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Review

Virtual Assistants in Industry 4.0: A Systematic Literature Review

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Abstract: Information and Communication Technologies are driving the improvement of industrial processes. According to the Industry 4.0 (I4.0) paradigm, digital systems provide real-time information to humans and machines, increasing flexibility and efficiency in production environments. Based on the I4.0 Design Principles concept, Virtual Assistants can play a vital role in processing production data and offer contextualized and real-time information to the workers in the production environment. This systematic review paper explored Virtual Assistant applications in the context of I4.0, discussing the Technical Assistance Design Principle and identifying the characteristics, services, and limitations regarding Virtual Assistant use in the production environments. The results showed that Virtual Assistants offer Physical and Virtual Assistance. Virtual Assistance provides real-time contextualized information mainly for support, while Physical Assistance is oriented toward task execution. Regarding services, the applications include integration with legacy systems and static information treatment. The limitations of the applications incorporate concerns about information security and adapting to noisy and unstable environments. It is possible to assume that the terminology of Virtual Assistants is not standardized and is mentioned as chatbots, robots, and others. Besides the worthy insights of this research, the small number of resulting papers did not allow for generalizations. Future research should focus on broadening the search scope to provide more-significant conclusions and research possibilities with new AI models and services, including the emergent Industry 5.0 concept.

Keywords: Virtual Assistants; Industry 4.0; ambient assisted working; Technical Assistance

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1. Introduction

In the Industry 4.0 (or Industrie 4.0) (I4.0) paradigm adopted by the German government, the industrial processes are improved through Information and Communication Technologies (ICT). One of the main goals of I4.0 is to provide real-time information to humans and machines, making the production process more efficient and flexible [1]. This industrial environment sensing can be achieved by using concepts such as Ambient Assisted Working (AAW) [2], based on the I4.0 Design Principles [3], which defines Technical Assistance as one of the pivotal areas, split into Physical and Virtual Assistance.

Despite its widespread adoption, there is no unified and universally accepted definition of the “Industry 4.0” concept in the literature. In this perspective, the I4.0 Design Principles, which can be defined as Interconnection, Information Transparency, Decentralization of Decisions, and Technical Assistance, based on [3], represent the possibility to systematize knowledge and support professionals in developing appropriate solutions [4,5]. The Technical Assistance principle considers that, in I4.0 intelligent factories, through Virtual and Physical Assistance, the role of design centered on the human operator [6] is to perform functions with higher added value, enabling strategic decision-making and problem-solving with flexibility [3,7].

In this perspective, Virtual Assistance is a method to provide information quickly and efficiently, based on the ability to filter and interpret information from enormous databases and provide suggestions based on that information [3]. Usually, it can be performed by chatbots or Virtual Assistants. A Virtual Assistant (VA) can be defined as a software agent that can perform tasks or services based on commands or questions [8], an abstraction layer that sits on top of services and/or applications and performs actions using these services and app, with implications of fulfilling the user intent [9]. With the increasing use of VAs in other areas of business such as customer relationship and marketing, e.g., Amazon Echo © or Google Assistant ©, the use of this interaction mode is expanding into I4.0.

The development and use of VAs in many contemporary environments, such as finance, health, education, and production, bring significant advantages: full-time availability, multi-language capability, real-time response, inexpensive maintenance, being easy-to-replicate, extensive knowledge capabilities, and services available via text or speech [10]. On the other hand, despite these positive advances, some issues are posed to the wide adoption of VAs, such as user security and privacy, noisy industrial environments, and ethical issues [10,11].

The research on VAs in I4.0 has gained significant relevance due to their growing and extensive adoption in I4.0 settings, where data-driven decisions play a pivotal role in better-informed decision-making. However, the current literature lacks comprehensive and systematic reviews specifically addressing VA applications in the I4.0 domain, as most-existing reviews focus on other domains such as education [12], health [13], and mobility [14]. As a result, the principal contribution of this paper lies in presenting a Systematic Literature Review (SLR) dedicated to exploring VA implementations within the Industry 4.0 domain, as well as considering the I4.0 Technical Assistance Design Principle [3].

In this context, the presented paper, through an SLR, aims to (1) identify the characteristics of the Technical Assistance Design Principle in I4.0 present in the literature, (2) describe the specific services for the I4.0 domain offered by VA solutions, and (3) outline the challenges and limitations for the application of VA in I4.0.

The article is structured as follows: Section 2 presents the theoretical framework, stating the main concepts used in the paper; Section 3 explains the methodology adopted for conducting the research; Section 4 presents the discussion, analysis, and results; Section 5 presents the study conclusions.

2. Background

The Industry 4.0 (I4.0) concept has emerged from the collective and strategic vision of policymakers, researchers, industry representatives, and other stakeholders aiming to foster and promote digitization and interconnectivity in manufacturing industries [1,15–17]. With the adoption of new technologies and concepts such as the Internet of Things (IoT), Artificial Intelligence (AI), and automation, the I4.0 paradigm enables production that is more-efficient and -productive, delivers better quality, allows greater customization, and is increasingly sustainable [18,19].

However, with the implementation of cybernetic systems and those based on distributed and cloud-based systems, there are issues regarding the following fields: economic, where large investments are required to implement these new technologies and systems, it being technological necessary to integrate new technologies with legacy systems, which can be complex and difficult, and scientific: there is a need to advance research, especially in areas such as Big Data and AI, in order to fully realize the potential of I4.0. The implementation of VAs in Information Systems in the manufacturing context presents challenges related to the environment, integration, security, personalization, and real-time [20–22].

Based on the I4.0 paradigm and its characteristics, the Industry 4.0 Design Principles (Figure 1) are as follows [3]:

- Interconnection: the ability to connect machines, devices, and systems to enable seamless communication and data exchange across the entire value chain;
- Decentralized Decisions: the ability to make decisions autonomously based on real-time data and analytics.

- Information Transparency: the ability to capture, store, and analyze data from across the entire production process, enabling greater visibility and control.
- Technical Assistance: the use of advanced technologies such as AI, Augmented Reality (AR), and Virtual Reality (VR) to support workers and optimize production processes.

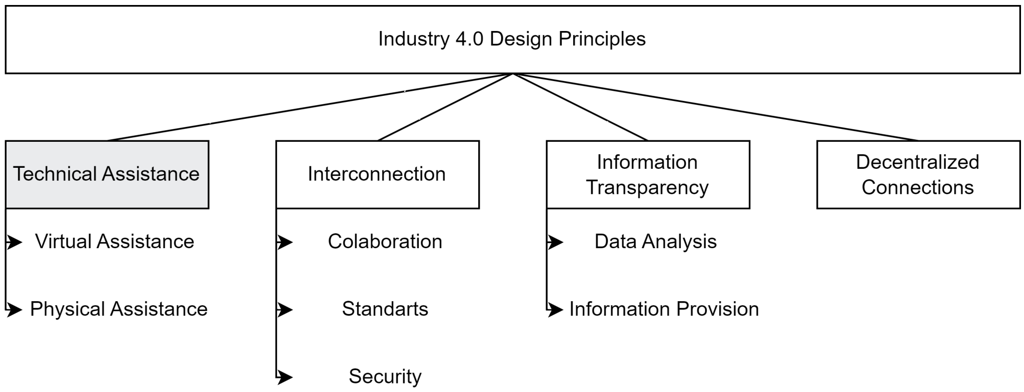

Figure 1. Industry 4.0 Design Principles—based on [3].

The Design Principle of Technical Assistance is based on one of the fundamental principles in smart factories in Industry 4.0, which is that humans transition from machine operators to strategic decision-makers and flexible problem solvers, the so-called Operator 4.0 [23–25]. With the increasing complexity of their work, humans need to be helped by assistance systems. These assistance systems need to be able to perform repetitive or exhaustive tasks and also require smooth and intuitive interaction with humans to achieve the expected effectiveness and success [3]. Usually, this interaction is provided by chatbots or VAs.

A VA can be defined as a software agent that performs actions or services based on commands or questions, which can be activated by voice commands or text-based inputs or can operate proactively based on the analysis of the environment or context [8], an abstraction layer that sits on top of the system and performs actions using the system services and applications. VAs incorporate technologies such as machine learning, speech recognition, question answering, dialogue management, language generation, text-to-speech synthesis, data mining, analysis, inference, and customization [9].

Very similar to VAs are chatbots, computer programs designed to answer questions and engage in conversation with humans via text or voice [26]. As a VA is an abstraction between the user and a specific service or application to fulfill the user's intention and chatbots are a means of interaction between humans and computers [9], it is possible to refer to a chatbot as a fundamental piece of a VA that allows us to input instructions to the assistant in a natural way as if we were assigning a task to a worker.

VAs have fundamental characteristics to deliver a user experience capable of fulfilling the defined objective. Typically, VAs have three main modules: (1) the user interface, which exchanges information with the user, (2) the core, responsible for processing user information, and (3) external data and services, which perform the search for information and task execution. In addition to chatbots, VAs are considered conversational agents because they allow interaction with the user through natural language (text or voice), thus simulating a human conversation. To achieve this characteristic, chatbots and VAs have similar design and implementation features [27] and are applied in areas such as marketing, customer support, education, and agriculture.

The need for increased efficiency in all the fields and for VAs powered by AI and LLMs in computers, tablets, and smartphones is boosting the market, with the global market size of VAs reaching USD 2.48-billion in 2022 and with a projected growth rate of 24.3% over the next decade [28]. Three disruptive digital technological clusters are the center of the newest digital revolution: the IoT, AR/VR/MR, and VAs/chatbots/robots.

These technologies will result in an entirely new user experience level. VAs comprise one of these clusters and, powered by AI and Large Language Models (LLMs), such as chatGPT, could enormously increase the capabilities of a product or service solution. The VA solutions could create experiential value at the social, sensorial, and cognitive levels. In the manufacturing industry, VAs can assist the workers in increasing productivity and ensure better data-based decisions [29].

In I4.0, VAs can be considered as a ubiquitous interface for consuming available services by all stakeholders in the factory. VAs can be a complementary interface with tools, services, and data and present opportunities in the context of I4.0 such as a single point of integration with new and older services, the introduction of natural interaction in the factories, and knowledge management and standardization [20]. For this reason, we considered a relevant investigation, through an SLR, into the characteristics of the implemented VA solutions and services related to the I4.0 Design Principles [3], as well as their limitations.

Based on a previous exploratory analysis [27], the need for an SLR became evident. For this reason, and following the PRISMA guidelines, the concept of VAs was identified, and the study object was defined as the applications of VAs in the application domain, defined as Industry 4.0. In this context, the following Research Questions (RQs) were established, to be answered through the SLR:

- RQ1: Which characteristics of the Technical Assistance Design Principle in I4.0 (Virtual and Physical Assistance) appear in the analyzed VA solutions?
- RQ2: What specific services for the I4.0 application domain do the VA solutions offer?
- RQ3: What are the limitations regarding the application of VAs in Industry 4.0?

3. Methodology

The execution of this SLR of VAs applied to Industry 4.0 was achieved based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method [30]. PRISMA allows for systematic reviews to be performed through a well-defined protocol that enables us to identify, select, and evaluate scientific production in a particular branch of knowledge [31].

For this systematic review, we adopted the Google Scholar search engine. Inclusion Criterion 1 (IC1): Following the PRISMA methodology, the following search terms were considered: "("Virtual Assistant" OR "Virtual Assistance" OR chatbot)" as the concept, "("industry 4.0" OR "industrie 4.0" OR manufacturing)" as the domain of search, and "(application OR "use case")" as the object of search. After an initial iterative search–collect–refine process, we defined the following inclusion and exclusion criteria:

- Inclusion Criterion 1 (IC1): papers that contain the words specified in the search query applied to the Google Scholar database: ("Virtual Assistant" OR "Virtual Assistance" OR chatbot) AND ("industry 4.0" OR "industrie 4.0" OR manufacturing) AND (application OR "use case").
- Exclusion Criterion 1 (EC1): studies not published between 2018 and 2022.
- Exclusion Criterion 2 (EC2): studies not written in the English language.
- Exclusion Criterion 3 (EC3): studies not present in the following databases: ACM, IEEE, Science Direct, Springer, Taylor, and Wiley.
- Exclusion Criterion 4 (EC4): studies that do not have the terms "Virtual Assist*", or "chatbot" and "industr*", or "manufact*" in the title or abstract. In search queries, the "*" symbol functions as a wildcard character. It represents any combination of characters or words that may follow a specific prefix.
- Exclusion Criterion 5 (EC5): studies not related to Industry 4.0.
- Exclusion Criterion 6 (EC6): studies with no access to the full paper.
- Exclusion Criterion 7 (EC7): studies that, through an integral reading, do not present a relation to VA applications or implementations.

The review protocol and its implementation regarding the inclusion and exclusion criteria and the number of resulting studies are detailed in Figure 2. Based on IC1, 9190 studies were identified. EC1 limited the search period from 2018 to 2022. EC2 excluded studies not in the English language. EC3 excluded studies not present in the ACM, IEEE, Science Direct, Springer, Taylor, and Wiley databases, resulting in 7225 removed studies, narrowing the search down to 1965 studies.

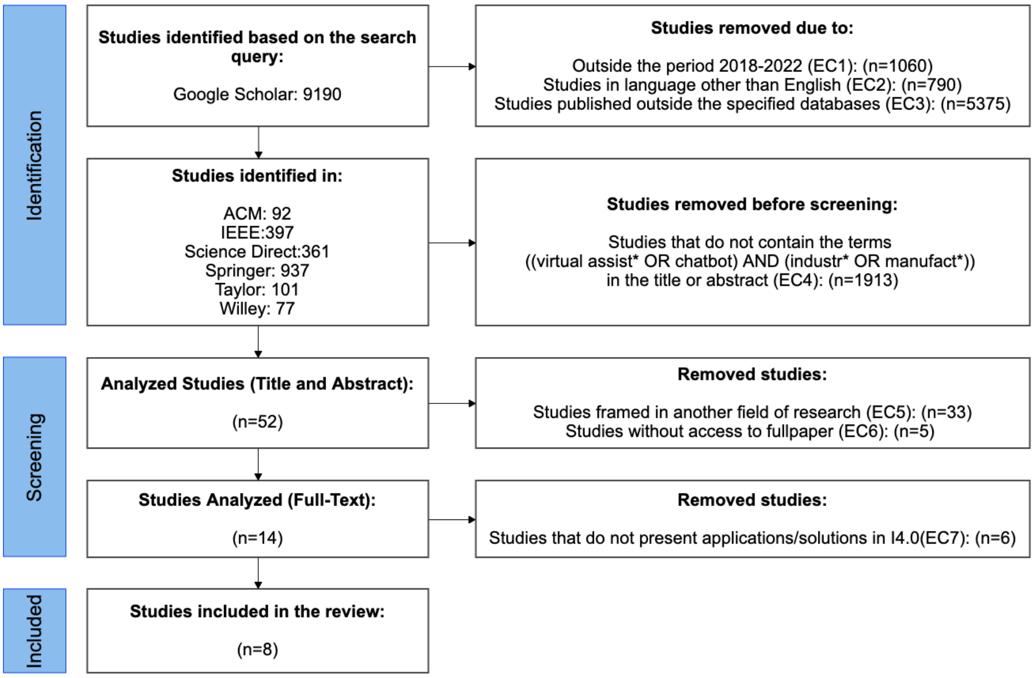

Figure 2. PRISMA protocol execution results.

The research focused on applications of VAs in the industry, so to identify the relevant studies, an automated tool for scanning the terms "Virtual Assist*", or "chatbot" and "industr*", or "manufact*" in the title or abstract of each reference (EC4) was used. This process helped us identify the 52 most-relevant studies for the research. Following this, a manual analysis was conducted on the remaining studies, and 33 studies that did not align with the research topic were discarded (EC5), as well as 5 studies that lacked access to the full paper (EC6). Finally, a comprehensive reading of the remaining studies identified 6 studies that did not pertain to applications or solutions in Industry 4.0 (EC7), according to the metric that defines the study's exclusion after 100 % of the authors agreed with its removal for being out of scope. The research resulted in 8 studies analyzed and discussed, taking into consideration the research questions. The authors understand the reduced number of studies after the exclusion criteria's application as a limitation, but clarify that all criteria of the SLR were strictly followed and 42% of papers were excluded in the last round because of a lack of access to the entire text.

4. Results and Discussion

The search and selection resulted in eight papers, organized by publishing year and presented, with the title and authors, in Table 1.

Taking into consideration the defined RQs (Section 2), the resulting papers (Table 1) were analyzed and grouped into three main categories:

- Characteristics of the Technical Assistance Design Principle present in the solutions;
- VA solutions oriented toward services in the context of Industry 4.0;
- Limitations for the adoption of Virtual Assistance solutions in Industry 4.0.

Table 1. Papers analyzed.

Title	Authors
Bringing a natural language-enabled Virtual Assistant to industrial mobile robots for learning, training, and assistance of manufacturing tasks [32]	Chen Li et al.
VR-enabled engineering consultation chatbot for integrated and intelligent manufacturing services [33]	Amy J.C. Trappey et al.
Virtual Assistance in the Context of the Industry 4.0:A Case Study at Continental Advanced Antenna [34]	Reis, A. et al.
Case study of using virtual and augmented reality in industrial system monitoring [35]	Dmitry Pavlov et al.
Chatbot in industry 4.0: An approach for training new employees [36]	Mario Casillo et al.
User-friendly mes interfaces: Recommendations for an AI-based chatbot assistance in industry 4.0 shop floors [37]	Mantravadi, S. et al.
Chatting about processes in digital factories: A model-based approach [38]	Rooein, D. et al.
Personal robotic assistants: A proposal based on the intelligent services of the IBM cloud and additive manufacturing [39]	S. Amendaño-Murrillo et al.

4.1. Characteristics of the Technical Assistance Design Principle Present in the Solutions

The principle of Technical Assistance in Industry 4.0 was divided into two groups: Virtual Assistance and Physical Assistance state that, with the increasing complexity of production systems, humans will transition from mere operators to decision-makers and problem-solvers [3]. To do so, systems need to provide filtered and understandable information to the user for an informed decision (Virtual Assistance). The support of ICT in human tasks (Physical Assistance) is also an important aspect, as with advancements in robotics, it can assist with repetitive or dangerous tasks.

In the following Table 2, the papers are compared taking into consideration the implementation of the Technical Assistance principle in their solutions, in its two modalities—Virtual Assistance and Physical Assistance—and whether they were explicitly based on the Technical Design Principles [3] or not. Figure 3 shows these in a graphical comparison of the three assistance types.

Table 2. Technical Assistance characteristics regarding the type of assistance.

	Virtual Assistance	Physical Assistance	Based on Principles
Li et al. [32]	✓	✓	-
Trappey et al. [33]	✓	-	-
Reis et al. [34]	✓	-	✓
Pavlov et al. [35]	-	✓	-
Casillo et al. [36]	✓	-	-
Mantravadi et al. [37]	✓	-	✓
Rooein et al. [38]	✓	-	-
Amendano-Murrillo et al. [39]	-	✓	-

"✓" signifies the consideration of the characteristic, while "-" indicates that the characteristic is not present.

4.1.1. Virtual Assistance

Virtual Assistance refers to remote support through a digital interface, providing information, guidance, decision-making support, learning, and training, among other features. VAs in the I4.0 paradigm play an important role in providing real-time information so that operators or directors can have accessible and filtered information for better decision-making. Li et al. [32], Reis et al. [34], and Mantravadi et al. [37] presented solutions that enable real-time information retrieval reflecting the status of a machine or factory. Li et al. [32] connected machines and robots through APIs to visualize the state of robots and the tasks they were executing, to monitor machines, and to act quickly in case of failure or breakdown. Reis et al. [34] presented an assistant from the perspective of production directors and managers, where the assistant responds to production status information (recorded stoppages, quantity of produced products, etc.) and performs automatic reports, acting as an interface and automatic filter for factory systems such as an MES or ERP. Similar to [34], Reference [37] also presented a chatbot that acts as an interface between the MES and the workers.

VAs and chatbots, with their ease of communication with users through natural language techniques, also provide important help in providing static information, with the main goal being teaching and information about production processes. Trappey et al. [33], Casillo et al. [36], and Rooein et al. [38] presented solutions that provide information and answer questions based on an initial Knowledge Base (KB). Trappey et al. [33] presented a framework that can answer various questions based on FAQs and, with the help of VR technologies, can provide information in 3D environments. Casillo et al. [36] presented a chatbot that acts as an assistant in learning and training new workers in manufacturing and serves as a means of providing knowledge to workers during the production process training. Rooein et al. [38] introduced and proposed a chatbot usage framework to adapt and learn from a company's work processes. A way to adapt to each process was presented through graphs, with the objective of helping, guiding, and teaching new employees about the processes.

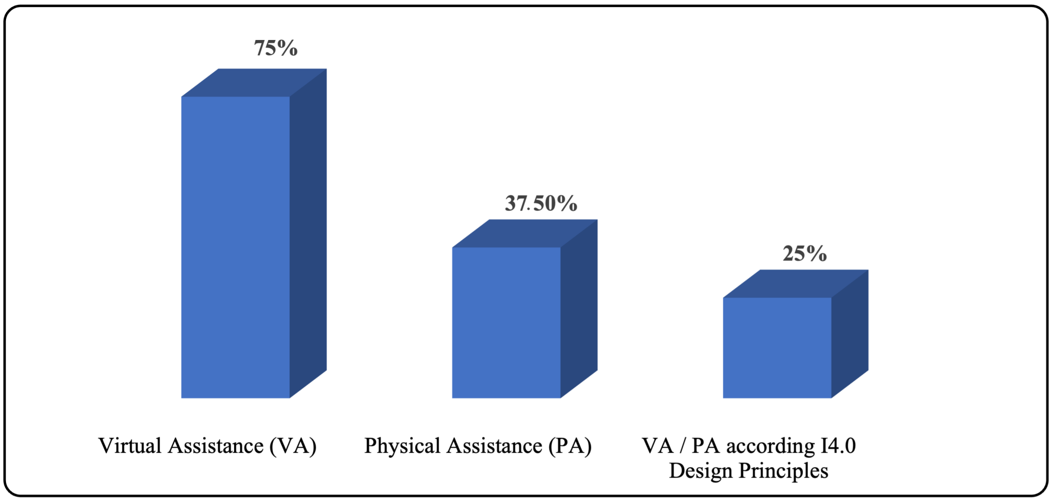

Figure 3. Distribution of papers based on the Technical Assistant Design Principle

4.1.2. Physical Assistance

On the other hand, Physical Assistance includes on-site help from the worker, either through task execution or through the provision of tools and information to troubleshoot his/her work and problems. VAs in this category can not only act as a request interface for task execution, but also for monitoring.

Li et al. [32] and Amendano-Murrillo et al. [39] presented solutions that allow for the invocation or local execution of tasks, either through API connection with robots, as was the case in [32], where the VA can ask robots to perform tasks requested by the user, or through the solution itself, which has hardware available that allows for task execution, as in the prototype presented in [39], where the robot has cameras and stepper motors that allow for actions to be performed.

Pavlov et al. [35] and also Li et al. [32] allowed for local information about the status of work machines and their production process. In [35], the authors proposed a monitoring system with the help of VR/AR. This solution differs from assistants that are usually based on interaction with chatbots because, with the help of VR and AR, it informs the worker in real-time of problems and also helps him/her with his/her task by informing them of what needs to be done, as well as the factory status. In [32], with the integration of robots with the API, as mentioned earlier, not only does it allow for tasks to be performed, but it also receives the status and logs of tasks and robot problems, helping workers in problem-solving.

4.2. VA Solutions Oriented toward Services in the Context of Industry 4.0

An assistant is someone or something that helps the user and responds to his/her questions, requiring the knowledge and information necessary to provide the user with the requested answer or execute a task. VAs have some common services and features, mainly in their interface for communicating with the user, as well as mechanisms and services for "translating" user input into language that the computer understands, in order to answer a question or perform a task.

Therefore, VA solutions oriented toward a specific area, in this case the industry, need to add or have specific knowledge or services oriented toward the application area. Regarding these services and modules specifically for I4.0, the analyzed papers presented collaboration in two ways. For dynamic information, these services collaborate with the existing services and legacy systems through the creation of integration services. In another way, for static information, these services build a knowledge base based on real processed data. A synthesis of this kind of services is demonstrated in Table 3.

Table 3. VA solutions oriented toward services in I4.0.

	Dynamic Information	Static Information
Li et al. [32]	✓	-
Trappey et al. [33]	-	✓
Reis et al. [34]	✓	-
Pavlov et al. [35]	✓	-
Casillo et al. [36]	-	✓
Mantravadi et al. [37]	✓	-
Rooein et al. [38]	-	✓
Amendano-Murrillo et al. [39]	✓	-

"✓" signifies the consideration of the characteristic, while "-" indicates that the characteristic is not present.

Li et al. [32], Reis et al. [34], Pavlov et al. [35], and Mantravadi et al. [37] presented integration services that help support their solutions. Li et al. [32] presented an integration service to an API for the control and monitoring of a specific type of robot. Reis et al. [34], with the help of middleware, could extract information from existing services and data, in this case the MES. Pavlov et al. [35] presented integration modules with sensors present in the factory for capturing information, while Mantravadi et al. [37] and Reis et al. [34] presented an integration service with the MES.

Trappey et al. [33], Casillo et al. [36], and Rooein et al. [38], as solutions that do not provide information in a real context, but in providing static information, i.e., [36] or [38], which are training and learning solutions, used a KB, a previously organized database, to provide information to the solutions based on it.

When considering the relevance of real-time information in these environments, it is also possible to relate Physical Assistance to a greater need for real-time information. Comparing Table 2 (types of assistance—Physical or Virtual) with Table 3 (type of information associated with the services—static or dynamic), it is possible to infer that studies based on Physical Assistance relate to services based on dynamic information, while studies related to training and machine operation/maintenance relate to static information. When considering the growth of Cyber–Physical Systems (CPSs) in I4.0, the number of studies related to dynamic information, often in real-time, seems to indicate a growing relevance in the use of services based on dynamic data.

4.3. Limitations for the Adoption of Virtual Assistance Solutions in Industry 4.0

The introduction of the new paradigm of Industry 4.0 brings new challenges that need to be addressed and solved for its implementation to be efficient and advantageous. Based on [20–22], some challenges related to the design and implementation of VAs and information systems in the industrial context have been identified. They are:

- Environment: adaptation to noisy environments and adverse conditions in factories;
- Integration: integration with legacy and heterogeneous systems in factories;
- Security: ensuring the security and privacy of sensitive production data;
- Personalization: customization and adaptation to meet the specific needs of each industry;
- Real-time: real-time decision-making, considering the human limitation in processing large volumes of information.

The solutions presented in the papers are analyzed in Table 4, with the objective of understanding if these challenges are considered in their implementation. Adapting to noisy and adverse environments in the factory is important because the solution needs to have all the conditions to communicate and interact with the user in an adverse environment. Among the analyzed papers, only [39] was concerned with adverse environments in factories, such as noise, where the solution presented was subjected to various environments and presented satisfactory results.

Table 4. Limitations addressed by the solutions.

	Environment	Integration	Security	Personalization	Real-Time
Li et al. [32]	-	✓	-	-	✓
Trappey et al. [33]	-	-	-	✓	-
Reis et al. [34]	-	✓	✓	✓	✓
Pavlov et al. [35]	-	✓	-	✓	✓
Casillo et al. [36]	-	-	-	-	-
Mantravadi et al. [37]	-	✓	-	-	✓
Rooein et al. [38]	-	-	-	✓	✓
Amendano-Murrillo et al. [39]	✓	✓	-	✓	-

"✓" signifies that limitation was addressed, while "-" indicates that the limitation was not addressed.

As discussed earlier, integration with various legacy services and modules of a particular industry is crucial to the execution of the VA's purpose. The papers [32,34,35,37], as previously presented, offered integration services with APIs or databases.

In the I4.0 paradigm and in other areas, one of the biggest challenges is computer security and data privacy. In the industry environment, data security and privacy are even more of a concern as they deal with very sensitive data, such as customer data or confidential information. Among the analyzed works, only Reis et al. [34] presented a security method and barrier to sensitive factory data, having created an independent database that is updated with factory data through middleware that allows data flow control. The other works that had direct integration with data did not present any kind of data security and filtering. Papers that did not present integration or did not require such integration only need to consider this in the choice of data to populate their databases.

Designing a solution with customization in mind allows the solution to adapt to other industries, not just the one it was created and tested for. In general, all analyzed solutions present characteristics (modules/services) that allow the addition and modification of their area of operation. Casillo et al. [36] and Rooein et al. [38], being training-oriented, were those that had greater customization and adaptation capacity to new environments and processes.

With the transition from operators to decision-makers, the provision of real-time information is critical, as the decisions and actions are taken based on it. The solutions presented that aim to support decision-making and monitoring [32,34,35,37] take into account real-time information to better inform users. The other solutions that are more specific to providing static and training information do not provide this capability.

5. Conclusions

The Industrial Revolution 4.0 (I4.0) and the use of VAs have transformed the industrial landscape in recent years. Real-time contextual data made it easier for the information systems to assist workers on the production floor, administrative staff, supervisors, and production managers. VAs are closely linked to this movement, improving productivity and efficiency in modern smart factories. In the face of the VA solutions' global market size increasing and the projected growth rate for the upcoming decades, research in this area is relevant and necessary.

This Systematic Literature Review explored the use of VAs in the context of Industry 4.0 (I4.0), discussing the Technical Assistance Design Principle in I4.0 and identifying the characteristics of VA solutions, the specific services offered by VAs in I4.0, and the limitations for their application in I4.0. First, it is mandatory to establish a clear distinction between VAs and chatbots, as these terms are often erroneously interchanged in various research papers. Therefore, we concluded that the terminology "Virtual Assistant" is not widely applied in the I4.0 applications literature. To clarify, chatbots are computer programs designed to answer questions and engage in conversation with humans via text or voice. VAs are computer program solutions capable of autonomously executing complex tasks based on human inputs, typically through chatbot interfaces. Essentially, a chatbot constitutes a component of a VA solution.

Related to the characteristics of the I4.0 Technical Assistance Design Principle present in VA solutions (RQ1), all the applications present both Physical and Virtual Assistance. The VA applications focus on providing real-time filtered and contextualized information or static information mainly for learning purposes, while Physical Assistance applications are mainly oriented toward performing tasks and helping the user in decision-making. It is possible that Virtual Assistance is more widely spread than Physical Assistance because Virtual Assistance demands only software development with no need for the additional physical components that Physical Assistance needs.

Regarding the specific services for the I4.0 (RQ2), the applications present two main kinds of services: integration with legacy systems for information retrieval and task execution linked to various services and the processing of static information to be used by applications. All solutions have similar characteristics, following the main characteristics of a VA.

The main limitations of VA applications in I4.0 (RQ3) concerning information security, which is very important since sensitive data are handled in the industry and the adaptation to noisy and unstable production environments, where most applications do not take these adversities into consideration. Future research and development could focus on addressing these limitations, and the new AI-based models and services represent new possibilities and challenges in the VA research area.

All criteria of the SLR were strictly followed, and 42% of papers were excluded in the last round (EC7) because of a lack of access to the entire text. The authors understand that the reduced number of studies remaining after the exclusion criteria's application—a small group of eight studies—makes it difficult to draw general conclusions. On the other hand, the reduced number of studies was due to the "Virtual Assistant" and "chatbot" concepts not being widely used in applied studies, a requirement to answer the RQs.

The authors recognize that the small number of resulting papers, while providing some worthy insights and results, did not allow for generalizations. Therefore, the authors recommend that future work could broaden/refine the search terms to provide more-significant conclusions on the subject of Virtual Assistants in Industry 4.0. Regarding the context of I4.0, future research should include voice interface development and evaluation considering the noisy production floors and industrial environments. Additionally, there is a need to explore the integration of Virtual and Physical Assistance to enhance the relevance of Cyber–Physical Systems within the I4.0 paradigm. This integration could also encompass the adoption of cutting-edge Large Language Models (LLMs) such as GPT4 and others. Furthermore, future research could include the Industry 5.0 concept and explore its potential implications for the research field.

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