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Industry 4.0: a systematic review of legacy manufacturing system digital retrofitting

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Abstract. Industry 4.0 technologies and digitalised processes are essential for implementing smart manufacturing within vertically and horizontally integrated production environments. These technologies offer new ways to generate revenue from data-driven services and enable predictive maintenance based on real-time data analytics. They also provide autonomous manufacturing scheduling and resource allocation facilitated by cloud computing technologies and the industrial Internet of Things (IoT). Although the fourth industrial revolution has been underway for more than a decade, the manufacturing sector is still grappling with the process of upgrading manufacturing systems and processes to Industry 4.0-conforming technologies and standards. Small and medium enterprises (SMEs) in particular, cannot always afford to replace their legacy systems with state-of-the-art machines but must look for financially viable alternatives. One such alternative is retrofitting, whereby old manufacturing systems are upgraded with sensors and IoT components to integrate them into a digital workflows across an enterprise. Unfortunately, to date, the scope and systematic process of legacy system retrofitting, and integration are not well understood and currently represent a large gap in the literature. In this article, the authors present an in-depth systematic review of case studies and available literature on legacy system retrofitting. A total of 32 papers met the selection criteria and were particularly relevant to the topic. Three digital retrofitting approaches are identified and compared. The results include insights common technologies used in retrofitting, hardware and software components typically required, and suitable communication protocols for establishing interoperability across the enterprise. These form an initial basis for a theoretical decision-making framework and associated retrofitting guide tool to be developed.

Keywords: Digital retrofitting / upgrading / Industry 4.0 / manufacturing / machines / systematic review

1 Introduction

Industry 4.0 represents an exciting new stage in the evolution of industry, especially in the manufacturing sector. The term "Industry 4.0" refers to advancements in manufacturing including automation, data exchange, and the creation of smart factories which use Cyber-Physical Systems (CPS), Internet of Things (IoT), and cloud computing [1]. As global systems become increasingly digital, integrated collaborative manufacturing systems are necessary to enable the interoperability between areas of production systems and, to satisfy the differing requirements of end-users [2,3]. Manufacturing firms increasingly rely on data gathering and processing, and the dissemination of that data within an interconnected production system [4,5]. Within Industry 4.0, manufacturing is more efficient, costs are more optimised, and new business models have been introduced [6] which has led to an increase in competitiveness in the marketplace. Industry maintains a significant amount of legacy equipment, which is the backbone of industrial operations. However, legacy equipment can prevent manufacturers from transitioning to Industry 4.0 and attaining a competitive edge [7].

As a result of the necessity to build up digital connectivity within the production line, companies are faced with a decision; whether to upgrade existing assets or replace them with new ones [8,9]. Replaced machinery can result in positive short-term effects resulting from the digitisation of the production line. However, this choice requires costly and is in conflict with principles of sustainable production [10,11], in that it wastes functional machinery. It has become increasingly attractive and cost-effective to retrofit machinery to solve this problem.

Retrofitting can be defined as the process of introducing changes to traditional machinery to make it more efficient, while simultaneously minimising financial and time costs

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and risks [12,13]. Industrial infrastructure can be automated and can have its lifespan extended by retrofitting machinery with hardware, software, and networking capabilities to gather data for processing and analysis [5,14]. Retrofitting can also contribute to sustainability and overcome heterogeneity within the overall production process [3,15] resulting from the increasing number of heterogeneous devices [2]. Retrofitting facilitates a standardisation of communication protocols, services, and platforms [16] and thus improves the interoperability and connectivity within a collection of machinery. Standardisation, transparency, and information availability critical requirements of smart factories [16,17] can improve all production phases. Integrating IoT components into legacy machines is an essential step in converting them into Industry 4.0 standards. Although retrofitting is considered an attractive solution, small and medium-sized enterprises (SMEs) can face challenges in retrofitting due to the complexity of their prevailing systems and the heterogeneity of protocols and operating systems [18].

SMEs have a lower level of digital maturity, rendering them less capable of overcoming the challenges they face [19]. Compared with large companies, which are making headway in the adoption of smart manufacturing, SMEs often struggle [20]. It is necessary to invest money and human resources to transition to smart manufacturing [21]. For SMEs in particular, retrofitting represents the opportunity to change their manufacturing process strategically and effectively. Smart manufacturing has a profound impact on the ecosystem of the industrial sector. Achieving smart manufacturing requires integration of horizontal and vertical processes. This leads to the creation of new ecosystems in an interconnected environment. While larger companies are more likely to be able to choose whether to integrate vertically or horizontally, SMEs must rely on external suppliers and partners to implement their change to smart manufacturing [22].

In this study, an in-depth systematic literature review was conducted to better understand how digital retrofitting for manufacturing is practiced within the context of industry 4.0 and to systematise the existing body of knowledge in this area. It classified prior studies based on their characteristics, including whether they were theoretical or empirical, the retrofitting approaches studied, and potential applications investigated. A comparative analysis of retrofitting solutions is also included in the paper. The following three research questions were investigated:

- What digital retrofitting options are available for legacy machines?
- What are the advantages and disadvantages of each approach?
- Which technologies are commonly used in digital retrofitting?

The remainder of the paper is arranged as follows: Section 2 provides background information about the topic of legacy machine retrofitting. Section 3 outlines the methodology of the literature review as well as the main review principles. Section 4 presents the result and a rational discussion in terms of research questions. Section 5 provides a conclusion summarising the study's novel contributions, limitations, and avenues for future research.

2 Background

In the past, technological innovations and changes have had a significant impact on industries. There have been several industrial revolutions which have been characterised by such paradigms. In terms of paradigms, there are three: the First Industrial Revolution was characterised by mechanisation, the Second Industrial Revolution was characterised by electricity, and the Third Industrial Revolution was characterised by electronics and automation [1]. Data science and advanced computing are key drivers of the Industry 4.0 paradigm. In contrast to previous industrial revolutions, the most crucial difference between Industry 4.0 is the elimination of humans from the manufacturing process. A previous industrial revolution led to a reduction in the human's role in production, but preserved his important role in the production process. However, a new industrial revolution will eliminate humans from the production system [23].

Smart factories incorporate flexible production systems with interconnected processes and operations through CPS and cutting-edge technologies [24]. These systems are auto-optimising and can adapt to and learn from new conditions in real-time, so that production processes can be managed autonomously [25]. Smart manufacturing is related to digital manufacturing. In short, it refers to a set of manufacturing procedures involving using data and digital technologies to manage and supervise manufacturing activities [24,26]. As a result, advanced digital technologies enable people to gain better insight into manufacturing processes. This new level of information allows manufacturing processes to be enhanced and improved, allows fast diagnosis of problems and faults, to overcome challenges in a relatively short period of time by turning data into actionable information [27]. Several studies have identified this approach as a new way of lean manufacturing, which can be used to drive improvements and provide opportunities to increase efficiency and flexibility [24,28]. Industry 4.0 technologies can provide the manufacturing industry with opportunities to optimise its processes, asset performance, customer experience, and workforce engagement [29]. Moreover, productivity and efficiency may be improved, both of which are conducive to reducing costs and increasing revenue. Enhances manufacturing resilience and flexibility to meet challenges associated with sustainability, maintaining competitiveness, and attracting more workers.

According to Sufian [30] smart factories feature characteristics such as connectedness, optimisation transparency, proactiveness, and agility, as well as their associated benefits, such as asset efficiency, improve quality, lower cost, increase safety, and reach sustainability. This results in enhanced labour and resource productivity, as well as greater utilisation of assets due to a reduction in machine downtime, maintenance costs, quality inspections, safety issues and time to market. As a result, SMEs will gain competitive benefits of improved costs, quality, time, flexibility, optimised productivity, real-time diagnosis and prognosis, computing performance, and integration [6,31–33]. Implementing big data analytics techniques could result in a 15–20% increase in returns on

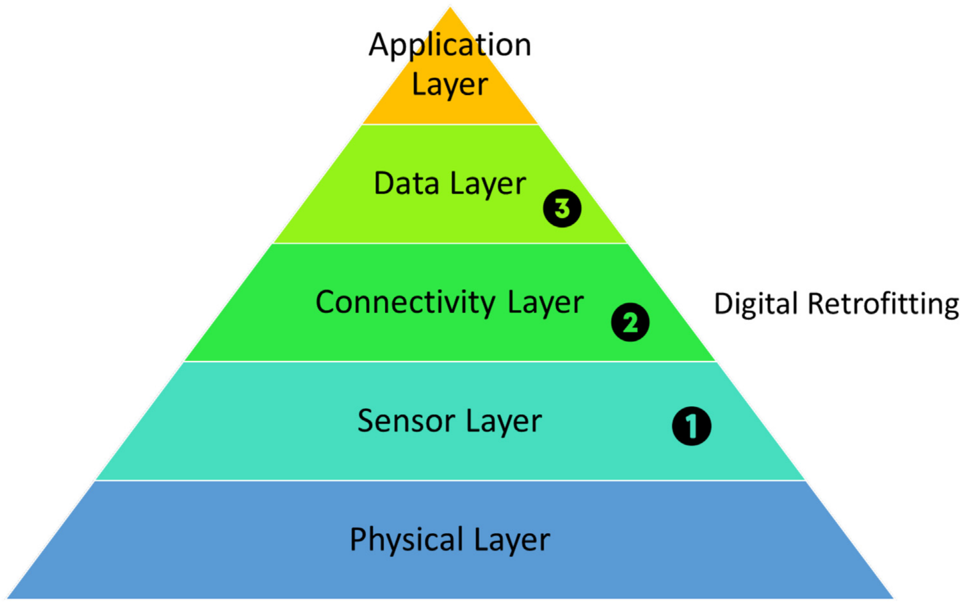

Fig. 1. The five-level model for retrofitting.

investment for industries [34]. According to McKinsey report [35] factories' digitalisation can increase productivity by up to 5%, reduce the cost of quality and maintenance by up to 20% and 40%, respectively.

In a study by Rohmann et al. [36] nine components of Industry 4.0 were described (IIoT, autonomous robotics, simulation, horizontal/vertical integration, cloud computing, cybersecurity, additive manufacturing, augmented reality, Big Data, and analytics) and their potential impact on future industrial production. Kampe [37] reviewed eight industry 4.0 technologies (IoT, Big Data, Artificial Intelligence, Robotics, Additive Manufacturing, Cloud Computing, Simulation/Visualisation, cybersecurity) and outlined their potential impacts. The most recognised technological constituents of Industry 4.0 are big data, IoT, cloud computing, additive manufacturing, and CPS [38]. A number of other key enablers of smart manufacturing exist [39], including the Industrial Internet of Things (IIoT) and Cyber-Physical Production Systems (CPPS).

Industry 4.0 incorporates novel ideas in industrial processes. The use of technologies like the IoT, CPS, cloud computing, and big data in industry has been shown to increase efficiency while also increasing customizability and autonomy [5,18]. These technologies are Industry 4.0's central characteristics and its most crucial features, especially in the areas of manufacturing. The technologies of Industry 4.0 have strong influences on efficiency and productivity in manufacturing [40]. It is these benefits encourage companies to connect production lines, products, and transport systems digitally [3].

Industry 4.0 and smart manufacturing has the potential to increase flexibility and efficiency but also requires interoperability among machines for seamless communication [41]. However, process plants tend to have long lifespans of up to 20 years, meaning that some operational machines may not be capable of communicating with other factory units [42]. This issue can be resolved with digital retrofitting. Digital retrofitting describes the upgrading of legacy machines and their integration into an IoT network to facilitate the acquisition and transmission data [18]. Digital retrofitting differs from traditional retrofitting in that the latter is primarily employed in manufacturing as a way of upgrading mechanical parts with the aim of making it easier to continue using an old machine [43]. On the other hand, digital retrofitting involves fitting machinery with features of Industry 4.0 such as sensors, actuator and connectivity gateways in order to minimising time and financial costs.

Available literature presents numerous technical challenges and possible solutions in relation to the retrofitting of legacy industrial systems. Within these settings, several reference models, including Reference Architecture Model Industrie 4.0 [44] and Industrial Internet Reference Architecture (IIRA) 4.0, have been developed [45]. In most cases, these reference models are organised from discussions of physical to application concerns. This paper follows the five layers concept as presented by [3,46] which conceptualises smart manufacturing in terms of value generation. The five-level model separates the various layers, including the physical, sensor, connectivity, data, and application layers as shown in Figure 1. In digital retrofitting, standard strategies typically pay attention to three layers; sensor, connectivity, and data. These layers must be organised to facilitate the creation of data of value using the existing physical assets.

In the remainder of this section, four subsections are presented as follows: The first subsection discusses sustainability in retrofitting. The second subsection discusses the value generation from retrofitting. Connectivity in retrofitting is covered in the third subsection. As a final point, subsection four discusses the main challenges associated with retrofitting.

2.1 Sustainability in retrofitting

Digital retrofitting is associated with sustainability as it negates the need to buy or build entirely new equipment and reduces a company's waste footprint by reusing existing machines rather than wasting material and money on new machines [47]. It extends the lifetime of the manufacturing equipment and enables its application in a new phase of use, resulting in more economically and environmentally sustainable practices [47].

According to Jaspert et al. [3], retrofitting has four advantages relating to sustainability. The benefits include maintaining legacy systems, utilising existing bases of machinery, extending machine lifecycles, and reducing downtime. There has been much research about how retrofitting allows companies to utilise their existing installed bases of machinery [9] as well as keep their machines operational for several years longer than they initially planned [48,49]. Retrofitting is a way of extending the lifespan of equipment that can no longer receive manufacturer maintenance [50]. According to Straus et al. [51], Stock and Seliger [15], and Kim et al. [16] the implementation of functions such as predictive maintenance can extend the life of production machines, can facilitate new phases of their use, and can reduce unplanned downtime. Digital retrofitting also enables a migration process that is minimally invasive, without affecting the operational system and without causing environmental harm [50,52]. In addition, retrofitting can contribute to human and infrastructural safety in manufacturing by enabling alert functions for early detection of faults.

2.2 Value generation

Even though there is an overlap between the terms value and benefit, many people use them interchangeably [53]. Value denotes how users perceive a service, product, or task's ability to meet their needs, such as performance, quality, or speed while benefits speak to the positive results achieved by a company through transformation [54]. A transformation like digital retrofitting is expected to help create better amounts of tangible and intangible value. Regarding tangible value, digital retrofitting is more relevant at the operational level. At this level, value is experienced by companies, original equipment manufacturers, and machine users. The markets and governments experience value indirectly. The benefits and value of the digital retrofitting process will be apparent in the production and goods. On the other hand, the machine users and other stakeholders will realise intangible benefits in relation to satisfaction and servitisation.

For the company, digital retrofitting introduces value at several levels. For example, when machines are digitally retrofitted, it becomes possible to connect them through IoT devices, which can be achieved by installing new sensors or mining data from the machines' programmable logic controller (PLC) [81]. After managing, clustering, and analysing the data, enterprises involved in manufacturing can generate tangible value from it by applying a predictive approach to maintenance, which could lead to the equipment lasting longer [3]. Added to this, data-driven applications like visualising the status of machines, product monitoring, and quality inspection can support effective decision-making to improve efficiency and reduce costs [17]. These decisions, based on the benefits provided by retrofitting machines, can result in the use of fewer resources and energy and which also adds value to the environment. For the organisation, McKinsey [35] suggests that digitalisation can increase productivity by up to 5%, lower quality costs by up 20%, and maintain costs by up to 40%.

The market and customers can benefit indirectly from digital retrofitting. This is because digital retrofitting provides timely information and machine availability [55]. Within such an environment, companies can respond to change faster and ensure that they have enough products in the market [30]. When companies with digitally retrofitted machines can sustain the products and services required, value is extended to customers. Suppose one considers that customers perceive value as a quotient between benefits and costs [56], and retrofitting can lower costs. In that case, it becomes apparent that the perception of the value of the products among customers will be increased. In terms of the government, retrofitting delivers value by making it easier to monitor industry activities and utilising working time to reduce total energy consumption during peak times and when energy is insufficient to meet demand.

The data-driven services made available by digital retrofitting make the analysis of information and dissemination of knowledge easier for the original equipment manufacturers, which could, in turn, create value for the company [57]. One of the main points where a company extracts value is its employees. The easier analysis of information and dissemination of knowledge could create an environment where employees are better able to do their work, which could increase job satisfaction. Safety is also an important factor in job satisfaction, and digital retrofitting could provide the information required to create a safer environment as it becomes easier to detect faults at an early stage [27], while also giving an idea of the health of machines, ensuring that the risk on unexpected failure is reduced.

Digital retrofitting can help companies gain added value by creating new revenue streams. For instance, the generated data could be sold to third-party developers. Such third-party companies use algorithms and performance models to train data from machines [58,59]. The data-driven application made possible by this knowledge can assist companies in moving from traditional manufacturing to smart manufacturing [17]. Through this, companies can play a role in creating smart cities by integrating facets like smart energy systems, smart transportation, and smart healthcare. Therefore, it is posited that smart manufacturing is crucial for bringing together key features of a smart city, like digital technologies, the environment, health and safety, and sustainability [60]. All these factors play an integral role in improving the quality of life within society and creating value [61].

2.3 Connectivity in retrofitting

A primary challenge of digital retrofitting scenarios is heterogeneity of technology, because early industrial communications networks were designed and developed according to a variety of serial-based interfaces which is no longer the prevailing approach. These communication networks would later become the de facto standards which resulted in a market with many and varying standards [62]. Many companies involved in industrial equipment applied many such protocols. As a result, legacy manufacturing systems are characterised by heterogeneity in communication protocols. Numerous serial-based protocols, including standard RS-422/RS-485, Modbus, and PROFIBUS, remain popular because of the longevity of their systems [63]. As many legacy protocols are incompatible with IoT protocols, this has resulted in a substantial demand for adapters, switches, and gateways.

Legacy systems have necessitated communication protocols to meet industry requirements. Several communication protocols facilitate connectivity and data exchange with legacy systems, such as Open Platform Communications Unified Architecture (OPC-UA), Message Queue Telemetry Transport (MQTT), and MTConnect. The machine tool data captured digitally by machining tools, such as computer numerical control (CNC) machines and their integrated sensors [62], often requires standardisation. The OPC-UA was created by the OPC Foundation to enable Machine to Machine (M2M) communication and industrial automation [64]. The MQTT protocol (developed by IBM) [65] facilitates the transfer of data to multiple clients. The MTConnect is an XML-based, read-only standard protocol that facilitates the gathering of manufacturing data [66]. The Representational State Transfer (RST) architecture with Hypertext Transfer Protocol (HTTP) comprise the system through which most applications that connect to the internet exchange data [67], such as smartphone apps and web browsers. This is another contemporary data protocol which legacy machines must be made compatible with in their data transmission through retrofitting.

2.4 Challenges in retrofitting

In spite of the fact that the fourth industrial revolution has been underway for more than a decade, the manufacturing sector, in particular small and medium-sized enterprises (SMEs), continue to face challenges with regards to upgrading manufacturing systems and adopting Industry 4.0 technologies [68]. Companies must either replace or upgrade legacy assets in order to transition to Industry 4.0. There is no doubt that this is not an easy task as the industry maintains a significant number of legacy assets [55]. Due to this, there are a variety of challenges associated with the adoption of new technologies, both within and outside the organisation; however, a few challenges are more frequently listed in articles as the most significant. In this paper, three key challenges are identified: financial constraints, a lack of knowledge, and the complexity of the new technology. For manufacturing SMEs, the cost of implementing an Industry 4.0 project remains one of the major obstacles to adoption [62]. This is due to the lack of clear mechanisms and awareness of funding schemes [66], the limited availability of funds to support investments and the limited amount of data available to demonstrate the return on investment [69]. Financial constraints include the cost of new equipment and training staff and lack of demonstration of potential benefits and opportunities [70–72]. Lack of knowledge includes the absence of clear strategies, lack of awareness of Industry 4.0 technologies, as well a lack of knowledge of where to begin and how to apply it [73–75]. The complexity of Industry 4.0 technologies and the different terminologies that are being used, the integration and interoperability between legacy operational technology and information technology (IT-OT) and new equipment are still complex [76–78].

Table 1. Search boundaries and keywords.

Search Boundaries	SCOPUS, Compendex, Web of Science, and Google Scholar, Research Gate, Science Direct
Keywords Search	Retrofit* upgrade* update*modern*, digit*, legacy, machine*, equip*, Industry 4.0, manufctur* and factor*

Cybersecurity is a key challenge to enabling connectivity in manufacturing and a significant barrier to adopting Industry 4.0 [24]. In the event that a manufacturing machine is hacked, the production process can be stopped, or may even pose a danger to workers if the machine is manipulated externally [72]. To ensure privacy and security of connected devices over the internet, there are regulations and codes of practice available [79]. In order to build successful connectivity architecture will require the involvement of the IT department in the early design stages in order to ensure secure communications.

The intrinsic disadvantages of SMEs, such as resource scarcity, skill limitation, competency of employees, and managing change, have long been recognised as barriers to adopting I 4.0. It is possible to alleviate some of these obstacles by addressing the internal knowledge gap, developing absorptive capacity, collaborating with academia and other partners, and preparing employees for digitalisation [66,72].

3 Methodology

A systematic review of the literature was conducted with the aim of providing an all-inclusive evaluation of the technologies, methods, applications, and approaches related to retrofitting discussed in academic discourse in recent years. The focus of the review is on articles published between 2015 and 2021 that discuss retrofitting of legacy machines. This time frame is salient in that Industry 4.0 was introduced in 2011 and launched in 2013. Industry 4.0 pioneering technologies were recognised in publications in 2015.Thus, publications related to Industry 4.0 retrofitting before 2015 are less common than after 2015. The literature for this review was gathered from six databases, including Science Direct, Research Gate, Google Scholar, Web of Science, Compendex, and SCOPUS. Other articles were identified using the references of other articles, which is a process called backward and forward searching. As is indicated in Table 1, specific phrases and keywords were used to narrow down the relevant articles: *retrofit**, *upgrad**, *updat**, *modern**, *legacy*, *machin**, *equipment*,

Table 2. Inclusion and exclusion criteria.

	Inclusion	Exclusion
Literature Type	Indexed journals, book chapters, conference proceedings	Non-indexed journals, magazine articles, news articles, industry reports
Language	English	Non-English
Timeline	Between the years 2015 and 2021	Before year 2015, duplication
Study Field	Manufacturing	Building-Civil engineering

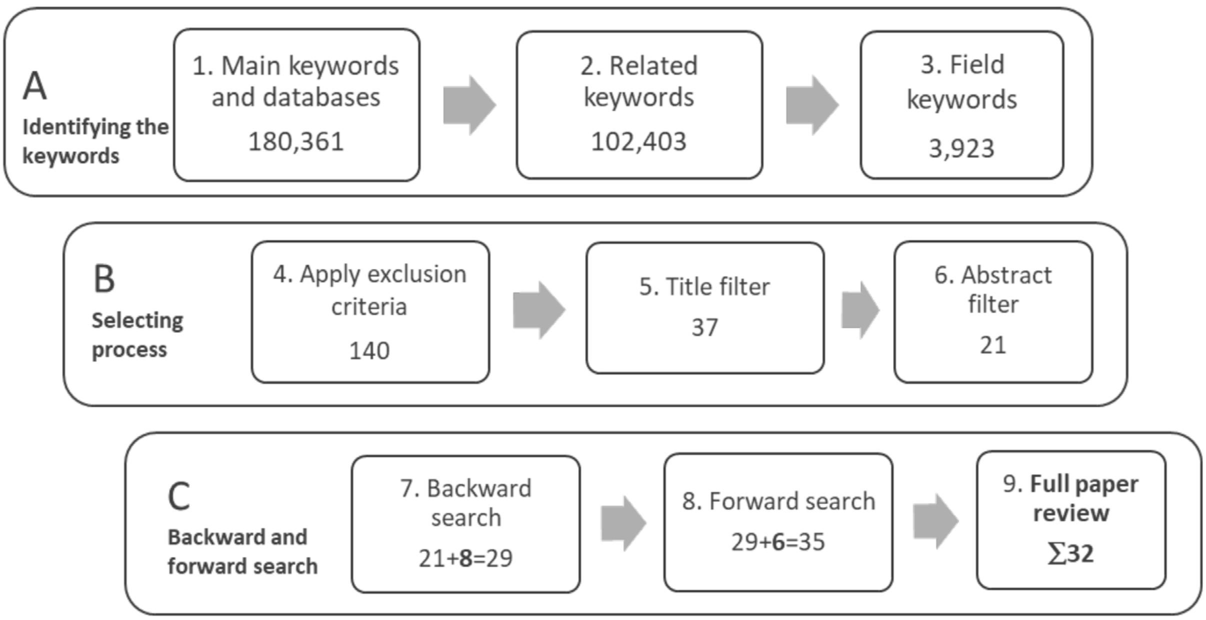

Fig. 2. Three phases of the search process.

Industry 4.0, and *I4.0*. The Boolean logical operators (OR, AND, and NOT) were used to extend or narrow the research scope. Both the inclusion and exclusion criteria were considered in this literature review, as can be seen in Table 2. The exclusion and inclusion of articles were based on four criteria: the field of study, timeline, language, and type of literature. Given that most of the literature is in English, this review is more likely to represent a comprehensive review of the international literature on the subject.

The approaches taken by Suppatvech et al. [80] and Jaspert et al. [3] were followed to search for and select papers. There were three main phases in the process as presented in Figure 2; (A) keyword identification, (B) a selection process, and (C) a backward and forward search.

Each of the three phases has three intermediate phases. For this study, nine steps were taken in order to identify and select relevant papers. In Phase A, the first task involved defining a keyword from which the search string would be derived. Based on the topic of the study, retrofit* was defined as the primary keyword in the search. Using the asterisk ensures that all the forms of the term such as (retrofitted and retrofitting etc) are considered. Four synonyms of retrofitting were identified (upgrd*, updat* modern* and digit*) as primary synonym words (see Fig. 3). From the screening results, it is clear that retrofitting is a significant topic in several fields of research, including material science and civil engineering, which are beyond the scope of the present study. To compensate for this, three keywords, (industry*, factor*, and manufacture*) with the logical operator AND were added to the search string to narrow the scope to this literature review results. Most of the results obtained concerned traditional retrofitting, involving concepts like upgrading the security of machines or retooling of worn-out machine equipment. As a result, the scope was narrowed down further in Step 3 by refining the search string using terms like *internet, Industry 4.0, legacy machin*, Equip** to narrow the search results to digital retrofitting and retrofitting of legacy machines.

Tables 1 and 2 and Figures 2 and 3 provide an overview of the search strings and keywords used in the present study's literature search. In total, the search strings yielded 3923 articles in the initial data collection phase. In the second phase (Phase B, Step 4), a filter of exclusion criteria was applied which removed duplicates, narrowed the search timeline, and the types of literature. In the second step of Phase B (Step 5), the titles were screened primarily based on the frequency of the word retrofit and associated words. Next (in Step 6), the abstracts of the remaining articles were reviewed for relevance to the research topic.

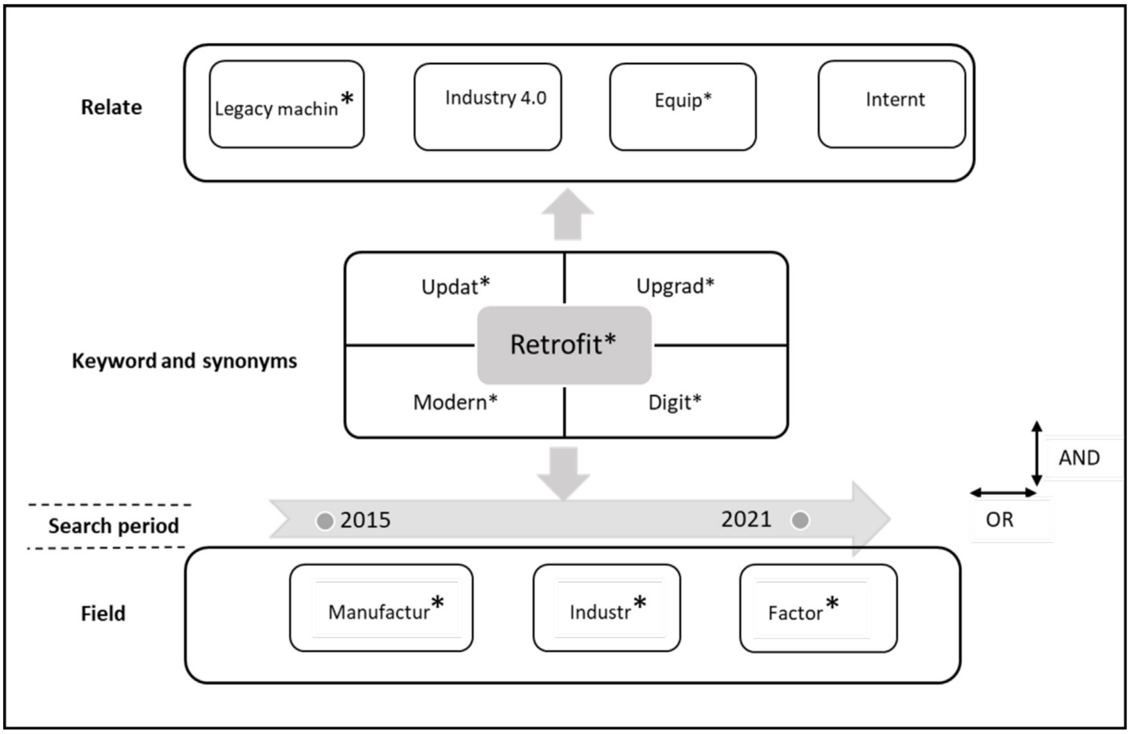

Fig. 3. Selected search keywords.

Any article not relevant to the topic was removed. In the selection phase, 21 papers remained. Finally, in Phase C, the backward and forward searches were applied to consider other pertinent publications not covered by the keywords [81]. This resulted in the addition of eight more papers in the backward search and another six in the forward search. Due to backward and forward searches, some articles not containing the keywords of the current search were included in the results.

In the last step (Step 9), the collection process involved a full-paper review of the papers obtained. Papers were evaluated based on whether they contained information on retrofitting, or a minimum level of detail in relation to retrofitting equipment, or technology connected with the retrofitting of machines. After eliminating the papers that did not meet these criteria, the number of remaining papers was reduced to 32. Table 3 summarises the resulting database. The overview contains information relating to the papers used in the study, including whether the study was theoretical or empirical and the kind of machine studied. To understand the trends which emerge in these publications, descriptive and thematic analyses are presented in the next section.

4 Results and discussion

4.1 Descriptive analysis

In this section, the results of a qualitative analysis of the 32 papers identified in the systematic review are presented and discussed. The papers in the final database were analysed considering the year of publication, research method, types of publications, type of case study, and geographical location of the authors to evaluate the topic from a broad perspective. The results show that in 2015, only one paper was published on the topic of retrofitting of industrial machines. This can be attributed how new the concept of Industry 4.0 was. The term and its associated topics were first launched in 2013. During the years 2016 and 2017, the research gradually increased to 3 and 5 publications during these years respectively. The annual number of publications maintained a peak frequency of 6 papers per year during the period from 2018 to 2020, which represents 56% of all the papers found in this study. In the last year until December 2021 there were 5 publications related to our topic as shown in Figure 4. Growth trends are expected to continue in the coming years as more success stories are reported from industry.

The papers selected for systematic review were primarily from academic journals (53%) and conference proceedings (38%), with the remainder being chapters in edited books (9%). In this study, business reports were not included due to concerns over their credibility and lack of academic rigour, despite being potential sources of knowledge about current developments in digital retrofitting solutions. Conference proceedings were used as a scientifically rigorous alternative sources of current information, because they met the criteria for selection (see Tab. 2).

The systematic study included an analysis to identify which papers presented theoretical studies and which presented empirical studies. A total of 23 publications contained theoretical studies on retrofitting of machines which identified methodologies or general steps to follow for retrofitting. A total of 28 papers (72% of our selected papers) were empirical studies which identified specific solutions or applications (see Tab. 3).

Table 3. Final dataset with 32 articles.

No	Articles	Title	Theoretical study	Empirical study	Case study types		
					CNC machine	Robotic arm	Lab equipment
1.	Stock and Seliger [15]	Opportunities of Sustainable Manufacturing in Industry 4.0	√	√			√
2.	Lins, Guerreiro [5]	A novel methodology for retrofitting CNC machines based on the context of industry 4.0	√		√		
3.	Arjoni, Madani [8]	Manufacture Equipment Retrofit to Allow Usage in the Industry 4.0		√	√	√	√
4.	Ferreira, Albano [82]	A pilot for proactive maintenance in industry 4.0		√	√		
5.	Lins and Oliveira [47]	Cyber-physical production systems retrofitting in context of industry 4.0	√	√		√	
6.	Contreras Pérez, Cano Buitrón [6]	Methodology for the retrofitting of manufacturing resources for migration of SME towards Industry 4.0	√	√	√		
7.	Langmann and Rojas-Pena [83]	A PLC as an Industry 4.0 component		√			√
8.	Vachalek, Bartalsky [84]	The digital twin of an industrial production line within the industry 4.0 concept	√	√			√
9.	Al-Maeeni, Kuhnhen [43]	Smart retrofitting of machine tools in the context of industry 4.0	√	√	√		
10.	Pueo, Santolaria [76]	Design methodology for production systems retrofit in SMEs	√	√	√		
11.	Zambetti, Khan [57]	Enabling servitisation by retrofitting legacy equipment for Industry 4.0 applications: benefits and barriers for OEMs	√	√			√
12.	Guerreiro, Lins [13]	Definition of Smart Retrofitting: First Steps for a Company to Deploy Aspects of Industry 4.0	√	√	√		

Table 3. (continued).

No	Articles	Title	Theoretical study	Empirical study	Case study types		
					CNC machine	Robotic arm	Lab equipment
13.	Di Carlo, Mazzuto [42]	Retrofitting a Process Plant in an Industry 4.0 Perspective for Improving Safety and Maintenance Performance		√			√
14.	Niemeyer, Gehrke [85]	Getting Small Medium Enterprises started on Industry 4.0 using retrofitting solutions		√			√
15.	Lima, Massote [86]	IoT Energy Retrofit and the Connection of Legacy Machines Inside the Industry 4.0 Concept	√	√	√		
16.	Lins, Augusto Rabelo Oliveira [87]	Industry 4.0 Retrofitting	√	√			√
17.	Etz, Brantner [41]	Smart Manufacturing Retrofit for Brownfield Systems	√	√		√	
18.	García, Cano [12]	Digital retrofit: A first step toward the adoption of Industry 4.0 to the manufacturing systems of small and medium-sized enterprises	√		√		
19.	Herwan, Kano [40]	Retrofitting old CNC turning with an accelerometer at a remote location towards Industry 4.0	√	√	√		
20.	Tzou, Fan [55]	Embedded smart box for legacy machines to approach to I4.0 in smart manufacturing	√				√
21.	Garcia-Garza, Ahuett-Garza [88]	A Case about the Upgrade of Manufacturing Equipment for Insertion into an Industry 4.0 Environment	√	√	√		√
22.	Jónasdóttir, Dhanani [89]	Upgrading Legacy Equipment to Industry 4.0 Through a Cyber-Physical Interface	√	√	√		
23.	Kancharla, Bekaert [90]	Augmented Reality Based Machine Monitoring for Legacy Machines: a retrofitting use case		√			√
24.	Tantscher and Mayer [18]	Digital Retrofitting of legacy machines: A holistic procedure model for industrial companies		√	√		

Table 3. (continued).

No	Articles	Title	Theoretical study	Empirical study	Case study types		
					CNC machine	Robotic arm	Lab equipment
25.	Schulz [91]	FDI and the Industrial Internet of Things	√				√
26.	Kostolani, Murín [92]	An effective industrial control approach	√	√			√
27.	Haskamp, Orth [49]	Implementing an OPC UA interface for legacy PLC based automation systems using the Azure cloud: An ICPS-architecture with a retrofitted RFID system	√	√			√
28.	Rupprecht, Trunzer [93]	Concepts for Retrofitting Industrial Programmable Logic Controllers for Industry 4.0 Scenarios	√	√			√
29.	Ferreira, Arif [94]	Retrofitting, open-sourcing, and characterisation of a legacy fused deposition modelling system		√	√		√
30.	Biesinger, Meike [95]	A digital twin for production planning based on cyber-physical systems: A Case Study for a Cyber-Physical System	√	√		√	√
31.	Xing, Liu [96]	Low-Cost Precision Monitoring System of Machine Tools for SMEs	√	√	√		
32.	Zhong, Wang [97]	An IoT-enabled Real-time Machine Status Monitoring Approach for Cloud Manufacturing		√	√	√	

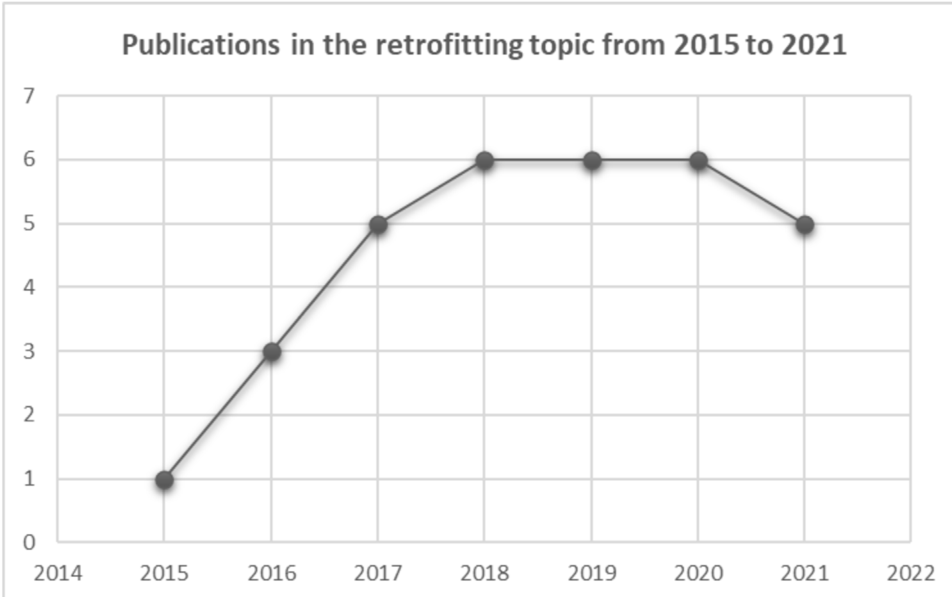

Fig. 4. The timeline of publications.

Care was taken to identify the type of case study and machines being retrofitted in the papers. CNC machines were the most frequently studied machines (50% of the total papers analysed). The second most frequent machine type studied was industrial robotic arms (16% of the total papers analysed). 53% of the studies used lab-scale equipment which could simulate the retrofitting process and validate the approach taken, but these studies could not simulate the actual industrial environment.

The selected papers were published in 12 separate journals and 5 separate proceedings, showing a wide variety of perspectives. The top two sources of the reviewed literature were Procedia CIRP (16% of the publications) and Procedia manufacturing (10% of publications).

Finally, according to the geographic location of the first author, the interest in digital retrofitting was spread across five continents, including Europe, North and South America, Asia and Australia. Most of the publications were from European countries, representing 60% of the total number of papers. This indicates a strong interest in the topic in Europe, especially in Germany, which comprises 28% of the total publications. This potentially reflects the growing acceptance of digital retrofitting by firms in developed countries due to the significant benefits for sustainability and the prospects for enhancing profitability as well as accelerating industrial growth. Moreover, the concept of Industry 4.0 originated in Germany as a high-tech strategy which aims to computerise manufacturing. North and South America account for the second largest contribution of papers at 28%. Significant interest in the topic comes from Brazil which comprises 16% of the publications. The contribution of other countries including New Zealand, Japan, and Taiwan accounted for 12% of the total number of papers.

4.2 Thematic analysis of the literature search

There has been extensive research on retrofitting. Since 2015, many articles have been published which discuss retrofitting to upgrade systems to Industry 4.0 standards. However, most of these studies focused on general requirements. An extensive literature review shows that these contributions can be split into two main groups: theoretical and practical studies (see Fig. 5).

4.2.1 Theoretical studies on retrofitting

4.2.1.1 Standard

Theoretical and methodological studies provide high-level concepts and general steps to follow when retrofitting machines. However, they lack detailed explanations relating to implementation and concrete steps that can guide practical applications. For instance, studies with high-level reference architectures proposed by Weyrich and Ebert [98] can guide the design of I4.0 systems. Furthermore, Lee et al. [99] establish reference architectures in the Reference Architecture Model Industrie 4.0 (RAMI4.0). The authors provide a unified 5-level architecture as a guideline for implementing a CPS. Likewise, Industrial Internet Reference Architecture (IIRA) aims to increase interoperability, the implementation of technologies, and the improvement of standards [98]. The NAMUR Open Architecture (NOA) aims to access data from the shop floor and make it securely usable for factory and equipment monitoring [100].

These architectures present a high level of abstraction and a large degree of freedom in application. Due of their generality, they fail to articulate concrete realisations and are challenging to apply in practice [101]. Moreover,

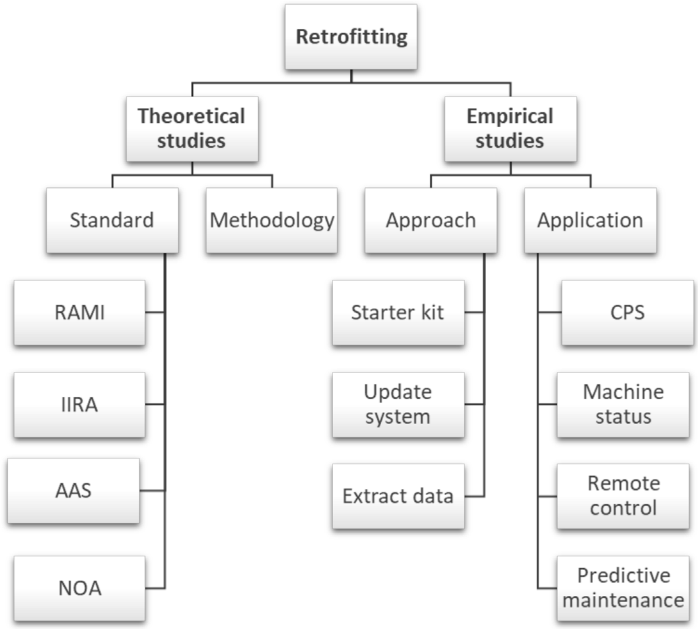

Fig. 5. Thematic analysis of publications.

reference architectures do not concentrate on the retrofitting of systems and their specific requirements. García et al. [12] implement an Asset Administration Shell [102] to retrofit manufacturing resources within the RAMI architecture. AAS is a standard used to describe assets electronically [103].

4.2.1.2 Methods

A study by Niemeyer et al. [85] outlines an educational approach using training modules that lead organisations through the basics of digital transformation to successfully embrace Industry 4.0. Pérez et al. [6] provide a step-by-step procedure for asset migration towards Industry 4.0. Although their work highlights concrete requirements of digital transformation, their focus is on their proposed methodology and not on specific applications. To demonstrate the efficacy of the proposed methodology, the authors used a CNC [104] lathe machine as part of a case study. A similar study was conducted by Pueo et al. [76] who illustrate the general steps with a resource allocation matrix for retrofitting. A gear-rolling tester machine was rebuilt as a case study in their study. However, rebuilding the machine is not a cost-effective solution, and therefore was not reviewed further in this study.

4.2.2 Empirical studies on retrofitting

The field of digital retrofitting in manufacturing has attracted a growing number of academics and practitioners. In general, most articles on this topic have been found to be conceptual rather than empirical.

Empirical research contributes to the development of theories as well as the validation of proposed theories [105]. As opposed to conceptual works, empirical studies provide implementation solutions along with functional requirements. Several papers reviewed in this study present practical approaches to retrofitting that illustrate requirements for retrofitting machinery using low cost and sometimes open-source technology. These studies provide a range of possible solutions for upgrading legacy machinery. However, the studies are generally limited to specific approaches or types of systems and are not applicable to all or most situations. Accordingly, this study provides a comprehensive overview of retrofitting solutions, applications, and technology that have been described in recent publications. The following section presents information on the classification of empirical studies related to retrofitting.

4.3 Classification of empirical studies

In this section, two classifications of published work on retrofitting are presented to systematically organise the reviewed papers in order to address the research questions (see Tab. 4). The first classification scheme is based on the approaches proposed in the literature. The second classification scheme concerns the applications of the machines being retrofitted. Under the first scheme, three categories are identified for retrofitting legacy machines based on interoperability and connectivity between legacy systems and the new technology. These are:
–Group 1: Starter kit solutions.
–Group 2: Embedded Streaming Gateway.
–Group 3: IoT Hardware based Solutions.

The first approach (i.e., starter kits) is implemented without connectivity and interoperability with legacy systems. In the second approach, the software of programmable logic controllers (PLCs) is updated to enable connectivity. The third approach involves adding hardware components to achieve full integration between operational technology and information technology (OT-IT) and enables interoperability and connectivity with legacy systems. In

Table 4. Retrofitting approaches and applications from empirical studies.

Author	Retrofitting approach			Retrofitting applications			
	Starter kit	Embedded gateway	IoT hardware	CPS	Machine status	Remotely control	Predictive maintenance
Stock and Seliger [15]	√			√	√		
Lins, Guerreiro [5]			√		√		
Arjoni, Madani [8]			√	√	√		
Ferreira, Albano [82]		√		√	√		√
Lins and Oliveira [47]		√		√		√	
Contreras Pérez, Cano Buitrón [6]			√	√		√	
Langmann and Rojas-Pena [83]			√	√			
Vachalek, Bartalsky [84]		√		√	√		√
Al-Maeeni, Kuhnhen [43]			√	√			
Pueo, Santolaria [76]		√			√		
Zambetti, Khan [57]		√			√		√
Guerreiro, Lins [13]			√		√		√
Di Carlo, Mazzuto [42]			√	√			√
Niemeyer, Gehrke [85]	√			√		√	
Lima, Massote [86]			√		√	√	√
Lins, Augusto Rabelo Oliveira [87]			√	√	√	√	
Etz, Brantner [41]			√	√		√	
García, Cano [12]			√	√		√	
Herwan, Kano [40]		√			√		√
Tzou, Fan [55]	√				√	√	√
Garcia-Garza, Ahuett-Garza [88]	√				√		√
Jónasdóttir, Dhanani [89]			√	√		√	
Kancharla, Bekaert [90]			√		√		
Tantscher and Mayer [18]			√		√		
Schulz [91]		√			√		
Kostolani, Murín [92]			√	√	√	√	
Haskamp, Orth [49]			√	√	√		
Rupprecht, Trunzer [93]			√		√		√
Ferreira, Arif [94]			√			√	
Biesinger, Meike [95]		√		√	√		
Xing, Liu [96]			√		√		√
Zhong, Wang [97]			√		√	√	√
Total	4	8	20	17	22	12	12

terms of the objectives anticipated from retrofitting, four potential targets were identified: developing cyber-physical systems, machine status sharing, remote control of machines, and predictive maintenance. The following sections discuss each of the three solutions in detail.

4.3.1 Starter kit solutions

Starter kit solutions (also known as sensor kit solutions) provide a cost-effective, easy, and quick way to retrofit machines because direct connectivity with a legacy system is not attempted in these systems. Instead, the connectivity set is offered by a third-party vendor in the form of a fully integrated package of sensors, connectivity software, and hardware, as well as a data analytics platform [57]. The results of our study show that only 12.5% of total papers used starter kits as a digital retrofitting solution, which is the lowest percentage of the three.

This type of solution collects data to show the status of machines and contributes to measuring the overall equipment effectiveness (OEE), its performance, and to perform machine data analysis [85]. As mentioned, this approach does not directly connect the legacy equipment to the IoT network as the data can be processed in a stand-alone manner. However, data from the machine can be integrated into an existing application or platform. The starter kit solutions are therefore useful for companies wanting to try a new technology without requiring expertise in the new technology. It can also be implemented without disrupting current systems or changing existing components. There are many studies that adopt this type of solution to work toward smart manufacturing. Fan and Chang [55] describe how starter kits can detect machine operating status, calculate machine availability, and can measure power consumption. A similar study conducted by Niemeyer et al. [85] shows the potential to measure and obtain machine data in a short period of time. García-Garza et al. [88] describe an upgrade kit to collect data from the shopfloor and share it in real time to help facilitate decision-making.

It is important to mention that although the sensor kit approach provides companies with the convenience of sharing data about machinery without modifying the machine itself, it has some limitations regarding the power of collected data because it is not generated by the actual machine but rather by mounted sensors.

4.3.2 Embedded streaming gateway

These solutions enable connectivity of the machine with the IoT network by updating the machine's software without adding new IoT hardware. This approach is also known as an embedded system update solution. Given that this approach does not require any additional hardware, it reduces installation time and hardware maintenance costs. However, this type of solution is only achievable if the PLC has sufficient processing power to apply the protocol transformation tasks without affecting the original control functions [93]. Although this solution involves short downtime for updating, it could be risky if the system does not have a strong computing processor to support control and connectivity. Some embedded solutions modify the original PLC control code like the approach presented by Langmann and Rojas-Pena [83]. They describe an adapter executed as a function block directly in the PLC code. This approach can be dangerous as it affects the primary functioning of the PLC which controls the system and alterations may result in failure to generate data. Authors like Rupprecht et al. [93] consider the addition of PLC code as a significant issue to safety and reliability. Therefore, this modification in PLC code is not explored further in this study.

Another example of this approach is accomplished by Jiang et al. [106]. They use an embedded Linux system as a smart gateway to run and convert the code before publishing it. Haskamp et al. [49], on the other hand, integrate Siemen's legacy PLCs directly into cloud environments through data adapters running on a PC which converts Siemen's S7 protocol to an OPC UA protocol. According to our results, the percentage of papers that adopt this approach is 25% of all papers. This solution provides a direct connection without an IoT gateway however, it suits modern machines with good computing processes and could be risky.

4.3.3 IoT hardware-based solutions

This type of solution uses interoperability and connectivity with legacy systems through the addition of IoT hardware. This is the most common approach to retrofitting because it extracts original data from legacy machinery and allows the use of new sensors to generate meaningful data. This approach, associated with heterogeneous protocols, uses data which requires interconnection and interoperability between legacy systems and new technology [83,107]. This integration between legacy and new technology is generally challenging.

Several studies covered in the literature review use this approach to upgrade legacy machinery to align it with Industry 4.0 standards. For example, Kostolani et al. [92] carried out a specific implementation using an industrial gateway called Siemen's Simatic IoT 2040 to collect, transform, and process data and to enable remote control of machinery. A similar study by Lima et al. [86] conducted on CNC machinery used IoT devices such as energy sensors, switches, and gateways to monitor energy data in real-time. Givehchi et al. [2] proposed an interoperability layer that accesses field-level data through a commercial gateway called the Raspberry Pi.

Most of the papers shortlisted for review in the literature review (62.5%) used this approach. This was the most common approach for digital retrofitting, complemented with IoT hardware to extract data and achieve full OT-IT integration. This solution group provides robust data that can be collected from legacy machines and new sensors. However, it is more complex to implement due to the heterogeneity of protocols governing networks and data.

4.3.4 Comparison of retrofitting solutions

In Table 5, ten essential factors are compared to evaluate the primary retrofitting solutions. These factors are divided into challenges and applications for retrofitting. The

Table 5. A comparison of various factors among retrofitting solutions.

Retrofitting solutions for legacy machines			
Evaluation factors	Starter kit	Embedded gateway	IoT hardware
IoT hardware	Required	Not required	Required
Interconnectivity and interoperability	○	◐	●
Homogeneity	●	◐	○
Risk	○	●	◐
Time to install	○	◐	●
Power of data	◐	◐	●
Complexity	○	◐	●
Evaluation of potential applications for each approach			
Application/ Approach	Starter Kit	Embedded Gateway	IoT hardware
Show machine status	●	●	●
Predictive maintenance	◐	●	●
Remote control	○	◐	●

challenges include the need to add IoT hardware (such as a gateway or sensors), the level of interconnectivity and interoperability with legacy systems, the level of homogeneity in protocols and data, the level of risk regarding affecting the original operating system, the period of time for installation, the power of the data (whether it is produced by the original operating system or from installed sensors), and finally, the level of complexity (in terms of programming and coding). The applications include the capability to perform predictive maintenance, the capability to track machine status, and the capability to monitor machines remotely (the symbol in Tab. 5 is explained in Fig. 6).

Regarding the ability to monitor machines remotely, authors like Rupprecht et al. [93] argue that data access should be unidirectional and the remote-control systems within the industry should be internally managed. For these reasons, remote-controlled systems are more likely to be accepted. Remote-controlled systems also reduce security concerns. For these reasons, cybersecurity for remote control solutions should be implemented strictly.

According to Table 5, it is clear that starter kit solutions are convenient, low risk, and have the ability to share machine status and facilitate predictive maintenance. However, they are not able to generate data from the original operating system. On the other hand, embedded streaming gateway solutions depend on the ability of the computing system and its sensors to enable connectivity and provide meaningful data. This type of solution can share machine status and facilitate predictive maintenance. However, it can be a risky solution as it can compromise the original operating system. The implementation of IoT hardware-based solutions provides meaningful data that enables monitoring of machine status, predictive maintenance, and remote control of the machines. These types of solutions require IoT hardware such as gateways and sensors. However, IoT hardware solutions are considered complex solutions due to heterogeneities in protocols, networks, and data between legacy machinery and contemporary technology.

○	**Low level**
◐	**Medium level**
●	**High level**

Fig. 6. Explanation of the symbol in Table 5.

4.4 Different understandings of retrofitting

Retrofitting has a wide variety of applications. The current study identifies four main applications: machine status monitoring, achieving CPS, remote control of the machine and predictive maintenance of the machine. The results of this review show that the highest percentage of the reviewed articles (69%) aim to monitor machine status. This can be considered as the fundamental aim of retrofitting. Achieving CPS was found to be the second most common goal of retrofitting with 53% of the reviewed articles focusing on it. Finally, the aims of predictive maintenance and remote control were both found in 37.5% of the reviewed papers.

Different authors provide different definitions of retrofitting based on the objectives of their studies. For instance, Lucke et al. [108] define retrofitting as a method of enhancing existing machinery in order to gather information about its status. Lins and Oliveira [47] on the other hand, describe retrofitting as the transformation of industrial equipment into a cyber-physical production system (CPPS). Others like Jónasdóttir et al. [89] explain that retrofitting can enable remote control of machinery. Straus et al. [51] and others demonstrate the concept of predictive maintenance by retrofitting legacy machines and analysing sensor data. Others survey the industry and suggest that the integration of new technologies has the potential to drive sustainable manufacturing [15,109].

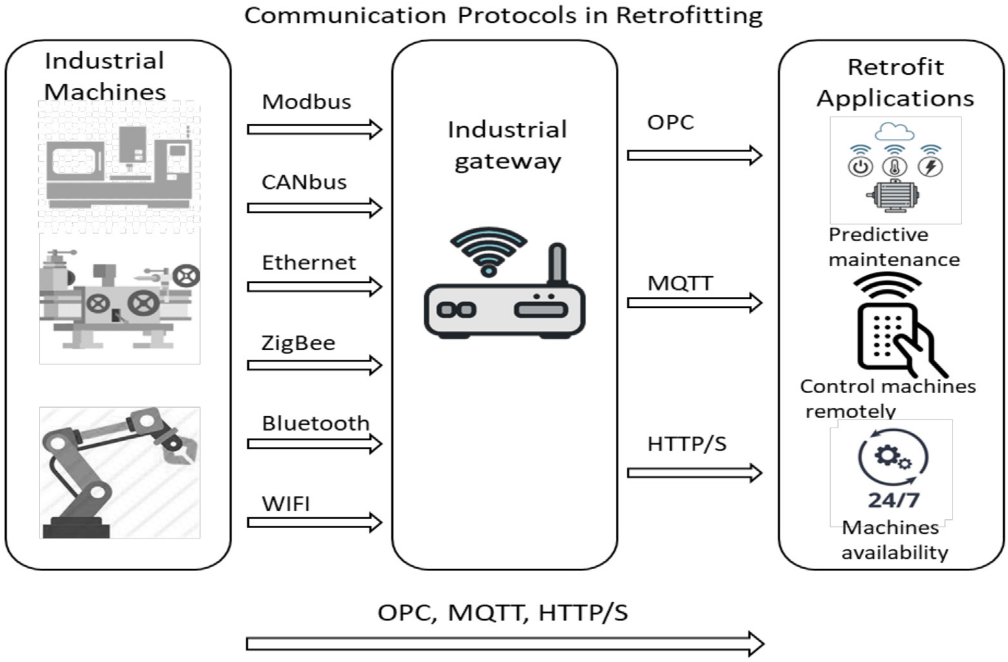

Fig. 7. Communication protocols in digital retrofitting.

Industry still lacks a uniform understanding of retrofitting due to the wide variation in retrofitting objectives and applications. For example, the concept of CPS is still ambiguous in the context of retrofitting. Some authors like Arjoni et al. [8] and Biesinger et al. [95] argue that CPS can be achieved through the real-time sharing of machine status. By contrast, others such as Lins et al. [87] and Lima [86] state that real-time data sharing and remote control of machinery is needed in order to achieve CPS.

4.5 Communication protocols in retrofitting

Of the literature reviewed, 28 papers mention the type of communication protocols used in retrofitting of machines. These were grouped into two categories. The first group contained legacy protocols, including serial protocols, such as Modbus, TCP, and Canbus, and next generation protocols, such as Ethernet. The second group contained modern protocols that support IoT, such as OPC and MQTT. The digital retrofitting process involves converting legacy protocols to new ones to meet communication protocol standards and enable connectivity. According to the results reported in literature, Modbus is most commonly used in when retrofitting legacy machines (39%), followed by Ethernet at a percentage of (36%). Regarding modern protocols, most papers (75%) utilised OPC as an open protocol to facilitate digital retrofitting. The second most common modern protocol was MQTT, which was used in 25% of the papers reviewed. Finally, only 14% of papers used other protocols such as AMQP, RabbitMQ, REST, and SSH.

Most papers dealing with communication networks describe at least one type of communication network, including Wi-Fi, Bluetooth, ZigBee, RFID, and cellular. Among these papers, 81% report the use of WIFI, making it the most popular communication network followed by Bluetooth (72%). This could be due to its flexibility and mobility in addition to its low cost and ease of implementation [110]. Furthermore, ZigBee and RFID accounted for 15% each, followed by cellular, which accounted for only 8% of reviewed papers. As a result of our analysis, two nodes of communication in retrofitting were identified (see Fig. 7). The first node is between the legacy machines and the gateway, the second one is between the gateway and the end-user applications.

4.6 IoT devices used in retrofitting

Regarding the use of IoT devices (such as sensors, actuators, and gateways) the majority of reviewed papers (88%) state that gateways are the primary hardware used as part of digital retrofitting solutions. The use of sensors, actuators, and other IoT devices was discussed in 59% of the papers. This indicates that digital retrofitting requires the incorporation of new technology and Internet of things devices with legacy machines. In terms of sensors, four types have reportedly been employed in retrofitting, namely vibration, energy, temperature, and acceleration sensors. Of these, vibration and temperature sensors were the most commonly used sensor for retrofitting (with reported use in 22% of the papers). Sensors can be used to provide data on machine health, to enhance product quality, or to perform predictive maintenance. Energy and acceleration sensors were the second most common sensors, with reported use in 13% of the papers. In some studies, microphones and pressure liquid sensors were employed to enhance the quality of products. Furthermore, actuators were used widely in digital retrofitting, and were discussed in 31% of the reviewed papers. Two different types of gateways were reported in the literature. These include industrial gateways designed for industrial applications, and commercial gateways like Raspberry Pi and Arduino designed for commercial purposes. The percentage of papers that used industrial or commercial gateways was the same, with 44% for each. In retrofitting, gateways play an essential role in enabling connectivity, converting protocols, and sometimes in performing edge computing.

4.7 Miscellaneous topics related to digital retrofitting

4.7.1 Related technological aspects

From the literature review, four important areas that are associated with digital retrofitting were identified and are discussed in this section. These are data integration, machine operating systems, programming languages, and cyber security technology. Results of the literature review indicate that most studies (34%) use OPC to integrate data, regardless of whether the data is integrated by hardware or through web-based software. Some studies (9%) use the Node-Red platform, as it is a free and open-source tool for integrating IoT hardware devices. Applications can be created quickly using this system, especially those that trigger on a specific event, such as IoT applications. The Node-RED platform provides engineers and technicians with powerful and flexible tools for creating and configuring real-time applications. It enables developers to wire up input, output, and processing nodes to create data processing flows, to control electronics or to send alerts [111]. In terms of operating systems, both Windows and Linux (22% and 15% respectively) were used for retrofitting applications in the literature. In terms of programming languages used in digital retrofitting, the three most commonly used were Python 15%, Java 15%, and C++12%.

Concerning cybersecurity, very few studies focused on this topic, with only 12% of papers discussing secure communication. Authentication and encryption frameworks using secured protocols such as OPC and MQTT were discussed by Haskamp et al. [49] and Tzou et al. [55]. Transport Layer Security (TLS) or Secure Sockets Layer (SSL) certificates were discussed by Ferreira et al. [82].

4.7.2 Other requirements

The growth in digitalisation, automation, and Industry 4.0 technologies have led workers in manufacturing to rethink routine tasks and devote more time to high-value tasks such as monitoring datasets for preventative maintenance [40,82]. In particular, the main skill gaps are associated with digital skills, using technology, and managing it, especially for ageing workers [112]. Manufacturing enterprises must be prepared to support this development by ensuring that their existing workforce has the required level of digital skills as well as other soft skills such as problem-solving, creativity, and critical thinking. It is important to help existing employees become familiar with new technologies as well as recruiting those who are already proficient in digital and technical skills. In order to accelerate the adoption of Industry 4.0 technologies, it is essential that the company has access to technical expertise. This can be accomplished by outsourcing specialists, collaborating with technology providers, or forming partnerships with external organisations that can provide access to knowledge transfer, skills acquisition, and talent recruitment, including academic institutes, digital catapults, and innovation hubs [30].

Governments can play the most important role in the digitalisation of SMEs under Industry 4.0. In particular, governments can ease the initial digital transition steps, including the adoption decision phase. A supporting role for government also includes addressing the infrastructure gap, the financial gap by providing SMEs. with tangible incentives for digital investments, and the digitalisation policy gap by enforcing supportive cyber laws and other laws that encourage digitalisation [64].

Due to the fact that digital transformation is associated with change, resistance should be expected since people often resist procedures that aren't part of the norm. A successful transition into a smart factory requires understanding and accepting change and managing it effectively within the organisation [24]. To be successful, manufacturing SMEs are required to gain the support of the entire organisation, win stakeholder agreements, and establish effective communication channels. Moreover, addressing concerns such as (fear of the unknown, fear of change, no job security, and trustworthiness in technology) and building cross-functional teams in order to prepare for and implement change [28].

4.7.3 Implementation

Adopting Industry 4.0 is a complex process involving integrating various technologies and developing technical-functional principles. However, digitalisation under Industry 4.0 is also scalable, meaning that SMEs can begin their Industry 4.0 transition through a limited adoption and implementation of essential digital technologies. At the same time, SMEs can take advantage of these technologies to improve their operations at a reduced cost. As well as addressing weaknesses in internal capabilities, companies may also seek and leverage external support and incentives. This will enable SMEs to improve their digitalisation maturity, allowing them to capitalise on the complementarities in Industry 4.0 technologies to push digitalisation to its full potential [64].

According to Sufian [24] a six-stage implementation methodology lays out the theoretical and practical frameworks for implementing Industry 4.0, specifically in manufacturing. The first stage of the adoption journey is the strategy stage. Implementation strategies should be supported by the top management team. The second stage focuses on connectivity, which identifies options to build the infrastructure for connectivity. Integration is the third stage, which discusses strategies for integrating information and operational technologies. The fourth and fifth stages are the analytics and artificial intelligence stages, which feature the analytical methods and tools used to transform data into actionable information. Finally, a scale stage outlines various options that can be adopted to scale, optimise, and continue developing the roadmap's different stages.

5 Conclusion

The focus of this paper was on practical studies in refitting that provide insights related to the research questions. The paper identified retrofitting solutions and evaluated them from the perspective of the user so as to get an understanding of the advantages and disadvantages of each solution. Common technologies, including hardware, software, and communication protocols usually employed in digital retrofitting, were also identified in the paper. In this study, retrofitting publications were reviewed with the aim of coming up with a comprehensive overview of digital retrofitting solutions, applications, challenges and related technologies. With regards to solutions, this study identified three basic types of solutions and applications for digital retrofitting as commonly reported by publications while also assessing retrofitting.

An analysis of previous studies shows that these studies pay more attention to specific approaches but do not survey or formulate generalisable ideas. It has been posited in this paper that the decision relating to whether one should upgrade legacy machines is a challenging decision to make. This can be attributed to the fact that there are numerous approaches and objectives in relation to upgrading, which calls for dynamic, strategic decision-making and evaluating different requirements on a case-by-case basis.

It can be concluded that companies in manufacturing need to embrace change, rethink the way they carry out routine tasks, and collaborate with other industries and institutions of learning to enhance their competitiveness. It is noted that when systems are retrofitted, implementing Industry 4.0 technologies becomes, even more cost effective, particularly in instances where budgets for retrofitting are limited.

For industry and academia, this review paper has several benefits in that it clarifies the state of retrofitting. It also helps develop a common conceptual framework. The study's findings can help policymakers plan for infrastructural development by choosing the most suitable approaches when retrofitting for Industry 40. Like all other studies, this review has limitations. For example, its main focus is only on retrofitting practices and technologies, which involve IoT components like sensors, gateways, and applications for gathering data from machines and processing such information. As a further limitation, the study ignores the rebuilding of machines or equipment and focuses on digital retrofitting.

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