68], Metal cutting [93], [117], Industrial robot [17], Assembly line [77], Metal forming [97], [112], Modular Production System [56], Candy packaging [52], Lab experiment [113], [118]
		Python-OPC UA	High-bay shelf warehouse [94]
		OPC DA	Steel Mill [20]
		Profibus sniffers	General machine tool [120]
		ProfiNet fieldbus	Sand core [68], Phone assembly experimental plant [110], Lab experiment [108], FMS system [55]
		ModBus	Metal cutting [72], [83], Metal forming [112], Candy packaging [52], FMS system [65]
		ModBus & OPC UA wrapper	Water industry [112]
		NFS & Kafka	Olive oil processing [95]
Messaging protocol	The chosen data messaging protocol.	Message Queue Telemetry Transport (MQTT)	Textile [71], [97], Limestone processing [90], [91], Food processing [51], FMS system [16], Industrial robot [89], Metal cutting [117], Modular Production System [56], Metal forming [97], Metal de-burring and grinding [103], CNC machining [115]
		AMQP	FMS system [16]
Programming platform	The platform for programming and execution environment, connecting the hardwares with protocols.	Node-RED	Lab experiment [57], [111]

as Raspberry Pi are considered promising low-cost and effective candidates to integrate into the existing machine and enhance data acquisition, and simultaneous processing [120]. Raspberry Pi is the dominant candidate for its reasonable price, simple configuration, and ease of operation with an open-source ecosystem. The connectivity of legacy systems can be enhanced by utilizing on-the-shelf gateways, and industrial providers such as Laird, SECO, and Siemens are trustable partners for the choice. Lucke *et al.* in Ref. [67] reported the application of self-developed kits as SmartBoxes in the retrofitting of the industrial loom and metal forming jigs and fixtures. Meanwhile, traditional field-bus such as PROFINET has been under development to enable the use of legacy devices. As in Ref. [108], a virtual PROFINET architecture is proposed and validated through experiment as a promising low-cost and reduced-resources solution.

For the wireless communication technology, enhancement adoption based on LoraWAN technology is proposed as a gateway toward legacy networks in Ref. [116], which shows the flexibility and scalability of the application. Another similar approach based on this technology is also used in Ref. [57], [111], which emphasizes the usage for IoT development in brownfields.

There are many promising candidates for the retrofitting work, such as Profibus, CANOpen, and DeviceNet, which are proposed as the core communication protocol in Reference Architecture Model Industry 4.0 (RAMI 4.0) [121]. OPC UA seems to be the appropriate option for the migration towards I4.0 [12], with simple data acquisition, monitoring, control, and analysis. In Ref. [122], a case study is conducted to integrate OPC UA with legacy devices with proprietary protocols. However, in some cases, alternatives such as OPC DA and AMQP are in place, dependent on the specific case of legacy system [73]. Deployed protocols must be complied with the recent industrial standard, as legacy machines are usually accompanied by old communication protocols [59]. An integrated solution such as Modbus-OPC UA wrapper is proposed in Ref. [102] to adapt to a large part of legacy machines in the industry. Noticeably, the variants of Modbus, such as Modbus RTU and Modbus TCP, can also be coupled with protocol converters, consequently enhancing the retrofitting possibilities. Programming platform such as Node-RED is mentioned as a low-cost execution environment, and favorable for retrofitting with legacy PLCs [57], [111].

In general, the connectivity enhancement for a legacy system is implemented according to an architecture that the authors usually suggested in their projects [16], [57], [112], [115], [123]. These architectures are the prerequisite output that needs to be designed in the very beginning stage of the retrofitting project. This aspect will be described in the section V.

C. DATA MANAGEMENT

The data treatment characterizes this level. Up to this level, the process data are available and need to be connected to integrated storage for further processing [39]. With the data shortage in quantity and quality as the nature of the legacy system, smart data modeling, simulation, and visualization is a promising approach to full automation ideas [124]. Due to that, data storage, visualization, and analysis are emphasized in this stage, as listed in Table 7.

TABLE 7. Advancement in the data layer.

Type of technologies	Description	Specific type of software platform	Industries & Use cases
Data collection platform	Deploy open source streaming processing platform for data storage and query.	Apache Kafka	Metal cutting [92]
Data Storage	Non-relational databases to contain acquired data.	InfluxDB	Plastic injection [114]
		MongoDB	Metal cutting [72], [93], Olive oil processing [95]
		ElasticSearch	Assembly line [59]
		IBA server	Metal forming [125]
		HANA Database	Metal cutting [117]
Cloud computing	The use of cloud computing platforms for for data post-processing (i.e. clustering, visualization).	Microsoft Azure & Amazon Web Services	Oil extraction [54], Metal de-burring and grinding [103]
		Amazon Web Services	Limestone processing [90], [91], Food processing [51], [73]
		Microsoft Azure	Car assembly [75], FMS system [79]
		Siemens Mindsphere & GRV Software	Metal cutting [83]
		Thingworx	Textile [15], CNC machining [126]
		Ubuntu Cloud	Didactic plant [18]
		Google Cloud & OpenNebula	Industrial robot [82]
		Google Cloud SAP Cloud Platform	Assembly line [77] Metal cutting [117], Modular Production System [56], Metal forming [58]
		Blynk Could	Material handling [104]
Data visualization	Visualize the real-time data from the production process for monitoring purpose.	Grafana	Plastic injection [114]
		Losant	Metal casting [109], Steel Mill [20]
		PyQt5	High-bay shelf warehouse [94]
		Chronograf	Metal cutting [72]
		Siemens TIA Portal	Sand core [68]
		AWS IoT SiteWise	Food processing [73]
		Kibana	Assembly line [59]
		Thingspeak	FMS system [74], Metal forming [97]
		Tableau 10.4	Metal forming [58]
		Kasem web portal	Lab experiment [113]
Data processing/ ingestion software	Process the acquired signal from sensors.	Pulse Labshop	Metal cutting [92]
		PTC Kepware	Textile [15]
Web technology	Push communication scheme, reduce the information retrieval latency.	WebSocket/SocketIo	Oil extraction [54]
		WebSocket	Metal cutting [117], CNC machining [115], Metal forming [69]

Separate soft-wares are mentioned for different purposes. Industrial big data management tools are used for comprehensive platforms due to their abundant add-on packages, such as Apache Kafka [59]. Free service such as Blynk [104] is also an option for a low-cost solution. Commercial cloud platforms are deployed from Microsoft, Amazon, Siemens, Google, and SAP. Real-time processing capability is the desired requirement in choosing the product [63], [97]. On the availability of data, machine learning techniques can be applied for further optimization [75]. By integrating legacy devices to the cloud-based IoT platform, even the geographically dispersed manufacturing system can be monitored remotely [56]. In general, the availability of data is the foundation for the higher application toward smart manufacturing [74], which is discussed in the next section separately. It is worth mentioning that once the legacy system is retrofitted with the data visualization [126] and equipped with web service [18], or mobile HMI [64], [104]. The operators will be the ones who benefit the most in their work. This aspect is the main focus of the next industrial revolution, thus reflected in the concept of Operator 4.0 discussed in the following.

D. OPERATIONAL APPLICATION

After the aforementioned retrofitting work is done, the automation and connectivity level of the factory is enhanced.

TABLE 8. Process management on retrofitted system.

Main advantages	Description	Industries & Use cases
Process parameters tracking	The process vital parameters can be observed.	Plastic injection [114], Electronic manufacturing [76], Industrial motor-driven system [85], Oil extraction [54], Steel Mill [20], Food processing [51], Oilfield [81], CNC machining [88], [126], [127], Textile [15], Metal casting [124], Aluminium casting [80], Didactic plant [18], Metal cutting [93], Glass forming [39], Water industry [112], Metal forming [58], Metal de-burring and grinding [103]
Process automation	The activation of actuators, valves, switches can be automated based on the equipment parameters.	Didactic plant [18], Industrial robot [82], Metal forming [58]
Equipment condition monitoring	The parameters of the equipment can be monitored based on real-time data calculation and visualization.	Plastic injection [114], Electronic manufacturing [76], Iron & Steel production [84], Limestone processing [90], Industrial equipment [86], Steel Mill [20], Car assembly [75], Oilfield [81], CNC machining [115], [126], [127], Metal cutting [93], Industrial robot [82], Material handling [104], Assembly line [77], FMS system [74], Water industry [112], Metal de-burring and grinding [103]
Tool condition monitoring	The condition of the used tools can be monitored based on acquired data.	Metal cutting [92], [118], CNC machining [88], [106], [128]
Schedule material flow	The material flow and manufacturing order can be tracked and ordered based on the operational state of the machine/equipment.	Metal cutting [87], CNC machining [128], Metal casting [124], Material handling [105], Metal de-burring and grinding [103], Experimental plant [21]
Process optimization	The process parameters can be adjusted based on the data acquired and product quality assessment.	Glass forming [39], Fabric knitting [78], Metal de-burring and grinding [103]
Production monitoring	The production and manufacturing Key Performance Indicators (KPIs) can be manipulated remotely, based on Human-Machine Interface or live report.	Textile [71], [97], Metal casting [109], Oil extraction [54], Fabric knitting [78], FMS system [16], [79], Metal cutting [118], Assembly line [77], Metal forming [58]

Therefore, monitoring and management activity [115] supported with data is available in hand. This application level is on the top of the IoT level, which deals with management philosophies and techniques. In this part, some of the prevailing ones will be discussed based on the evidence and suggestion from relevant work.

1) PROCESS MANAGEMENT

With the retrofitted system, there are process management philosophies can be applied. In Table 8 we summarized the favorable management advantage of the digitization that the brownfield development could offer.

A legacy system without any advanced PLC or Supervisory Control and Data Acquisition (SCADA) system infrastructure usually faces unexpected downtime, which undermines the business [95]. Noticeably, the most prevailing advantage that comes from retrofitting is the process parameters tracking ability of the system [102]. Taking into consideration that process critical parameters consideration is one of the beginning steps in the conducted projects [76], [100], this advantage is the inherent characteristic. This advantage is preferred in processing industries with continuous manufacturing systems such as oil extraction, food processing, water processing, mining [51], [54], [58], [81], [112]. It can lead to process automation which cuts down the manual work [18]. With the process automation, the loss of raw materials can be decreased by the automatic activation of valves, switches, and actuators [58].

Equipment conditions can also be kept a close eye on in the same way [114], based on the acquired data. Machinery

TABLE 9. Quality management on retrofitted system.

Main advantages	Description	Industries & Use cases
Defect detection	The defect products can be detected immediately, and alert can be made to inform human operator.	Plastic injection [114], Metal casting [109], Steel Mill [20], Car assembly [75], Fabric knitting [78], Assembly line [77], Metal stamping [97], Metal de-burring and grinding [103], Gear production [63], Lab experiment [118], Aluminium casting [80]
Quality variation control	The variation of working condition from the process or from different machines can be visualized and help to find the root cause.	Plastic injection [114], Car assembly [75], Metal casting [124], Assembly line [77], Metal de-burring and grinding [103], Aluminium casting [80]
Defect prevention	The defect can be prevented by using machine learning algorithms to predict the possible defective outcome beforehand.	Metal casting [109], Steel Mill [20], Car assembly [75], Oilfield [81], Assembly line [77]
Quality improvement	The production quality can be improved automatically during production phase, or gradually with the aid of recorded data.	Fabric knitting [78], Glass forming [39], Metal forming [58]. Metal de-burring and grinding [103], Gear production [63]

parameters, which are vital for production, usually being under the monitoring [20], [84], [90]. Tool condition monitoring is applicable for machine tools that have machining tools that need to be replaced for quality and safety purposes, such as CNC machining [92].

Thanks to the data-driven management for each elementary process, an IoT-based manufacturing monitoring system can be constructed as the guiding rule for future ways of improving overall performance and management [74]. Based on the elementary processes in the system, the material flow in the work-cell in particular [87], or in the facility in general [105], can be monitored. Scheduling tasks will be more manageable and can be conducted automatically [103]. This advantage can link to the concept of just-in-time production discussed in the later subsection. The process optimization can be taken further based on the available data, and process-oriented knowledge [39] regarding the produced quality, machine condition, or material flow. The highest application in this aspect is production monitoring, in which the production KPIs or objectives can be adjusted and manipulated remotely [58].

2) QUALITY MANAGEMENT

Quality management is essential in every manufacturing plant. For the legacy system, the lack of connection between machines makes it more challenging to discover the source of quality defect and variation, as well as track the passage of the defect order [124]. However, along with the retrofitting process, there are philosophies of quality management that are ready to be deployed. By applying along with the fused technologies, the operator decision factor can be eliminated [63], human inconsistency can be reduced, thus reducing the quality variation and defect products as well as scrap materials [103]. In Table 9, the related concepts are categorized from previous retrofitting projects.

The detection of a defective product can be recognized directly by product specification-related sensors such as tension with fabric product [78], or indirectly with other derivative parameters such as noise with gears [63]. In the next step, when the process parameters that affect product quality are defined and kept track of, and quality data is collected throughout the production phase, the variation that causes the

TABLE 10. Ways of DT elaboration.

Tools	Method of DT elaboration	Use cases & Industries
Vision system	Utilize cameras, or scanning method to recognize the objects in the physical system, then applying algorithms to develop the virtual system.	Cameras, Steel Mill [20], Phone assembly experimental plant [110]
		Light Detection and Ranging (LiDAR) scanning, Material processing [129]
		Computer vision programmed in LabView platform, Experimental plant [21]
Indoor Positioning System	Using RFID location tag to create the virtual world of manufacturing plant.	FMS system [79]
Microsoft HoloLens	Utilize augmented reality to manipulate with CAD models, real machine parts and its tool set.	Metal forming [130]
Smart Glasses	Data-driven decision making can be taken real-time with visualized monitoring report of the system condition.	CNC machining [106]
Sensorkits	Using Deep Learning algorithms trained by acquired data from sensors to create the DT of physical assets.	Oil extraction [54]
Software	The DT can be constructed with the aided software and relevant algorithm	Siemens Tecnomatix Process Simulate, Experimental plant [21], [110], Assembly line [77]
		Simumatik3D, Sand core [68]
		MATLAB/Simulink, Metal cutting [93]
		Simufact forming, Metal forming [125]
		Unity Game Engine, Metal forming [112]
		FESTO CIROS Mechatronics simulation, Modular Production System [56]

quality problem can be tracked easily [103]. Thus, it leads to a higher level in quality management: defect prevention, in which the possible defect can be prevented proactively, regardless of the human decision on which product is good or bad [63]. At the organization level, the historical data can be used for further improvement on quality aspect [39], including the parameters self-adjustment of the machine [78], or the group work of operators in diagnosing the manufacturing processes [63].

3) DIGITAL TWIN

Digital twin (DT) is one of the critical players in I4.0 development in terms of plant-wide optimization [128]. The development of DT is desired in many retrofitting projects, as the goal of full-scope digitization is to be the foundation for other managerial activities, and resource planning [110]. DT can be used as the tracking simulator and integrated with the existing legacy control system of brownfield manufacturing facilities [129]. There are different ways to elaborate the DT from a retrofitted manufacturing system, as depicted in Table 10.

The generation of DT is a significant step toward complete digitization. The most frequently used method of DT elaboration is sensors-based, with the use of the sensors mentioned in the previous section. In Ref. [93], the authors stated that the operational status of the machine is not enough; thus additional sensor must be installed for DT elaboration. A vision system is a convenient tool to gather data from the physical world, for instance, a camera system [110], or LiDAR scanning [129]. Other commercial tools also proved their applicability in the industrial context, such as Microsoft HoloLens [130] and Smart Glasses [106].

In some retrofitting projects, the authors were unable to elaborate the DT of the whole system; thus, a critical part

TABLE 11. Security threats on retrofitted system and possible solution.

Possible security threats	Possible solution	References
Unsecured sensors connection (i.e., simple field bus connection).	No recommendation.	[133]
Insufficient protection from low-cost solution (e.g., Raspberry Pi devices).	Employ industrial grade hardware.	[17]
Security weaknesses in legacy machines connection (e.g., simple serial connection).	Integrated legacy machines into a block-chain framework.	[133]
	Adding industrial gateways.	[135]
	Employ a modified-MACsec encryption protocol.	[132]
	Employ an additional Data Acquisition (DAQ) module for M2M communication encryption.	[136]
Cyber-attack on data acquisition and storage systems	Employ data protection system.	[54]
Sensitive information transmitted in connection string from IoT gateway to cloud server.	Employ additional encryption configuration (e.g., Password-Based Key Derivation Function 2, Cryptographycally Secure Pseudo-Random Number Generator) .	[77]
Lack of data ownership	Apply cloud technology in providing appropriate data access suits the need of each client and country, complying with General Data Protection Regulation (GDPR).	[81]
Poor security tracking in the retrofitting progress, lead to the fail of comprehensive protection of system.	Consideration of security should be taken at each life-cycle phase of the system.	[134]
Lack of a comprehensive security by systematic design approach.	Develop an architectural framework with additional authentication and guaranteed integrity.	[137]

of the system is chosen to build the DT upon [54]. Another way to develop the DT is with the aid of simulation software. Siemens Tecnomatix Process Simulate is the most preferred tool due to the capability of obtaining soft real-time data directly from the OPC UA server [77]. In this way, a large-scale DT can be developed, with the whole facility restored in the digital world [110].

4) SECURITY

Data security initiatives that protect the system from intentional and accidental destruction are one of the main obstacles in SMEs [131]. As brownfield development is about modifying and fusing new technologies into the existing factories, where most of their dated machines only have been through a few security updates, the risk aroused [132]. This aspect of the old system is a raging problem, as they have been designed with little sense of security in mind, thus making them vulnerable to many types of attack [133]. Taken into consideration that legacy machines only have limited built-in IT security function (i.e., default password, no access control, undocumented back-doors) [134], and their security perimeter mechanism is opposed to the desired zero-trust network [132], a retrofitted system can be more vulnerable for cyber-attacks. Table 11 below depicts the posed threats and the remedy suggestion for them.

The use of sensors in the retrofitted system can create multiple attack surfaces, such as data proofing and sensor data transmission breach, as mentioned in Ref. [133]. However, the author has not given any countermeasure for this threat. In Ref. [17], the author discovered that the deployed retrofitting solution with Raspberry gateway is cheap, thus posing a threat to security problems. Noticeably this solution has been applied widely in many previous projects. The authors also suggested that another industrial-grade hardware platform be taken instead of this low-cost option.

Several solutions are given to secure the weakness in legacy machine connections. In Ref. [133], the authors suggested that legacy machines should be integrated into a blockchain framework to prevent cyber-attack on weak connections between them. Adding an industrial gateway is another answer [135].

In the context of a textile retrofitting project [22], the authors could not utilize the cloud solution in the concern of data security but a centralized server instead. This problem raises the fact that a full-scope IoT architecture may not apply to every legacy system without considering its intrinsic characteristics. This problem can be handled by providing appropriate data access with General Data Protection Regulation (GDPR) consideration, as suggested in Ref. [81].

An intriguing statement from Ref. [134] said that attempt to retrofit security functions for legacy systems could introduce new bugs and vulnerabilities, and it is also hard to ensure that new systems are thoroughly tested. New technologies such as Secure Multi-Party Computation and Distributed Ledger Technology should be deployed as mentioned in Ref. [137], which followed comprehensive design principles to bring the retrofitted system an immutable and transparent registry.

Due to the few retrofitting studies that mentioned the security aspect, it can be seen that this problem is underrated compared to the newly developed system. However, it may become more severe soon [132], as the use of retrofitted machinery may continue to be in place for a long time from now. When retrofitting a legacy system, special care should be taken before bringing dated machines into a connected world.

IV. RETROFITTING DEVELOPMENTS AS STEPPING STONES FOR INDUSTRY 5.0

From the previous section, it can be seen that the technologies now are abundant and very well-suited for brownfield development. However, while retrofitting works are implemented in the I4.0 context, the next I5.0 is introduced. This new industrial revolution is the extension of I4.0 with a sustainable mindset and focuses on the human workers. Preparing for this strategic transformation, in this section, we described several important I4.0 retrofitting specific developments considered the supporting foundations for I5.0. Based on the Energy 4.0 in energy management, the new possibilities of Lean 4.0, the concept of Operator 4.0, and new methods of Maintenance 4.0, these developments to I5.0 focus are established, providing guidance for managers to consider the corresponding targets.

A. INDUSTRY 5.0

I5.0 is still a new innovative concept but has shown some of its future aspects from early research, such as the future of work between human-robot [138], a symbiotic factory where human-machine can contribute their value [139]. The EU stated that the I4.0 had positively impacted digitization and Artificial Intelligence (AI) -driven technologies to increase production efficiency. Now is a proper time to move on to I5.0, where societal and environmental problems should be emphasized [24], with a focus on human-centricity, sustainability, and resilience. With this sustainability in mind, human workers will be accepted as an irreplaceable factor of any manufacturing system, thus requiring a human-centric approach from both economic and productivity points of view [140]. Sustainability is also strongly emphasized, as different opportunities for sustainable manufacturing in I4.0 are discussed in Ref. [87]. Retrofitting is an enabler for the existing manufacturing equipment approaching economic and environmental dimensions of sustainability. It can also be considered as machine preparation to enable smart communication and capabilities for technological aspects and business requirements as well [141].

Taking into consideration the different emphasis between I4.0 and I5.0 [142], novel innovation trends for I5.0 are enabled by several technological aspects [143]. Several primary pillars can be listed as individualized human-machine interaction technologies, DT, and simulation for human-machine systems modeling, data transmission and storage, analysis technologies, technologies for energy efficiency, renewable, storage, and autonomy [144]. As proved in Ref. [130], a retrofitting project can bring benefits to its operators in learning, manipulating, and performing their production tasks. Along with a detailed understanding of the process, and favorable conditions for quality management, retrofitting can be considered as a way to aim at a sustainable business model [100].

This promising result urges a comprehensive approach for retrofitting to improve energy management and reliability, sustainability aspects of a manufacturing system, and enhance the working efficiency of its human operator in the forthcoming I5.0. The following parts are the specific developments considered stepping stones for I5.0.

B. ENERGY 4.0

Energy efficiency is an emerging research topic in the modern smart manufacturing system, with the term Energy 4.0 indicating the digital transformation of the energy sector as a sustainable goal in I4.0 context [145]. The energy utilization can be an objective to retrofit the legacy system [83]. However, the energy footprint is unconnected and hidden from the database with a legacy system, making it hard to apply any optimization. Due to that importance, Table 12 will be dedicated to describing the expect-able result from a successful retrofitting project.

At first, the energy footprint can be tracked with the deployment of the energy mentioned above sensors [95], [146]. An IoT-based architecture for energy efficiency tracking is proposed in Ref. [147]. Then, based on the trained data from the normal state of energy consumption, the abnormal ones such as high consumption and unbalanced energy load can be pointed out, with corresponding notification and alert for the operator or manager [95].

Energy improvement is one key sustainability focus in I5.0 regarding energy as a resource. After retrofitting, the enhanced energy utilization is mentioned as one of the most

TABLE 12. Energy usage of retrofitted legacy system.

Effect on energy utilization	Description	Industries & Use cases
Energy footprint tracking	Gather energy consumption data from manufacturing system for monitoring purpose.	Aluminium frame accessories [146], Olive oil processing [95], Didactic plant [18], Industrial robot [82], Metal forming [69]
Energy problem notification	Analyze the energy consumption patterns to identify problems such as abnormally high consumption equipment, energy distribution problems, unbalanced energy load	Olive oil processing [95]
Energy efficiency recommendation	The system gives the recommendation for energy improvement, based on the collected and analyzed data.	Olive oil processing [95], Didactic plant [18]
Energy utilization improvement	Machine operation state, or switches, actuators can be changed based on the energy indicators, to enhance the energy saving.	Metal cutting [83], Industrial robot [82], Material handling [19]

TABLE 13. The possible advantages of Lean 4.0 in retrofitted system.

Main advantages	Description	Industries & Use cases
Work process standardisation	The work process can be standardized to avoid waiting time.	Metal forming [58]
Just-in-time production	Materials and tasks can be scheduled in exact time of need, avoid excessive stock of waiting line.	Metal cutting [87]
Quick Changeover	Shorten the time to changeover between different states of the equipment configuration or product variant.	Material handling [105]
Reduce machine/equipment waiting/waste time	Reduce the idle time, or time to set-up, time to repair of machine/equipment, stoppage time by recognizing and controlling its state.	Electronic manufacturing [76], Steel Mill [20], Oilfield [81], Fabric knitting [78], Metal forming [58]
Remove bottleneck in material flow	Rearrange the processes to avoid bottleneck that cause production deficiency.	Aluminium production [37], Gear production [63]
Continuous improvement	The process optimization and root cause analysis activity can be developed gradually with the available data.	Aluminium production [37], Fabric knitting [78], Textile [15], Metal casting [124], Gear production [63], Metal forming [69]

promising results [83], making it closer to the scope of I5.0. A recommendation can be given, aiming at a higher efficient operating condition [18]. In ideal cases, the improvement in the energy aspect can be performed through actuators and switches based on predefined energy indicators [19], [82]. This step reflects the self-optimization ability of the system.

C. LEAN 4.0

The well-known traditional Lean Manufacturing (LM) philosophies mentioned in Ref. [148] have evolved along with the industrial development in the ever-changing context of I4.0 as described in Ref. [149]. The implementation of I4.0 technologies creates a unique effect for LM deployment in the operational strategy of the company [150]. This fruitful involvement is mentioned as Lean 4.0 [151], and some IoT technologies that enable LM are studied in Ref. [152]–[154]. LM philosophies share the same continuous improvement approach with the technical improvement of I4.0, thus considered as assistance for smart retrofitting [106]. As an aftermath of retrofitting projects, legacy manufacturing systems can adapt themselves to bring advantages under the proposed Lean 4.0, as listed in Table 13.

A critical aspect of LM is work standardization, establishing the standard for movement and task time for operators. The recorded data from the retrofitted system are suitable for this purpose, as demonstrated in Ref. [58].

The Just-In-Time (JIT) production can be facilitated to create a smoother production material flow and avoid excessive stock [87]. The more balanced, stable material flow can be supported by removing the production bottleneck as well, which is easier to be discovered by the retrofitted system [37], [63].

The flexibility and agility of the manufacturing equipment can be enhanced due to the Quick Change-Over (QCO) that is supported by the re-configurable system [105]. Other LM concepts, such as reducing the waiting time of machines and equipment, are validated by the case studies mentioned in Ref. [76], [78], especially useful in industries well-known for long change over time (i.e., steel mill and mining) [20], [58].

Continuous improvement is an essential factor in LM in general and in maintaining the effective usage of the system in the organization [99]. The core of this concept is the kaizen activity, which is done by a group of people to solve an organizational problem [155]. For the retrofitted system, this kind of activity is highly supported due to the availability of data, the visualization of the critical parameters, and the human-centric approach when designing the retrofitting solution [69].

TABLE 14. Operator 4.0 benefits on retrofitted system.

Main advantages	Description	Industries & Use cases
Analytical support	The worker can be supported by the relevant data and visualization to analyze the situation, and make quick decision based on given tutorials.	Steel Mill [20], Oilfield [81], Fabric knitting [78], Metal casting [124], CNC machining [106], Electrical cabinet maintenance [67], Metal cutting [93], Material handling [104], FMS system [74], Metal forming [58]
Stress-free work environment	Faults and machine failures are easy to detect without human consideration and require less work experience.	Plastic injection [114], Oil extraction [54], Steel Mill [20], Metal cutting [87], Fabric knitting [78], FMS system [74]
Higher-value contribution from human worker	Due to the data-based automation, the worker can have more time for value-added tasks, than monitoring the machine, waiting, doing manual data collection	Textile [71], Metal cutting [87], Fabric knitting [78], Industrial robot [82], Metal de-burring and grinding [103]
Human error reduction	The unintended error from the manipulation of the workers is stopped by the system, to avoid consequences of absent-mindedness.	Steel Mill [20], Car assembly [75], Metal de-burring and grinding [103], Metal forming [58]
Supported job training and learning	Provide the visualized data of normal and abnormal events, real situation example for the personnel training.	Textile [97], Metal casting [109], Oil extraction [54], Steel Mill [20], Metal forming [97], [130], Oilfield [81], Fabric knitting [78], Textile [15]
Healthy operator	Occupational Safety & Health (OSH) hazard will be prompted to the operator timely through user interface, smartwatch. The system can be stopped in a preventive manner.	Electronic manufacturing [76], Oil extraction [54], Oilfield [81], FMS system [74]

D. OPERATOR 4.0

The concept of Operator 4.0 is mentioned as the future of the human workers in the industry, where the I4.0 technologies assist the work of human labor [27], [28]. Enabling technologies of Operator 4.0 concept are summarized in Ref. [156]. At the first stage of I4.0 brownfield development, employees should be involved and motivated to support the change, as one of the three main elements in the smart retrofitting concept suggested in [106]. There are benefits for the operators that can be expected in a modern factory. With the elaborated DT, cognitive Operator 4.0 can enable a smarter decision-making environment [157]. In Table 14, the ideal advantages for Operator 4.0 after retrofitting are discussed with their benefits as demonstrated in industries.

Along with these benefits, an enterprise can overcome the lack of educated operators to increase its competitiveness [78]. By providing the person in charge of each process with its relevant parameters, it can be considered as analytical support for his task [67]. This aspect fosters the decentralized decision-making capability of workers, allowing them to take part in more knowledge tasks in sustainable manufacturing from human factor [87]. In some particular conditions, the human worker is the primary motivation to retrofit the legacy system [158] so that its workers can feel more comfortable with their work [109]. With the machine failures detected by the system, special tuition and knowledge are not required from the operator, thus leaving him a more relaxed work environment [114].

Operator 4.0 and even I4.0-related managers are the crucial roles in the manufacturing processes; thus, their convenience must be of higher priority when retrofitting a system [20]. With the assistance of the developed system, human intervention can be decreased, and the operators can have more time to concentrate more on the process optimization [103]. In the meantime, by isolating the error of operators, consequently reducing the number of non-conformance products, the operation efficiency can be improved [58].

A critical aspect of sustainable manufacturing is the development of human resources [24]. For this purpose, two retrofitting advantages that need to be considered are job training and learning effectiveness and the prevention of accidents in the workplace. With the advance in technology, data visualization augmented reality can aid the job instruction for workers, helping them to learn the tasks quickly with actual situation example [78], [130]. On the other hand, the system has more built-in safety functions that can halt or stop the production once a hazard is detected to prevent a further accident or danger that can happen on the shop floor [74], [76]. It can be observed that, by applying new technologies in a human-centric approach in a retrofitting project, not only the managers, but the operators will be the ones who get the crucial benefit during their daily performance [109].

As workforce resilience is severely tested during the Covid-19 pandemic, its importance is realized, along with other possible adverse realities such as resource scarcity, climate change, and skill gaps that can be added into the manufacturing context. The concept of Operator 5.0 is built upon the vision and paradigm of Operator 4.0 to guarantee manufacturing operations continuity, especially in difficult and unexpected conditions [28].

E. MAINTENANCE 4.0

A legacy system puts a heavy burden on maintenance activities, as outdated machinery lacks technical documents [68], [98], and historical degradation record [93]. The retrofitting approach can provide old machines with predictive maintenance and does not require cost-intensive re-engineering activities [88]. The availability of process monitoring sensors

TABLE 15. Maintenance 4.0 of retrofitted system.

Main advantages	Description	Industries & Use cases
Operating time recognition	The utilization time of the machine can be recorded.	Textile [15], [71], [97], Metal cutting [53], Oil extraction [54], Car assembly [75], Olive oil processing [95], Metal forming [69]
Maintenance parameters record	The vital parameters for maintenance, i.e. Overall Equipment Efficiency (OEE), Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR) can be calculated automatically based on acquired data.	Textile [15], Metal forming [69], [125], CNC machining [126], Metal forming [58], Candy packaging [52]
Failure recognition	The abnormal state during the operation of the machine can be recognized based on the trained data from normal running state.	Plastic injection [114], Metal cutting [53], [87], Metal casting [109], Industrial motor-driven system [85], Oil extraction [54], Car assembly [75], Oilfield [81], CNC machining [128], FMS system [74], Metal forming [58]
Fault finding	The machine part and mechanism cause the problem can be pointed out accordingly.	Plastic injection [114], Metal cutting [53] , Electronic manufacturing [76], Metal casting [109], Industrial motor-driven system [85], Oil extraction [54], Steel Mill [20], Olive oil processing [95]
Predictive maintenance	Specific maintenance tasks can be planned beforehand.	Textile [71], [97], Iron & Steel production [84], Aluminium production [37], Car assembly [75], Metal casting [124], Olive oil processing [95], Assembly line [77], Metal forming [58], Lab experiment [113]
Maintenance activities optimization	The system can assist the operator with the maintenance procedure, offer suggestions in maintenance aspects, thus the cost of work and spare parts can be optimized due to reliable data, avoid early replacement or excessive maintenance checking.	Textile [97], Metal forming [97], Electrical cabinet maintenance [67], Metal cutting [93].

in the I4.0 framework offers a favorable condition for predictive maintenance [113], [159], [160], which is a core concept of smart maintenance and Maintenance 4.0 [161]. Besides, there are more advantages of the system that can be expected, as described in the Table 15 below. They can be defined as enabling factors for Maintenance 4.0, with their benefits demonstrated in several industries.

The first significant advantage of retrofitting the legacy system is the operating time recognition of machinery, which the operators usually need to perform by hand [71]. After this step, the maintenance-related parameters such as Overall Equipment Efficiency (OEE), Mean Time Between Failures (MTBF), and Mean Time To Repair (MTTR) can be calculated for further production efficiency assessment [52]. Then with the use of machine learning, the failure state of the machinery can be recognized by learning from the normal-state data [127]. When the system runs into a problem, then the machine part and the mechanism in which the situation happened can be pointed out, making it easier to locate and replace the broken part [85].

For higher application, predictive maintenance initiative is supported, as the maintenance task can be suggested and planned based on the historical data [95]. The specialized maintenance DT elaborated in Ref. [93] can offer suggestions when condition-based or corrective maintenance activity needs to be taken. Instead of the traditional maintenance approach of time-based replacement, the retrofitted system can save unnecessary maintenance work and spare parts due to the integrated condition monitoring capability [67]. These advancements enhance the maintenance efficiency, while the maintenance cost can be cut down.

These aforementioned I4.0 developments can be considered stepping stones for the I5.0 initiative. As their

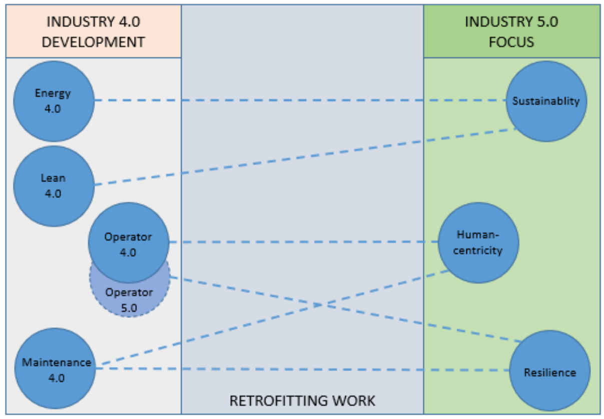

FIGURE 3. The retrofitting developments as stepping stones for Industry 5.0.

characteristics indicated, the gained benefits bring manufacturer advantages and readiness for further development. Figure 3 represents the connection between these I4.0 developments and the focus of I5.0. At first, in terms of Sustainability, the efficient usage of energy and manufacturing resources, from the concepts of Energy 4.0 and Lean 4.0, respectively. These concepts support a strong foundation for a sustainable operation of the firm at the micro-level and the whole value chain of the economy at the macro level. Lean-digitized manufacturing not only offers companies survivability in the I4.0 context but also a prior sustained competitiveness [162]. Energy utilization is an essential factor that may create an immediate impact on sustainability [145].

The operator 4.0 concept focuses on the human-centricity aspect, as workers and operators benefit from technology and digital transformation, which helps them fulfill their job requirements with less effort and higher value-added contribution [27]. Then the self-resilience of Operator 5.0 concept is forming in Ref. [31], aims toward a system effect from both human-machine system resilience and human operator resilience. Meanwhile, the advantages of Maintenance 4.0 enhance the Resilience of the system, as its readiness and reliability are strengthened and can provide input for a learning Human-Machine system for resilience prediction and control [163]. Due to the reported advantages, these developments are recommended as targets for every retrofitting project.

V. INDUSTRY 4.0 MATURITY MODEL AND BROWNFIELD DEVELOPMENT FRAMEWORK TOWARD INDUSTRY 5.0

With many studies related to "retrofitting" and "brownfield development" concepts, it can be seen that updating the legacy manufacturing facilities with I4.0 connectivity is the current trend. However, without comprehensive development guidance and goals, industrial managers may face difficulties deciding on different technical options and equipment regarding their pros and cons and respective priority for each implementation phase. On the other hand, as mentioned above from previous retrofitting projects, it can be seen that most brownfield developments are mainly focused on exploring the potential of I4.0, lacking a comprehensive organizational alignment. The advantageous effect on the human factor and energy utilization are byproducts that are underdeveloped and thus do not fit a sustainability perspective.

In the previous sections, we have collected the deployed technical equipment from retrofitting projects to provide trustable technical guidance for a similar project in the future. These categorizations can serve as a good background for decision-makers before any technology choices. In this section, organizational aspects of retrofitting are mentioned, which adds a coherent connection to technical aspects. At first, a simple three-step strategic planning model is suggested for manufacturing firms to sketch their retrofitting goal with a long-term vision. Then, a project-based approach is proposed to implement retrofitting activities and discuss the development goal with a long-term perspective on the threshold of the I5.0. In this approach, sustainable factors and other new concepts are regarded at the beginning of the I5.0 to provide facility managers and decision-makers with helpful information on their digitization transformation.

At first, a manufacturing firm may want to discuss brownfield development at a strategic level to decide the corporate motivation for the change. For legacy systems, the corporate understanding should get accustomed to the concept of I4.0 and I5.0 before getting into further action. A three-step strategic planning model is proposed as in Figure 4, taking into consideration the compatibility of the three-step model suggested by TUV SUD for I4.0 transformation [164]. A similar approach can be observed from the three steps to customizing a digital transformation road map from the Ingenics consulting, which discusses a tactical process of developing a strategy baseline, creating envisioned goals before coming to a transformation road map [165]. In the beginning, a strategic baseline should be established, in which the status quo of a large-scale business area should be identified, along with the corporate potential of retrofitting. For the firm to realize the business potential, the vision of I4.0 and I5.0 should be discussed thoroughly and can be based on the official guidance from EU [24], [142]. Then the strategic vision and goals should be set, influencing the objectives of retrofitting transformation later. The last step of strategic planning is to sketch a brownfield development or transformation framework. The framework can be elaborated based on the references from the literature, as an ideal one is suggested in the following section. In a compatible study in [166], the authors suggested the common understanding of I4.0 should be done at the first step of strategic planning, and a proposal for a project can be elaborated at the final step.

Based on the decision to pursue the brownfield development conducted by the top-level managers after the strategic planning, the retrofitting project framework should be elaborated, along with the key milestones and resources (e.g., financial and human resources, time, etc.). Once the project team is formed with key personnel, the action phase

FIGURE 4. Three-step strategic planning for brownfield development.

should be progressed. A novel project approach for brownfield development toward the I5.0 solution is proposed, as illustrated in Fig. 6. We aim to develop a strategic transition project framework used as a guide for retrofitting projects, bearing the sustainable goals of I5.0 in mind.

At the beginning, a maturity model is needed, which may serve as a backbone for the organizational deployment of the project. A brownfield development framework should be built upon a maturity model to ensure that every dimension of a digital business operation is enhanced in the later implementation phase. Companies should scrutinize every aspect of their current status to comprehend a thorough understanding of their current status before aiming at a future state, as the development implementation will change most of their organizational strategy [167]. An unbalanced development can cause a more severe knowledge gap for utilizing the retrofitted system later.

There are I4.0 maturity models that can be taken into consideration, such as Smart Manufacturing Maturity Model (SMSRL) and Manufacturing Operations Management (MOM). Their objectives, dimension, and purposes are diagnosed in comparison with Digital Readiness Assessment Maturity Model (DREAMY) in the ref [168]. DREAMY is deployed in Ref. [169] as an assessment tool to evaluate the digital readiness of main aspects of a firm, such as processes, monitoring, and control, technologies, organization. A digitization roadmap can be defined for implementation purpose [170]. Based on the proposed techniques, a manufacturing firm can identify and prioritize their relevant emergent need for brownfield development, as adopted in a similar project described in Ref. [62]. A detailed model of 62 items and an exemplary questionnaire can be found in [35], which emphasizes the organizational aspects. This research adopts a practical maturity model from the IMPULS Foundation in Ref. [171] as the structure for the comprehensive brownfield development. The main six aspects of the model are illustrated in Figure 5, with their required features respectively. These aspects can guide strategic planning and provide a balanced improvement in corresponding fields: strategy and organization, smart factory, smart operations, smart products, data-driven services, and employees.

In the Strategy and Organization dimension, the corporate culture should be favorable for the I4.0 adoption, with a clear

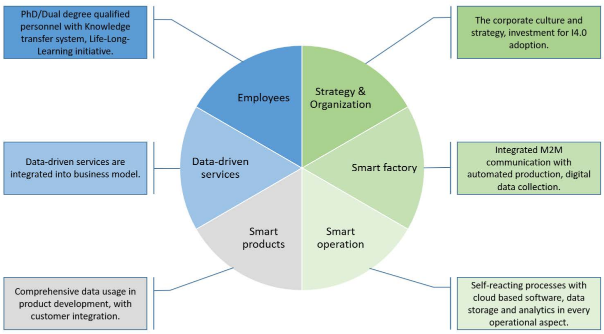

FIGURE 5. Digital maturity model for assessment of brownfield development.

strategy and proper time, capital, and resources investment. The patents and innovation should be kept on in centralized and integrated management. The manufacturing processes should be automated with automated equipment capable of digital data acquisition in the Smart factory dimension. Machine-To-Machine (M2M) communication should be integrated. An IT system is deployed to provide digital modeling in all areas and activities, thus facilitating data usage in every aspect of manufacturing.

The smart operation dimension is built upon that foundation as the smart factory is ready. Information is shared by deploying cloud-based software, data storage, and analytic platforms. With cloud computing capability, self-reacting processes are enabled in every aspect of the business operation, such as production, finance, sales, IT, R&D, and Logistics. The smart product is another dimension that measures the comprehensive use of product-related data for the development process and integrates customers with other data-driven services.

The Employees is the last dimension, which measures the readiness of the employee of the firm for I4.0. With automation being highly developed, employees are expected to have higher skills and are encouraged to involve in a knowledge transfer system with a Life-Long-Learning attitude. A comprehensive brownfield development strategy should cover all of these dimensions, as the immaturity in one dimension can cause weakness for the digital operation of the business in the later phase. On the other hand, the firm must pay equal attention to every dimension, and a balanced development at the same level should be realized.

Once the maturity model is chosen, the development can now be sketched. Through the literature, a transition model is usually deployed as a guiding direction for an overall picture. Even in Germany, the place where the concept of I4.0 stemmed from, lacking structured strategies to implement the I4.0 solution can also be a barrier [33]. Consider the investigation; many previous studies have already proposed a model or framework for a retrofitting project. A transition solution for retrofitting machinery from Industry 3.0 to I4.0 is mentioned in Ref. [64], in which technical as well as sustainable objectives are considered. A migration procedure for SMEs to retrofit their manufacturing equipment to accomplish the I4.0 requirement is also suggested in Ref. [12]. Different approaches of traditional retrofitting and smart retrofitting are compared in Ref. [130], as the conventional approach aims at the optimization of existing old machines and smart retrofitting aims at a further way of fitting them into the I4.0 context. A seven-stage for systematic brownfield development is suggested in [99], which aims at developing a platform for reconfigurable and changeable manufacturing based on an existing system. However, due to the abundance of new management aspects and concepts from the I5.0 context, the previous approaches are insufficient to integrate relevant criteria systematically.

This framework guides researchers or managers who want to start a retrofitting project in their manufacturing plants. Its core knowledge is the six-step digitization transformation roadmap proposed by Capgemini Consulting Ltd. [172]. Due to the technical concerns throughout the retrofitting project, smaller steps are broken down and identified for further clarification and explanation. The evaluation criterion is collected and organized systematically from their usage in the referred literature. Additional descriptions of step purpose, related consideration criterion, and deliverables are given. The details will be mentioned in the following paragraphs.

A. FIRST PHASE: DIGITAL MATURITY ASSESSMENT

This phase is the first stage in the framework, covering the first two steps in the projects: the digital maturity assessment and the beginning of the definition of the system design objectives.

Step 1. Digital maturity assessment

The need for digitization starts with the digital maturity assessment, in which the company should be well aware of its digital capability. Initiatives from previous successful projects are categorized according to different aspects of the maturity model mentioned above: Strategy and Organization, Smart factory, Smart operation, Smart products, Data-driven services, and Employees.

For the Strategy and Organization criteria, Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis can be deployed in this stage to define the change in business competitiveness and the whole value chain, as proposed in Ref. [61], thus clarifying the desired impact of the project. A model of micro and macro perspectives for sustainable manufacturing is mentioned in Ref. [87], in which the sustainability of the business itself in the more extensive value creation network is an urge for manufacturers to transform themselves. On the micro-scale, the authors mentioned that sustainability also needs to be incorporated into every factory aspect, namely equipment, human, process, and product. With many positive impacts on the business considered [14], digital transformation should be a strategic investment in business processes, products, and services.

For the Smart factory criteria, the transformation starts with every single process [76], [100], put the questions on how they are controlled and monitored now, and how they

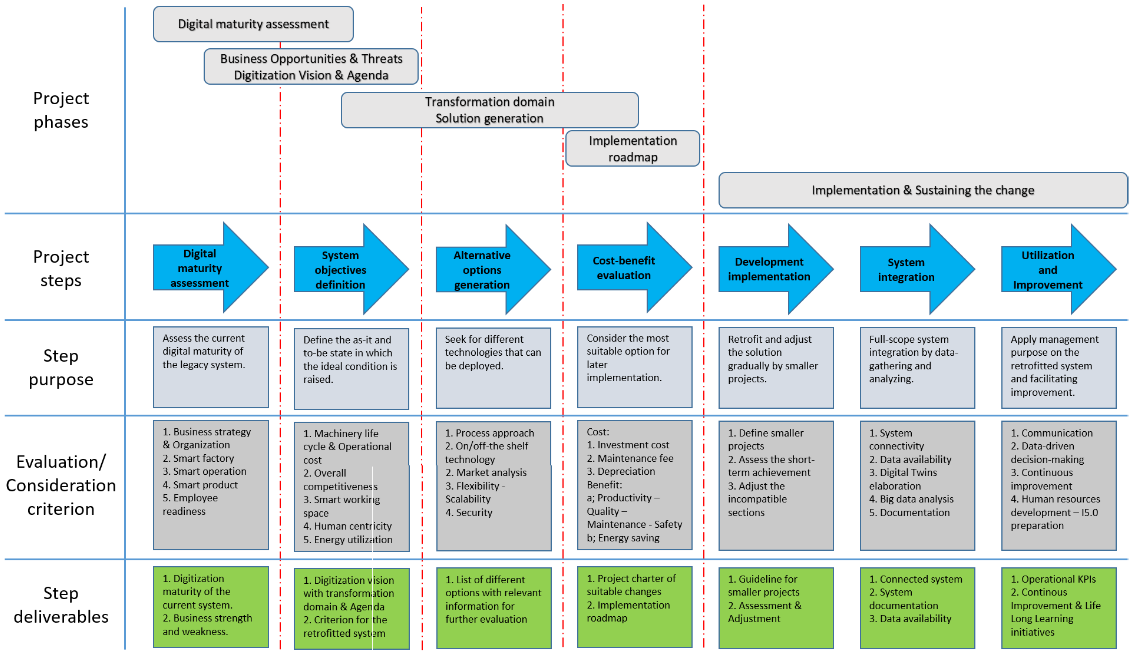

FIGURE 6. **Propose framework for I5.0 solution retrofitting project.**

should be [20], [109], from the viewpoint of the direct operator of that process. During a retrofitting project, the system hardware and software assessment is conducted, thus specifying the components that should be focused on as described in Ref. [130]. Technical specifications of the retrofitting considered machines need to be examined to clarify the possible intervention and modification that can be applied [76]. The author also stated that different component family types and installed technology must be classified from the most critical equipment. The difficulty of lacking technical documentation is a significant obstacle and can be coped with the optical recognition and semantic analysis proposed in Ref. [98], or the reverse engineering activities during the construction of DT [68]. Based on the elementary smart operation of processes and monitoring and controlling automation, the smart operation concept can be achieved, which aligns with the strategic goals and brings the desired operational efficiency over the legacy system [58]. Data-driven services is another domain in the maturity model, as the utilization of customer data foster the digitization of sale/services [35]. However, none of the retrofitting studies mentioned this aspect; thus, we conceived it as an opportunity for the application to gain more attention.

As suggested in Ref. [52], the product should become a participant in the process of data collection, make its data-driven optimization possible, and becomes a factor for knowledge-driven manufacturing. The correlation between smart products and smart production can be referred to from Ref. [173]. The re-use and re-manufacturing of products with a closed-loop life cycle is emphasized in Ref. [87] as an essential player. The use of data in product generation and retrofitting the old product family is suggested in Ref. [174] as a way to contribute more customer value with the aid of digitization.

Employee readiness is the last but not least factor that should be considered in this step. As human resources play a vital role in implementing digital transformation [175], managers must encourage employee innovation to transform their business, not only the technical system radically. Preparing for the brownfield development not only means applying the technological advancement but also equipping its human workforce with the necessary skill set, which may help them adapt to their new system [13]. Before going into the digitization journey, the company should assess whether its human resources are ready for the upcoming changes or not. Then, it should define clearly whether the retrofitting project is carried out with their team or they need to seek for external partner [14].

Based on the suggested maturity model, managers can have an organizational overview of their business before identifying the retrofitting objectives in the next step. One hint for the development can be the unbalance of the considered aspects, leading to a knowledge gap that obstructs further development. After this step, the firm should be well aware of its digitization maturity, its corresponding strengths, and weaknesses in the era of I4.0 and the threshold of I5.0. This result may come with the realization of opportunities and threats at both micro and macro level [87]. This aspect laps the beginning of the second phase of the project, as the activities may happen simultaneously.

B. SECOND PHASE: IDENTIFY OPPORTUNITIES AND THREATS. DEFINE VISION AND AGENDA

The beginning part of this phase is already finished by defining business opportunities and threats in the previous step. The digitization vision and agenda should be made at the end of this phase through the second step described below.

Step 2. System objectives definition

This step covers the end of the first phase, with the system automation being assessed more carefully, and the second phase, as the digitization vision and main agenda should be sketched. It also defined the transformation domain of the system as the third phase suggested. In this step, the objectives of the retrofitted system should be defined clearly, along with several important concepts.

Many considerations lead a company to decide to replace or retrofit a machine, which should be listed in this step. This step will define clearly the limits of the expected budget for the project instead of buying a new system. The first criteria are the machinery life cycle and the equipment operational cost. The industrial equipment replacement cycle is longer in the industrial market than in the consumer one, mentioned in Ref. [20], especially in industries with heavy hardware in which the machines may have years or decades of upgrade period. There are several approaches to define the retrofitting objectives to cope with that consideration, from an economic aspect, such as the life cycle cost (LCC) [176], or with maintenance and operational cost [177], [178], or life cycle assessment (LCA) in combination with the sustainable efficiency of a product process [146]. A variety of technical indicators, LCA, LCC, and the thermo-economic analysis, are studied in [179], to address the different effects of technologies that will be fused into the legacy system during the retrofitting work.

Other objectives for retrofitting purposes can come from the need to increase the overall competitiveness, including improving predictive maintenance [75], optimizing the energy consumption [83], enhancing the information flow within fragmented process chain [78]. These competitiveness aspects are indispensable in the I4.0 context, especially for SMEs [16]. In some cases, they can be as simple as increasing the system connectivity [72] to have a more transparent operation or transforming the existing infrastructure into a CPPS [180]. An analysis workshop using LM philosophies is proposed in Ref. [63], with the LM tools used in the evaluation process, which follows the main objectives such as improving quality, reducing costs, and lead time.

Smart working space is another objective of interest. An exemplary brownfield approach is mentioned in Ref. [105], as the work of extending the current legacy system into I4.0, which is followed by a proposed architecture and component for the factory operating system. In this smart and connected world, self-optimizing and self-learning can be desired targets [78]. The flexibility and agility of the system are mentioned in the projects in Ref. [19], [105]. In this phase, desired additional functionality or automation can be considered, taking into consideration the current legacy functionality during the gap identification step as utilized in Ref. [19]. This step may benefit the technological solution development in the next step.

Other sustainable objectives of the forthcoming I5.0 are safety, human centricity, and energy utilization. Some researchers have already integrated these aspects into their objectives, as in Ref. [64], the authors define system performance in metrics such as safety, energy consumption, emission, and Industry 4.0 capability. The indispensable existence of human workers in manufacturing systems is another motivation for retrofitting work [109], [158], making the shop floor a good working environment for them. Energy utilization might be matured in the near future, as the pioneer researchers have already taken their first step toward the energy retrofit initiative [58], [82], [83].

By the end of this step, the firm should have their digitization vision well-elaborated with their corresponding transformation domains by comparing the assessment result from the previous step with the desired criterion for the retrofitted system [19]. The transformation agenda is a good compass for the development later. Noticeably, these results are not individual work. A brownfield development cannot be digitized within a few days but through ongoing and adjusting phases. Consequently, it should be a teamwork effort with encouragement from the managers [175]. A good agenda with the concurrent-engineering approach allow the retrofitting team to understand the digital transformation, clearly define their system to support their tasks, and build up solution [58]. Discussions within the team are vital for the retrofitting project in particular, but also for a successful digitization process in general [22]. Other requirements can be gathered by interview or questionnaire as proposed in Ref. [66], or workshop with involved personnel in the manufacturing process [61]. By doing this step, the team can define the transformation priority order and starting point of the project steps.

C. THIRD PHASE: PRIORITIZE TRANSFORMATION DOMAIN. SEEK FOR SOLUTION

This phase overlaps from the second step, with sketched the transformation domains. In this third step, the team generates ideas on the needed solutions. It will continue until the fourth step, as in reality, options should be considered with their cost-benefit evaluation before any make-or-buy decision is made.

Step 3. Alternative options generation

In this step, different options should be brainstormed. This step can be done by a multi-disciplinary team from key disciplines within the company, as a cost-saving initiative from the beginning [81]. The team can utilize design thinking, a human-centered approach in which the workers are involved to sketch their ideal working condition [20], [109]. Consequently, a comprehensive overview of the ideal system can be formed.

A process approach will be deployed in this consideration. At first, the process-relevant parameters should be determined along with their limits as a starting point for optimization later [100]. As stated in Ref. [76], vital process parameters affecting product quality should be considered first. In the textile industry, parameters such as yarn tension, surface quality, temperature, humidity need to be measured [15], [22]. For food industries, the precise temperature is a special requirement for various chemical reactions; thus, temperature sensors should be deployed [73]. However, these parameters are dependent on the specific type of industry, without a universal parameter as baseline [22]. Besides, overall performance metrics such as energy consumption, line productivity, machine downtime need to be defined for management purposes later.

Based on those predefined parameters, the chosen sensors are defined by the selected monitoring strategy, monitoring position and orientation of sensors, execution of measurement [87]. Some requirements when choosing retrofit sensors are mentioned in Ref. [53], such as temperature range, weight, size, shape, energy supply, power consumption, data transmission type, sampling rate, frequency band, communication type, environment requirement: temperature, dust, liquids, chemicals. Besides, there are criteria for the economic aspects such as production time, small quantity, and a quick change in product design. In Ref. [73], the authors mentioned the requirements for the sensor node hardware system in the retrofitting architecture to achieve Plug & Play functionality. When the sensor node is established, different sensors can be attached, detected, and automatically configured [82], [181]. There are commercial sensor platforms, and sensor kits with embedded sensors are deployed as in Ref. [75], [88], [89]. The use of commercial instruments usually offers high quality and standards. On the other hand, some projects utilized the self-elaborated retrofitting kits [69], [181]–[183], which were open-source and easy to integrate new sensors and applications as modules.

Actuators can be considered based on the interested process parameters [77], or in pair with process-related sensors [67]. The close loop signal between sensor and actuator can enhance the process control efficiency by supporting the local automation with switches, valves, and controllers [98], [102]. The existing legacy actuators can be utilized to enhance the field automation, which eases the presence of human workers for simple tasks or manipulation [68]. Additional actuators can be employed in case the system lacks an actuator [64], or to broaden the capability of the existing hardware [82]. A self-built mechanism can be considered when the machine structure does not allow the use of commercial goods [80], or when introduced a new function into the retrofitted system [21]. This approach enables the I4.0 integration with possible extension and customization.

After considering the sensors and actuators, the connectivity should be in place, as designing system architecture is mentioned in Ref. [16], which lays the foundation for the later proposed IT platform. Legacy PLCs can be incorporated into the system by industrial communication protocols [57], with data exchange capability with other IoT components [107]. New PLCs can be added with the pre-built connectivity, to enhance the level of field automation [110]. Several IoT architectures for retrofitting are suggested in Ref. [112], [123], which shows the interactive sub-systems and layers, with their respective connectivity types and protocols. A computational system must be installed for the IT hardware, and a communication protocol must be chosen, as a digital retrofit methodology is mentioned in Ref. [16]. The same step will be applied for the data storage and cloud platform generation, which takes into consideration the natural characteristics of legacy system [22], [63], [97], which are available from the previous maturity assessment. Free platforms are available and can be an option for this domain [104].

Market analysis is an appropriate initiative in this step, as by identifying and analyzing similar functioning products available on the market, the technical characteristics, price, maintenance cost can be taken as benchmarks for further consideration when choosing alternative retrofitting options [64].

While designing the desired system, scalability is one crucial factor that needs consideration. Taking into consideration that the plant may be extended in the future, then the solution needs to be scalable [105]. Several suggested architectures deal with this problem by using the nodes system [18], [73], [82], as more sensors can be installed as nodes. In a more general way, the options should take into consideration further updates and re-configuration in the future [19], [104]; otherwise, the system might be obsolete soon after the new development wave [20]. On the other hand, security aspect should be considered from this step, as it may influence the choice for hardware and protocols will be added in the system [135], [136], or need to be kept in mind while connecting the system elements later [134], [137].

By the end of this step, a list of different options in the sensor and actuator, connectivity, and data layers should be ready, including technical specification, the reason to choose, the related cost. As the team is prepared to enter the cost-benefit evaluation step, this list can still be discussed and modified as the third phase continues. In the meantime, the consented development can be put into the implementation roadmap as elaborated in this step.

D. FOURTH PHASE: DERIVE IMPLEMENTATION ROADMAP

This phase is nested in this step, as the implementation roadmap for brownfield development should be made and agreed upon by the team effort. The deliverables in this step are the project charter of the future changes and milestones to implement them, as discussed in the subsequent implementation phase.

Step 4. Cost benefit evaluation

In this step, based on the available options generated from the previous step, a decision should be made on whether commercial gadgets should be chosen or self-elaborated kits should be used. There are several ways to conduct a cost-benefit analysis. Qualitative methods such as Analytic Hierarchy Process (AHP) are adopted in Ref. [64] to examine ten criteria of five alternative options. A structuring model of an economic evaluation can be recommended from Ref. [184], which considered the unique characteristics of digitization. In this research, data acquisition for investment in a retrofitting case is conducted in a workshop, which is an excellent method to ensure every related person in the project team comprehends the condition and assumptions. A comprehensive multi-criteria analysis takes into consideration different priorities from the technical domain (i.e., saving Not Good (NG) product, increasing overall efficiency), environmental domain (i.e., reducing CO2 and NOx emission), economic domain (i.e., reducing operating and maintenance cost) is studied in Ref. [179]. The AHP method is applied to consider different retrofitting solutions for an aluminum furnace. In Ref. [61], the authors suggested using the Total Cost of Ownership (TCO) for cost evaluation, then use other economics indexes such as Net Present Value, Profitability Index, Internal Rate of Return, Discounted Payback Period to compare different solutions, as well as to measure the level of achieved success.

Cost and benefit elements should be defined to build a cost model. The cost from different sub-systems such as the legacy system, cloud, service company, and end-user devices are considered in Ref. [136], and project managers can refer to the suggested rule to predict the required budget. The cost for hardware gateway or extensive setup is a concern in Ref. [72]. Besides, due to the loss of productivity during the implementation period, production interruption can be considered as a cost [86]. Some legacy PLCs are irreplaceable due to the risk of production downtime, thus can obstruct the retrofitting effort [57]. Rapid technology development can also make the system quickly become obsolete [20], which accounts for the opportunity cost of investment. The compromise between the cost for cloud service and computation time is also mentioned in Ref. [90]. Ref. [64] mentions the cost of design, acquisition, installation, operation, maintenance, and disposal. Notice that retrofitting projects usually utilize open hardware and software; thus, the development and implementation cost will be much lower than certified commercial solutions, as mentioned in Ref. [12]. However, the security problem should be kept in mind that a low-cost retrofitting solution may not be appropriate for safety-relevant applications [17].

Several benefits are mentioned in Ref. [15], e.g., reduction of the machine downtime, time to repair, reduction of manual work for data collection, and the enhancement in data-driven root cause problem-solving activities. The benefit from quality improvement [39], as well as maintenance saving, can be taken into account [67]. The save from energy loss can also be taken as a benefit of retrofitted equipment [58], [82]. A significant cost saving is recorded after a retrofitting project in the mining industry in Ref. [58] for the loss of production material, in which production cost reduction and energy consumption reduction are also expectable outcomes. Safety also should not be neglected as an essential gain from retrofitting project [54]. However, in the context of I5.0, another operator-centric dimension should be added. Given the machine operator as the center of the system, we proposed that other aspects such as the availability of real-time data analytic, augmented reality, easy integration wearable for the healthy operator should be taken into the model. A few criteria are mentioned in the conceptualization of Operator 4.0 in Ref. [27].

The implementation roadmap and the list of preferred solutions should be determined by the end of this step. An exemplary I4.0 roadmap can be adopted from the suggestion in Ref. [166]. From the next phase, the implementation is emphasized.

E. FIFTH PHASE: IMPLEMENT AND SUSTAIN THE CHANGE

In this phase, implementation and sustaining the change is mentioned in the original model of digital transformation [172]. However, as we focus more on the human aspect in sustaining the change, smaller steps are broken down for exploration.

Step 5. Development implementation

This step initiated the insertion of new technology into the legacy system. The brownfield development can be divided into different phases, such as in short-, mid-, and long-term for the full-scope solution [20]. This approach may enable the company with a flexible time frame for the project. A starting point, the chosen technology can be applied on one specific machine or a group of equipment as in Ref. [90], or on a laboratory environment [76] before being implemented into the production line, to avoid any interruption it may cause. The approach of implementing smaller projects after training in a learning factory is endorsed in Ref. [15] to ensure the field team has efficient support from experts and build their expertise, memorable understanding of retrofitting solution. The linking between equipment of new and old machines is mentioned in Ref. [58]. The implementation ended with the assessment or any needed adjustment for the deployed modules.

Step 6. System integration

After the development in the previous step, the established automation can be further integrated into the system, as we considered this step the system integration. At this time, the system connectivity is fully established, with the data is available in the storage and platform. The further elaboration of DT based on these data can act upon the legacy system as a tracking simulator [129]. At the end of this step, the retrofitted system is ready to be documented. Taking into consideration that there might be a lack of technical documents in the legacy system [98], the new system documentation should not be overlooked as it is a crucial stage in the development and a requirement for the utilization in the next step [99].

Step 7. Utilization and Improvement

After the full integration of the retrofitted system, managerial purposes can be applied to it as the last step in the project. To facilitate the successful utilization of the retrofitted system, the existence, modification as well as the goal of using it need to be communicated throughout the whole facility [99]. This action ensures all stakeholders understand their benefits and responsibilities in their work.

The first purpose is enhancing the utilization of the retrofitted system: making data-driven decisions based on the existing data. There are several operational KPIs such as improving productivity and safety [20], or improving safety and maintenance performance [54], dependent on the type of industry. Process variation can be controlled with early warning [58], to avoid the further negative outcome of breakdowns. With the help of the DT, a strategic set of KPIs can help the firm self-optimization along with its operation, as demonstrated in the Ref. [154].

The second purpose is deploying continuous improvement - kaizen activities - based on the historical data. These activities are human-centered, with the life-long-learning attitude, now it is easier with the available data and visualization. By working in the connected retrofitted system, the operators can be well aware of the system, the process, product quality, and the influence of human workers on the system. This human-centric approach is a core principle in the I5.0 initiatives [24]. It can be expected that the way businesses and people interact will be changed radically, as the possibilities of exploiting data-driven decision-making for system and processes optimization are available. The deeper digitization can bring even more benefits later [14]. This last step of the project can be considered the transition into daily operational activities. The technology and knowledge are fully fused into the system and its human workforce.

However, the skills gap of the workforce is one of the main barriers for enterprises to maintain and benefit from the developed brownfield [13]. The human factor required more attention to prepare for the next I5.0, as engineering education should be shifted toward more sustainable aspects such as Life-Long-Learning, human-centric design, and human-machine interaction experience [185]. This initiative should prepare the future workforce before the manufacturing facility entrance.

VI. RECOMMENDATIONS

At the core of the synthesis is the trend of brownfield development for I4.0 application, and now turning into the I5.0. In this research, extensive systematic searches are performed to get the overall impression from previous retrofitting projects of what they have done, their achievements, obstacles, and how they have been resolved. Our research questions have been answered detailed:

- *What type of industrial context in which the improvement have been done?*
  Many industries adopt the retrofitting approach [36], and each of them faces different problems integrating legacy equipment into the I4.0 environment. However, we believe that there are enormous options that are available, take into consideration that the managers, operators, and IT department should work together to exchange their knowledge [20], then the solution can be shaped.
- *What are IoT-based technologies have been used? What are the IoT layers in that the technologies were deployed?*
  It can be seen that the I4.0 technology nowadays is available for every on- and off-the-shelf option. The retrofitting work can be done in every IoT layer, with the sensors and actuators deployment, connectivity enhancement, data management. Our synthesis can refer to someone seeking a solution in a similar industrial context to their own.
- *What are manufacturing operation management improvements can be applied given the fact that the I4.0 technologies are ready?*
  Eventually, operation efficiency is an essential aspect after retrofitting a legacy system. We have summarized several management philosophies that can be applied, aiming at sustainable aspects of I5.0. Managers can comprehend what is offered once their digitization is finished.
- *What are the recommendation and future trends of brownfield development that should be concerned?*
  The ultimate goal of brownfield development is the readiness of KPIs, which give insight into the system operation in real-time [97]. We mentioned it in the last step of the proposed framework, which is a transition toward daily operation. Additionally, the emphasis on the human worker is still under the development of the Operator 4.0 concept. In the beginning phase of I5.0, it may require more attention. The future human workforce may have an early experience in terms of engineering education [185]. To prepare for the I5.0, we connected the retrofitted developments that can be stepping stones for further achievement.

According to the synthesis, some recommendations can be drawn based on the literature. The following paragraphs suggest a practical application of retrofitting-based development of the brownfield I4.0 and I5.0 solutions.

Firstly, retrofitting-based development should follow a comprehensive, organizational approach that covers every operational dimension to ensure a fully digital transformation of the business. These dimensions can be realized by adopting a maturity model and the strategy planning mindset in the initial assessment phase. It is crucial to have balanced development in every dimension, as any under-developed field may cause difficulties for further business digital operation and innovation.

Secondly, managerial purposes can only be deployed with a balanced and integrated technical enhancement in every IoT layer. The process and quality management can only be achieved by employing an integrated solution with proper sensors and actuators, effective connection, and additional tools for analysis, decision support. Thus, the retrofitting work should be done at every IoT layer, carefully selecting and target-specific orientation. This recommendation should be kept in mind while considering the technical development for cost-benefit evaluation.

Thirdly, to ensure that the developments are radical and systematic, an organizational comprehensive approach should be taken. A strategic planning model is considered to analyze the business situation and potential in the market. Based on the strategic plan, an overall framework should be sketched to ensure that the project activities are aligned with the long-term vision of the manufacturing firm. By following these guidance, the related personnel for the project can be involved early to elaborate their mindset, and the resources can be allocated efficiently. The suggested framework with the transition phase to daily operation at the end can prepare for a smooth utilization of the system.

Fourthly, the I5.0 focus will be built upon the stepping stones from the existing I4.0 development. Adopting these developments can benefit the next industrial revolution and vice versa; the under-developed operation can hinder further improvement.

VII. CONCLUSION

Brownfield development is fundamental with the existing manufacturing plant in terms of the continuous development of I4.0 and I5.0. This paper presented an extensive systematic review of the significant achievements throughout the previous brownfield development by retrofitting projects. The retrofitting approach can be a reasonable initiative for manufacturing plants with legacy machinery. This option does not require intensive capital investment, and any significant annual maintenance fee for the old machines becomes automated. On the one hand, several operational purposes such as increasing machine performance, minimizing production downtime, saving product-related cost, energy consumption can be achieved. On the second hand, the new connected IoT-enabled system can be easier to control, prone to human error, provide safety for its workers, be ready to optimize, and result in sustainable production and a short payback period. Thus the investment is fruitful economically.

This paper discusses the technical aspects of a retrofitting project, from the sensors and actuators applied to the connectivity techniques and possible data handling platforms. Based on that, the managerial concepts and purposes that become realistic are mentioned, proving the promising application in the production operation decision-making process. Several essential aspects of the retrofitted system are summarized, along with the existing problems and suggested solutions. Industrial managers can use this categorization as a reference to make the relevant decision on technical choices retrofitting their legacy system. To guarantee a comprehensive organizational scheme is developed, a strategic planning model is proposed to help the managers be aware of their potential with retrofitting for I5.0, which utilizes the same approach to I4.0 transformation but takes into consideration the forthcoming I5.0 vision and objectives. Once the managers decide to pursue the development, they can develop their implementation framework based on similar retrofitting projects collected from the literature. Consequently, a benchmark framework is given to guide the interested decision-makers in transforming their legacy manufacturing systems step by step.

The main suggestion of this research is the use of the I4.0 maturity model for the operational assessment of the firm before the development project. The measure of every dimension is critical for the development and strategy planning. The balanced improvement in these fields is an essential factor for sustainable growth for the firm. It can be seen from the retrofitting projects that smart products and data-driven services did not gain much attention as they should. This problem should be dealt with in future research, as the digitization of a given firm can only be successful and sustainable once the data is permeated throughout its value chain [186].

Considering that the next I5.0 revolution is human-centric, the emphasis on brownfield development for a more worker-friendly and stress-free work environment is still in its infancy. Noticeably, this aspect is one of the fundamental concepts for the current Operator 4.0 initiative. By the synthesis in this paper, we hope to encourage more facility managers and decision-makers to take the first step on their digitization journey so that their legacy system and workforce are ready for further industrial development and innovation.

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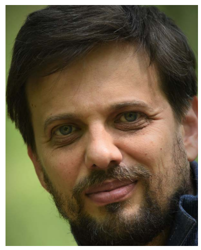
TUAN-ANH TRAN received the bachelor's degree in mechanical engineering in Vietnam, in 2015, and the master's degree in technical management in Hungary, in 2019. He has been working as a Lean Consultant in Vietnamese manufacturing industry and participating in multiple productivity, quality, and safety improvement projects. His current research interest includes related to data analysis in manufacturing operational management, from a systems engineering aspect.

TAMÁS RUPPERT (Member, IEEE) received the bachelor's degrees in mechanical engineering and in engineering information technology, in 2015, the master's degree in mechatronic engineering, in 2016, and the Ph.D. degree, in 2020. He is an Assistant Professor in computer science with the Department of Process Engineering, University of Pannonia. His research interests include process mining algorithms, discrete-event simulators, and supply chain management. His current research interests also include industry 4.0 (discrete event simulators, connected factory, and supply chain management) and big data.

GYÖRGY EIGNER (Senior Member, IEEE) received the B.Sc. degree in mechatronic engineering from the Bánki Donát Faculty of Mechanical and Safety Engineering, Óbuda University, in 2011, the M.Sc. degree in biomedical engineering from the Budapest University of Technology and Economics, in 2013, and the Ph.D. degree from Óbuda University, in 2017. He is the Acting Dean of the John von Neumann Faculty of Informatics and the Head of the Biomatics and Applied Artificial Intelligence Institution, where he is currently an Associate Professor. His main research interests include the application of advanced control methods in physiological relations, biomedical engineering, human-in-the-loop systems, and artificial intelligence base cybermedical systems. Having published more than 100 scientific works on these topics, his H-index is 7. He is a member of the Board of Governors of the IEEE Systems, Man, and Cybernetics Society, the Co-Chair of the Computational Cybernetics Technical Committee, and the Director of the Robotics Special College of the Óbuda University.



JÁNOS ABONYI (Member, IEEE) received the M.Eng. and Ph.D. degrees in chemical engineering from the University of Pannonia, Hungary, in 1997 and 2000, respectively, and the Habilitation degree in process engineering and the D.Sc. degree from the Hungarian Academy of Sciences, in 2008 and 2011, respectively. From 1999 to 2000, he was employed with the Control Laboratory of the Delft University of Technology, The Netherlands. He is a Full Professor in computer science and chemical engineering with the Department of Process Engineering, University of Pannonia. He has coauthored more than 250 journal articles and chapters in books and has published five research monographs and one Hungarian textbook about data mining. His research interests include complexity, process engineering, quality engineering, data mining, and business process redesign.