Advances in Manufacturing Technology XXXV
M. Shafik and K. Case (Eds.)

doi:10.3233/ATDE220557

Industry 4.0: A Review of Digital Retrofitting Solutions for Legacy Manufacturing Systems

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Abstract. Industry 4.0 technologies and digitalised processes are essential for implementing smart manufacturing within vertically and horizontally integrated industries. These technologies offer new ways to generate revenue from data-driven services and enable predictive maintenance based on real-time data analytics. 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) cannot always afford to replace their legacy systems with state-of-the-art machines. One option available in such cases is known as retrofitting, in which manufacturing systems of past generations are upgraded with sensors and IoT components to integrate them into a digital workflow across the enterprise. Unfortunately, the scope and systematic process of legacy system retrofitting and integration are not yet 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 our selection criteria and were particularly relevant to our topic. The results identify three digital retrofitting solutions.

Keywords. Digital retrofitting; Upgrading; Industry 4.0; Manufacturing; Machines; System.

1. Introduction

Industry 4.0 represents an exciting new stage in the evolution of industry, especially in the manufacturing sector. Manufacturing firms are increasingly relying on data gathering and processing, as well as sharing that data within an interconnected production system [1]. Within Industry 4.0, manufacturing has increased in efficiency, has been optimised for cost, and new business models have been introduced [2] which have 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 prevents manufacturers from transitioning to Industry 4.0 and attaining a competitive edge [3]. As a result of the necessity to build up digital connectivity within the production line, companies are faced with deciding whether to upgrade the existing assets or replace them with new ones [4]. Replacing machinery can result in a positive short-term effect on the digitisation level of the production line.

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However, it requires high investments and clashes with the concept of sustainable production by rendering operational machinery as waste [5]. It has become increasingly attractive and cost-effective to retrofit machinery to solve this problem. Retrofitting can be defined as a process of introducing changes to traditional machinery to make them more efficient, while minimising financial and time costs and risk [6]. Industrial infrastructure can be further automated and can have its lifespan extended by retrofitting it with software and networking capabilities to gather data for processing and analysis [7]. Retrofitting also contributes to overcoming overall heterogeneity in the production process [8]. It has been shown that retrofitting facilitates standardisation of communication protocols, services, and platforms [9]. Even though retrofitting is considered an attractive solution, small and medium-sized enterprises (SMEs) have had difficulty taking steps toward retrofitting due to the complexity of their prevailing systems and the heterogeneity of their protocols and operating systems [10]. Moreover, SMEs have a lower level of digital maturity, rendering them less capable of overcoming the challenges they face [11]. In this article, an in-depth systematic literature review was conducted to provide a comprehensive overview of retrofitting solutions. The following research question was investigated: What digital retrofitting options are available for legacy machines? The remainder of the paper is arranged as follows: Section 2 provides background information. Section 3 outlines the methodology of the literature. Section 4 presents the result and a rational discussion in terms of research questions. In conclusion, section 5 provides a summary of this paper.

2. Background

Industry 4.0 incorporates novel ideas into 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 [10]. Such technologies are Industry 4.0's central characteristics and constitute its most crucial features, especially in manufacturing, and therefore have a strong influence on efficiency and productivity [12]. These benefits motivate companies to have production lines, products, and transport systems connected digitally [13]. Industry 4.0 and smart manufacturing have the potential to increase flexibility and efficiency, but this requires the interoperability and communication among machines to be seamless [14]. Process plants, however, tend to have long lifespans of up to 20 years and some of the available machines today may not have the capabilities to communicate with other factory units [15]. This problem can be targeted with digital retrofitting. Digital retrofitting extends the lifespans of legacy machines by integrating these machines into an IoT network to make it possible to acquire and transfer data [10]. Digital retrofitting differs from traditional retrofitting in that the latter is primarily used in manufacturing as a way of upgrading mechanical parts with the aim of making it easier to continue using an old machine [16]. On the other hand, digital retrofitting involves adding Industry 4.0 features to processes and machines with the lowest time and financial costs possible.

3. Methodology

In this study, a systematic review of the literature was conducted with the aim of providing an all-inclusive assessment of the approaches to retrofitting discussed in academia in the last seven years. The review focussed on empirical studies on retrofitting legacy machines. As indicated in Table 1, the information was gathered from six databases, and specific keywords were used to narrow down the relevant articles. Both the inclusion and exclusion criteria were considered in this literature review, as can be seen in Table 2.

Table 1. Search boundaries and keywords.

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

Table 2. Inclusion and exclusion criteria.

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

The approaches suggested by Suppatvech et al. [17] and Jaspert et al. [13] were followed in the process of searching and selecting the papers. Generally, there are three main phases in the process (see Figure 1): A) Keyword identification, B) Selection process, and C) Conducting backward and forward search. Each of the three phases has three intermediate phases. In Phase A, keywords were identified and defined, and then a search string was derived for use in the review process. Tables 1 and 2 and Figure 1 provide an overview of the search strings and keywords used in the literature search. In phase B, a filter of exclusion criteria was applied. Finally, in Phase C, the backward and forward searches were carried out with the intention to identify other pertinent publications not identified by the keywords [18]. After eliminating the papers that did not meet these criteria, the number of remaining papers was 32.

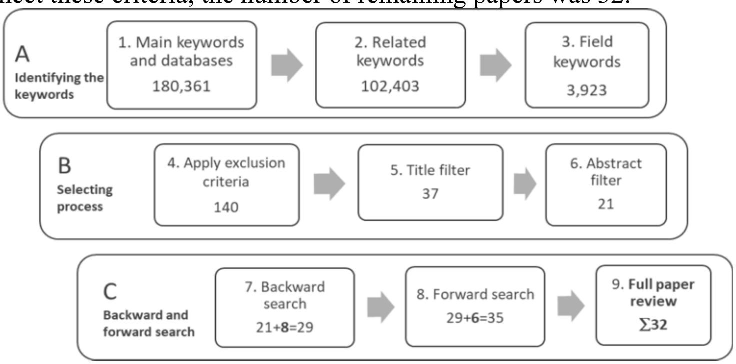

Figure 1. Three phases of the search process.

4. Result1s and Discussion

4.1. Empirical Studies on Retrofitting

The field of digital retrofitting in manufacturing has attracted a growing number of academics and practitioners. Articles on this topic tend to be conceptual rather than empirical. Empirical research contributes to the development of theories as well as the validation of proposed theories [19]. As opposed to conceptual works, empirical studies provide implementable solutions along with functional requirements. Several papers reviewed in this article present practical approaches and illustrate the requirements for retrofitting machinery using low-cost 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 situations. The following section presents information on the classification of empirical studies related to retrofitting.

4.2. Classification of Empirical Studies

In this section, the classification and systematic organization of the reviewed papers is described in order to address the research question. Three categories of solutions were identified for retrofitting legacy machines based on interoperability and connectivity between legacy systems and new technologies. These were: starter kit solutions, embedded streaming gateway solutions, and IoT hardware-based solutions.

4.2.1. Starter Kit Solutions

Starter kit solutions, also known as sensor kit solutions, provide a cost-effective, easy, and quick way to retrofit machines when direct connectivity with a legacy system is not possible. Instead, the connectivity set is deployed by a third-party provider as a complete package of sensors, connectivity software and hardware, and data analytics platform [20]. Our study shows that only 12.5% of total papers used starter kits as a digital retrofitting solution, which is the lowest representation among the three solutions. 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 machine data analysis [21]. 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. Kits can also be implemented without disrupting current systems or changing existing components. Fan and Chang [22] 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. [21] shows the potential of measuring and obtaining machine data in a short period of time. García-Garza et al. [23] describe an upgrade kit that can collect data from the shop floor and share it in real-time to help facilitate decision-making. 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.

4.2.2. Embedded Streaming Gateway Solutions

Embedded streaming gateway solutions enable connectivity of the machine with the IoT network without adding new IoT hardware, by updating the machine's software. This approach is also known as an embedded system update solution. Since 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 of transformation tasks without affecting the original control functions [24].

Although this solution involves short downtimes 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 [25]. These include adapter execution as a function block directly into 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. [24] 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. [26] who use an embedded Linux system as a smart gateway to run and convert the code before publishing it. Haskamp et al. [27] 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 the OPC UA protocol. According to our results, the percentage of papers that adopt this approach is 25%. This solution provides a direct connection without the need for an IoT gateway. It suits modern machines with good computing processes and comes with risk.

4.2.3. IoT Hardware-Based Solutions

This type of solution creates interoperability and connectivity with legacy systems by adding 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 [28]. This integration between legacy and new technology is generally challenging. Several studies reviewed in the current work use this approach to upgrade legacy machinery to align it with Industry 4.0 requirements. For example, Kostolani et al. [29] carried out a specific implementation using an industrial gateway called Siemen's Simatic IoT 2040 to collect, transform, and process data as well as to enable remote control of machinery. A similar study by Lima et al. [30] conducted on CNC machinery used IoT devices such as energy sensors, switches, and gateways to monitor energy data in real-time. Givehchi et al. [31] proposed an interoperability layer that accesses field-level data through a commercial gateway called a Raspberry Pi. Most of the papers shortlisted for review in this article (62.5%) used this approach. This is the most common approach for digital retrofitting; using 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 in protocols governing networks and data.

5. Conclusion

To conclude, retrofitting legacy systems leads to cost-effective implementation of Industry 4.0 technology. However, the complexity of the retrofitting process and prevailing ambiguous understandings of retrofitting are significant barriers to retrofitting, especially when investment budgets are limited. Most studies have focused on particular approaches without surveying multiple approaches and formulating generalisable ideas. This article investigates empirical retrofitting publications to provide a comprehensive view of digital retrofitting solutions. It identifies three fundamental types of solutions for digital retrofitting namely IoT hardware-based solutions, embedded streaming gateway solutions and finally, starter kit solutions. The decision to upgrade legacy systems is challenging due to competing objectives and approaches, which require variable strategic decision making to meet distinct requirements on a case-by-case basis. The findings of this study can assist policymakers to identify appropriate approaches in pursuit of Industry 4.0 standards. The adoption of Industry 4.0 technologies allows organizations to enhance their competitive advantage in both domestic and international markets.

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