Wearable and interactive mixed reality solutions for fault diagnosis and assistance in manufacturing systems: Implementation and testing in an aseptic bottling line

“Wearable and Interactive Mixed Reality Solutions for Fault Diagnosis and Assistance in Manufacturing Systems: Implementation and Testing in an Aseptic Bottling Line”

BOTTANI Eleonora, LONGO Francesco**, NICOLETTI Letizia***, PADOVANO Antonio**, TANCREDI Giovanni Paolo Carlo*, TEBALDI Letizia*, VETRANO Marco***, VIGNALI Giuseppe**

Affiliations:

** Department of Engineering and Architecture, University of Parma, viale delle Scienze 181/A, 43124 Parma, Italy*

*** DIMEG, University of Calabria, via P. Bucci, cube 44c, 87036 Arcavacata di Rende (Cosenza), Italy*

**** Cal-Tek Srl, Via Spagna, 87036 Rende (Cosenza), Italy*

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Abstract

Thanks to the spread of technologies stemming from the fourth industrial revolution, also the topic of fault diagnosis and assistance in industrial contexts has benefited. Indeed, several smart tools were developed for assisting with maintenance and troubleshooting, without interfering with operations and facilitating tasks. In line with that, the present manuscript aims at presenting a web smart solution with two possible applications installed on an Android smartphone and Microsoft HoloLens. The solution aims at alerting the operators when an alarm occurs on a machine through notifications, and then at providing the instructions needed for solving the alarm detected. The two devices were tested by the operators of an industrial aseptic bottling line consisting of five machines in real working conditions. The usability of both devices was positively rated by these users based on the System Usability Scale (SUS) and additional appropriate statements. Moreover, the *in situ* application brought out the main difficulties and interesting issues for the practical implementation of the solutions tested.

Keywords: Augmented reality; Smart technologies; System usability scale; Industry 4.0; Wearable technologies; Industrial safety.

1 Introduction

A main challenge in the industrial field concerns the adoption of new technologies enabling the Industry 4.0 philosophy and architecture (Frank, Dalenogare, & Ayala, 2019). The digitalization of the factories involves the concrete use of smart technologies, in line with the paradigms of connectivity and human-machine interaction by sending-receiving and sharing data and information useful to execute the manufacturing tasks (Ceruti, Marzocca, Liverani, & Bil, 2019). Smart technologies open to a wide range of opportunities for fault diagnosis and assistance enhancement in various fields. In the manufactory sector, the upgrade to the Industry 4.0 enabling technologies will contribute to improving the conditions of the workplace, as it can also be deduced from the interesting work by (Vukicevic, Djapan, Stefanovic, & Macuzic, 2019). The paper at hand refers to this context, as it discusses the development and application of two smart solutions based on Industry 4.0 technologies, designed *ad hoc* to support the worker’s tasks.

Furthermore, as for the previous industrial revolutions, the evolution of technologies implies new risks for the employees. This is why the European Agency for Safety and Health at Work (EU-OSHA) is researching the so-called New Emergent Risks (NER), to align the current model of risk assessment by evaluating the effects of new technologies on industrial processes (Kaivo-oja, Virtanen, Jalonen, & Stenvall, 2015). At the state-of-the-art, the current models used for risk assessment need to be reassessed to consider new categories of risks (Fernadéz & Peréz, 2015).

Among the enabling technologies available in Industry 4.0, augmented reality (AR), mixed reality (MR), and the use of big data coming from the real plant were identified as the most promising ones (Zezulk, Marcon, Vesely, & Sajdl, 2016). AR and MR in particular have had several applications in the last decade showing a good potential in solving industrial issues (Bottani & Vignali, 2019). The difference between AR and MR is quite small: in MR, virtuality and reality are equally merged, while in the case of AR, virtuality overlaps reality, which is prevalent (Flavián, Ibánez-Sánchez, & Orús, 2019). The use of an AR head-mounted display (HMD), or of a mobile app, to list the maintenance procedure instead of a physical media (Bendzioch, Bläsing, & Hinrichsen, 2020) could also bring advantages in ergonomic and economic terms.

Based on these premises, this paper discusses the design, implementation, testing, and usability assessment of a fault detection and early warning system, which leverages on novel wearable and interactive MR. The first one is a mobile app, developed for Android Mobile devices, and running on a common mobile smartphone. The second application is a wearable AR-based solution, which makes use of Microsoft HoloLens as HMD; this represents a development compared to the mobile app, as it can include AR/MR features that superimpose information on the physical layer and, at the same time, allow the workers to operate on the plant with free hands. Both solutions are expected to detect and communicate the status of the plant machines connected to the devices; in case an alert is observed, the solutions will guide the operator during the execution of the tasks required to restore the normal condition of the plant (e.g. maintenance operations or interventions on the machine). To this end, both solutions embody a comprehensive set of troubleshooting procedures; the AR system is also capable of indicating the precise location in the plant where the alarm was observed. For the solutions to work properly, they make use of specific Industry 4.0 features, such as the Internet of things (IoT) and the cyber-physical systems (CPS) architecture, which is useful for the connection of the machine's control unit to the devices.

The remainder of the paper is organized as follows. Section 2 provides a review of the literature relevant to this study, covering, in particular, AR and MR solutions applied to the manufacturing industry. Section 3 describes the context in which this research activity was carried out. Section 4 details the solution developed and the relating system architecture, while Section 5 explains the methodology for testing of the web solution in a real industrial context and includes outcomes, discussion, and interpretation, also thanks to the elaboration of the test outcomes through IBM Statistical Package for Social Science (SPSS) release 26 for Windows. The key lessons that can be derived from the practical experience are included as well. Suggestions for future research and the main conclusions are proposed in Section 6.

2 AR/MR in the manufacturing context

AR and MR are nowadays frequently adopted not only at a laboratory scale but often at an industrial level, especially in the manufacturing sector. As reported by many works (e.g., (Bottani & Vignali, 2019) or (Egger & Masood, 2020)), many AR/MR applications could be relevant in quality monitoring and inspection, assembling, maintenance, and safety activities.

As far as the assembly operations are concerned, an AR assistance system has been proposed by (Sauer, Berndt, Schnee, & Teutsch, 2011) to help operators completing complex tasks by visualizing, on a static screen, the CAD model of the assembled components overlayed on the physical workbench. As regards maintenance, the use of HMD helps operators to carry out maintenance tasks by following the interactive instructions, displayed as for the ARIOT (an IoT enabled AR system) (Wijesooriya, Wijewardana, De Silva, Gamage, & M., 2017). As regards the quality monitoring, a Spatial Augmented Reality (SAR) solution can help to visualize welding spots for increasing the efficiency of the manual work (Doshi, Smith, Thomas, & Bouras, 2017) or to indicate the correct spots and avoid operator's mistakes during the inspection (Zhou, et al., 2011). AR has also been used for measuring the segment displacement in tunnel construction, by overlaying the Building Information Modeling (BIM) on the physical layer (Zhou, Luo, & Yang, 2017). AR has been applied also in the logistic field; for example, marker-based systems can be used to reassemble pallets after acceptance sampling, in line with the Assistant Acceptance Sampling (AAS) procedure introduced by (Franceschini, Galetto, Maisano, & Mastrogiacomo, 2016).

Finally, as far as the safety issues are concerned, an improvement of the process control and the predisposition of adequate procedures can help solve a relevant percentage of work accidents. In a manufacturing environment that looks for the implementation of Industry 4.0 enabling technologies and for becoming "smart", the application of IoT and CPS architecture should be considered as a smart way of solving issues (Lee, Cameron, & Hassall, 2019).

The technological progress in computational power, together with the progress made in software efficiency, shows the potentiality of using these new features in the Industry 4.0 field. The smart solutions available are increasingly effective in reliability, functionality, and quality. In the specific case of AR, at the beginning of its introduction (Van Krevelen & Poelman, 2010) highlighted the main issues that represent the technical limits of the systems related to the AR. These issues include the portability, the necessity of using a power supply, the delay for the visualization on a display of the holograms (Van Krevelen & Poelman, 2010). In this field, significant developments have been made in the latency and resolution of the displays, together with the growth of additional capabilities, such as the power unit, the Graphics Processing Unit (GPU), and the development of new units, such as the Holographic Processing Unit (HPU) by Microsoft for HoloLens (Hermann, Pentek, & Otto, 2016). Similarly, IoT and CPS allow the development of smarter solutions, by some of the above technical limitations. Current works have shown the potential usage of AR in manufacturing and the particular attitude of being applied for maintenance, i.e. by following a projected assembly procedure (Wang, Ong, & Nee, 2016), a wiring harness, and safety operations (Masood & Egger, 2020); (Egger & Masood, 2020). Even in the food sector, application attempts on specific machines have been made by using software tools developed *ad hoc* (Vignali, et al., 2018).

The use of HMD has been tested in several contexts (Kellner, et al., 2012). In terms of safety, the main advantage of using an AR HMD is that the user has hands free to execute his/her tasks (Longo, Nicoletti, & Padovano, 2017). However, not all researchers agree on the maturity of this technology, especially when implemented in an HMD. The main issue is about the ergonomic aspects of HMD, as the device would result uncomfortable if worn for a long time. Moreover, the holograms added to the physical layer can occlude the operator's view (Hietanen, Pieters, Lanz, Latokartano, & Kämäräinen, 2020).

As far as MR is concerned, an application in the industrial context to alert employees and help them solve faults it is worth mentioning has been by (Espíndola, Pereira, Schneider, & Ventura, 2013). These authors presented the implementation of mixed visualization during maintenance operations to decrease the operation time and at the same time increasing safety for the operator during task performance. Apart from that, the declared usage of MR in the alerts management field is quite lacking in literature; indeed, a simple query carried out on January 28th with "mixed reality", "safety" and "industry" as keywords returned 21 papers, but apart from the abovementioned papers and two other studies carried out in the same contexts of this paper, none of them deals with this kind of solution. Specifically, what emerges is that this technology is widespread in the construction context (see for instance (Moore & Gheisari, 2019)), for learning purposes (Juraschek, Büth, Posselt, & Herrmann, 2018) or in the medical area (Hu, et al., 2019). For sure, this is one of the gaps intended to fill in the present manuscript.

3 Research aims and application context: W-Artemys project

Alert and early warning systems in manufacturing plants have significant benefits – including higher production efficiency, reduced downtimes, higher employee safety – and may truly represent a life-saving tool in case of industrial accidents. However, technological tools for employee training and *in situ* support purposes still require to be developed, tested, and integrated with each other. Training personnel does not only mean transferring all the information, content, and procedures that must be adopted to operate safely, but also ensuring that the operators understand the importance of such procedures, use state-of-the-art (sometimes unfamiliar though) technological tools and operate accordingly. For this reason, such technologies should be also smart (capable of interacting in an intelligent, intuitive, and rapid manner with the operator), augmented (capable of providing augmented content and information to the operator) and mobile (so that the employees have the technology always within reach but at the same time, they are able to do their own tasks).

The main aim of this study was to ascertain the usability and level of acceptance of an alert and early warning system based on wearable and interactive MR for enhancing employee safety in manufacturing systems and facilitating the interaction of the operator with industrial equipment and machinery. These aspects are indeed crucial for an effective technology adoption that will eventually yield significant benefits to the company.

This research study has been conducted in the context of the W-Artemys (Wearable Augmented RealiTy for EMployee safetY in manufacturing Systems) project funded by INAIL, the Italian National Institute for Insurance against Accidents at Work. The general aim of the project was to design, prototype, deploy and test an innovative system alert and early warning system and implement a seamless communication of the MR application with the industrial machinery via the Industrial Internet of Things (IIoT) to get real-time machine health information, such as work/idle status or active alarms. The project involved three Italian universities, and the developed solutions were deployed in the case of a real aseptic bottling line owned by one of the most important companies operating in the beverage field and based in the province of Parma, namely the renowned Parmalat, that was a project partner together with GEA Procomac S.p.A., the company producing the whole bottling line.

4 Architecture of the alert and early warning system

4.1 System modules and functionalities

The alert and early warning system here proposed has been conceived as a distributed and modular network of production resources (e.g. equipment or machines) that communicate and exchange messages over the enterprise network with an ad-hoc developed web application. The design and development of the system prototype has been conducted by the group of the University of Calabria, in collaboration with CAL-TEK S.r.l., a spin-off company with considerable experience in the development of Mixed Reality solutions for industrial operators. As such, the application is also able to communicate with the enterprise information systems (e.g. MES, ERP). Besides the web application, the system also includes two front-end solutions for in-situ operators:

- a mobile app, developed for Android Mobile devices, and running on common mobile devices (e.g. smartphones)
- a wearable MR-based solution, which makes use of Microsoft HoloLens as MR HMD; this represents a high-end development compared to the mobile app, as it can include AR/MR features that superimpose information on the physical layer and, at the same time, allows the workers to operate on the plant with free hands.

It is assumed that the physical equipment and machinery in the manufacturing systems are already able to connect to the enterprise network and allow machine-to-machine communication. The system detects and communicates the health status of the plant machines connected to the application; in case an alert is observed, the solutions (i.e. the mobile app or the MR-based app) will guide the operator during the execution of the tasks required to restore the normal condition of the machinery (e.g. maintenance operations or interventions on a machine). Indeed, the system embodies a comprehensive set of troubleshooting procedures and safety prescriptions, loaded on the applications beforehand. Besides, the

AR system is also capable of indicating the precise location in the plant where the alarm was observed. For the solutions to work properly, they make use of specific Industry 4.0 features, such as the Internet of things (IoT) and the cyber physical systems (CPS) architecture, which is useful for the connection of the machine's control unit to the devices.

4.2 System architecture

The general architecture of the developed alert and early warning system is shown in Figure 1: System architecture.. The central element of the architecture is the web application (the gray rectangle on the bottom right of the figure), which is intended for system administration purposes, manages the data, and interacts with the mobile and MR applications. As illustrated, the web app has been designed according to the Model-View-Controller (MVC) framework, typically used for designing web applications and mobile apps, and developed using the free and open-source PHP web framework Laravel (https://laravel.com/). It also includes a server with the open-source search engine software library Apache Lucene (https://lucene.apache.org/), the Java-based search platform Apache Solr and Node.js to execute Javascript code. The server is the main enabler of the *ad hoc* developed intelligent voice assistant that supports the employee when searching for information intuitively and rapidly. Moreover, the web app includes a MySQL relational database and an OAuth 2.0 login approach that enables a token-based user authentication. The login token is associated with the user account and not with the device, so that the notifications of new alarms will appear only on the device where the user (the operator) is currently logged in. This approach applies to both the mobile and MR apps.

The web application can be accessed by the system administrator via a web browser (see the upper part outside the web app's gray box). The system admin can use the web app interfaces to configure the system, enter specific data about the machines or add set up the troubleshooting procedures and safety prescriptions that will be later shown on the mobile and MR apps to the operator *in situ*. In particular, custom controllers have been developed to enable the admin to perform specific actions on the system, for example, to populate the list of the alarms for a given asset (e.g. a machine). Other custom controllers process the alarm information automatically and send the alert to the client applications – the mobile and the MR apps. The Class Diagram of such controllers is shown in Figure 2.

Once the administrator is logged in, the data, their structure, and their relations can be organized and configured flexibly to represent the specific domain of interest for the application or the specific machine under study. In this sense, a specific controller (AlarmsController) has been developed to handle the graphics in the web app and allow the user to insert data about the alarms. The data are organized according to a tree structure where the root node is the specific asset or equipment that is being digitalized. Each node is characterized by some attributes that are associated with the asset during the configuration by the system administrator. For example, a given machine, such as the rinsing machine (root node) may be characterized by a list of alarms (child node), where each alarm includes an ID string, the description, the type, the operator who can perform the work, the list of potential causes, the list of effects, the restoration procedure and the related anomalies, along with media files such as pictures, videos or audio files. It is important to note that this flexible structure guarantees improved horizontal scalability and can be easily replicated for each machine composing the production system. Figure 3 shows the web app user interface to enter alarms' information.

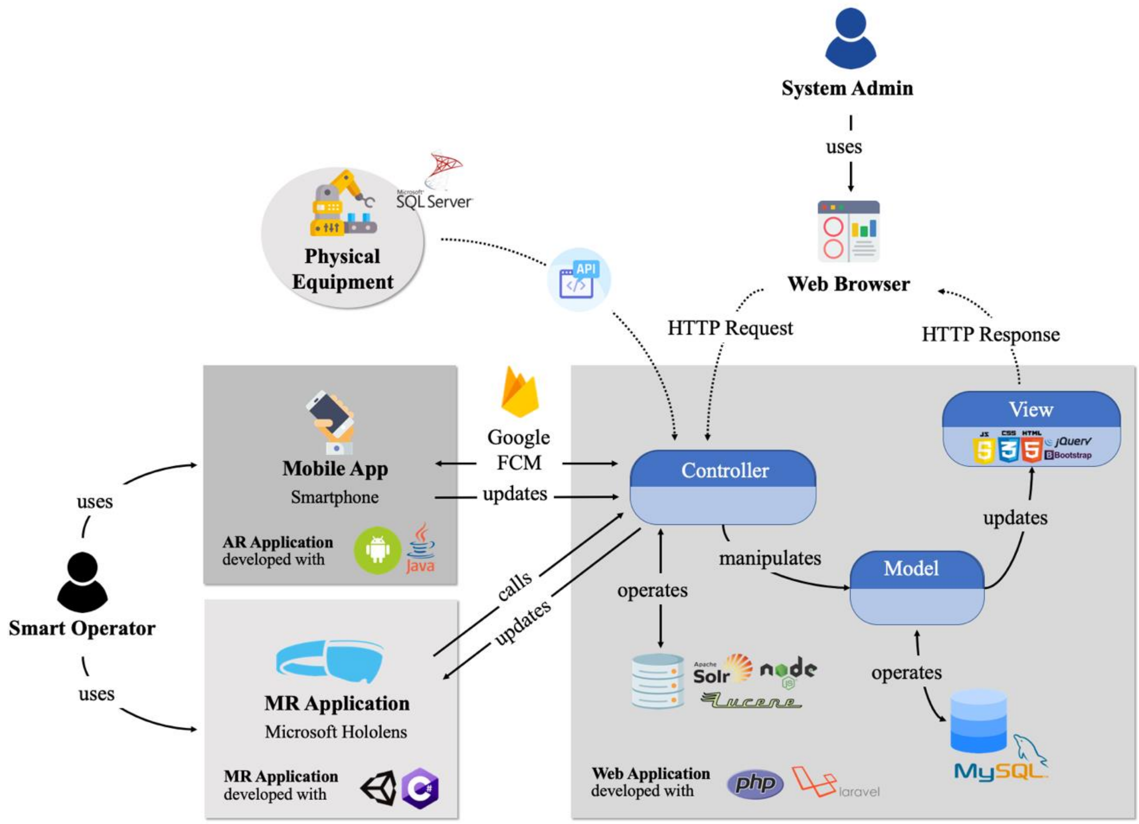


Figure 1: System architecture.

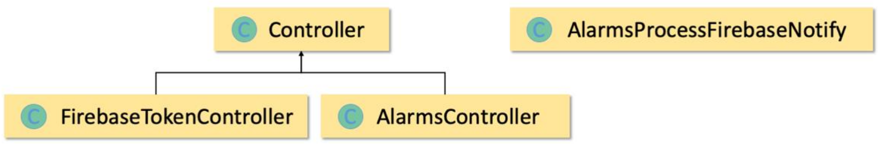


Figure 2: Controllers' class diagram.

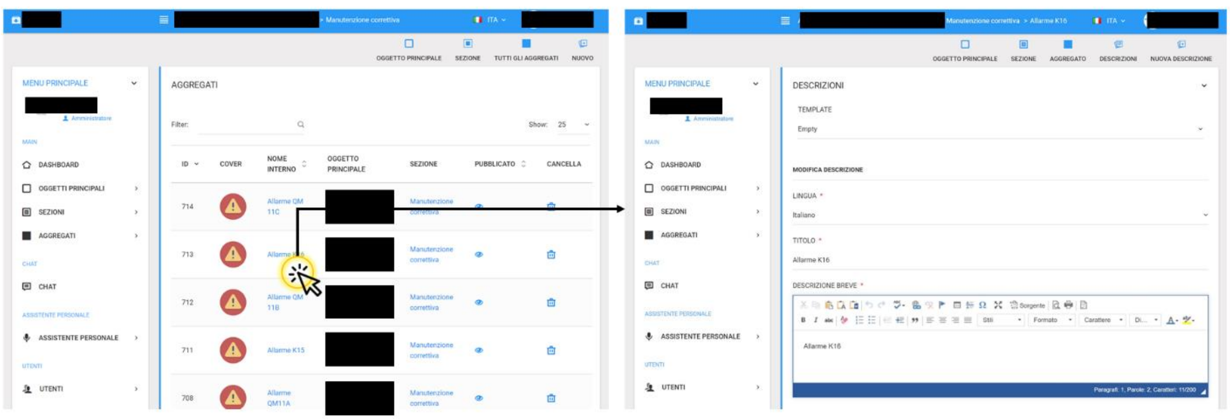


Figure 3: Web app user interfaces: a) list of implemented alarms; b) entering alarms' information

Once the machine has been configured and the alarm list added into the system, the web app connects with the real production resource (e.g. a machine) via TCP/IP protocol and interacts with it through application program interface (API) calls (see the upper left part of Figure 1). The web application has read-only access to the resource's database (e.g. the machine database, e.g. Microsoft SQL Server database), from which it retrieves information, including the alarm ID. When a new alarm ID is detected, the Firebase Token Controller (see Figure 2) searches for it in the list of alarms uploaded on the MySQL web application database by the system administrator. If there is a match, the client app is notified by the Alarms Process Firebase Notify controller immediately thanks to the Firebase Cloud Messaging (FCM) solution by Google. If the notification received on the mobile device or in the MR helmet is ignored by the user for some reason, the notification will continue to appear (see for example Figure 6), until the user clicks on it to check further info and to try to solve it. A summarizing activity diagram that reports and clarifies the role of each application is shown in Figure 4.

The alarm information finally reaches the mobile application or the MR-based application used by the operator (see the two gray boxes on the left of Figure 1). As previously mentioned, the mobile app has been developed in Java for Android mobile devices. In the case of this study, a Samsung S7 and a Samsung Galaxy Tab have been used.

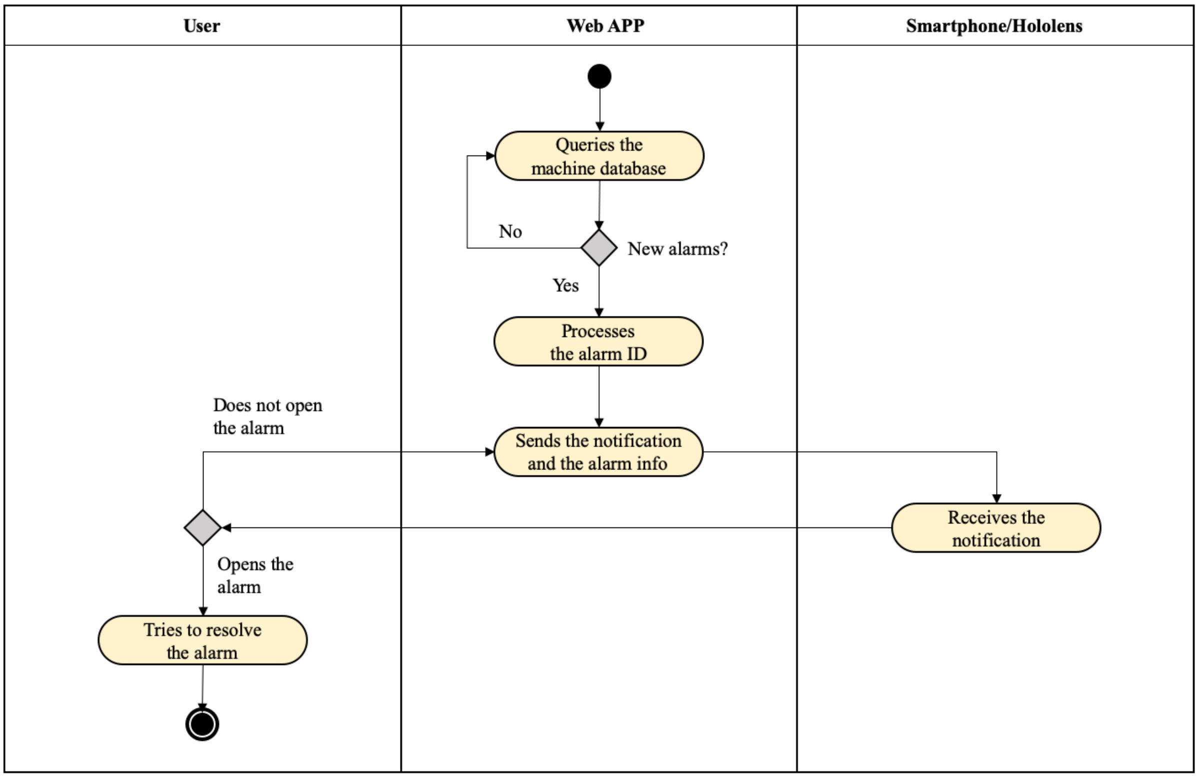


Figure 4: Activity Diagram.

Instead, the MR application has been developed with the Unity 3D game engine and written in C# for use with the Microsoft HoloLens. The 3D models and environments were built with the open-source 3D computer graphics software tool Blender (https://www.blender.org/). The application is extremely user-friendly and provides the employee an effective tool to interact with the real physical assets and equipment. If the employee wears the HoloLens helmet on the shop floor, notifications, the alarm list, and alarm information will appear over-imposed on the real environment as shown in the digital mock-ups of the application (Figure 5). Direct interaction with the graphics is possible through the gaze, the voice (thanks to the vocal assistant that is also integrated for the Microsoft HoloLens), and gestures.

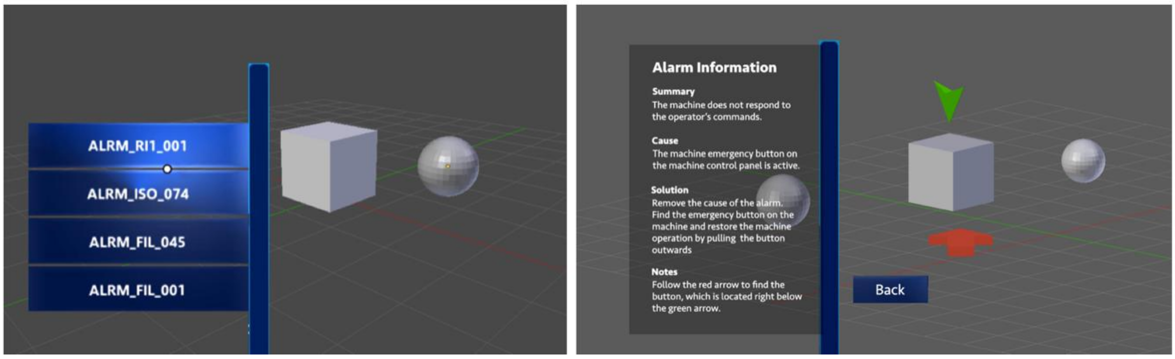
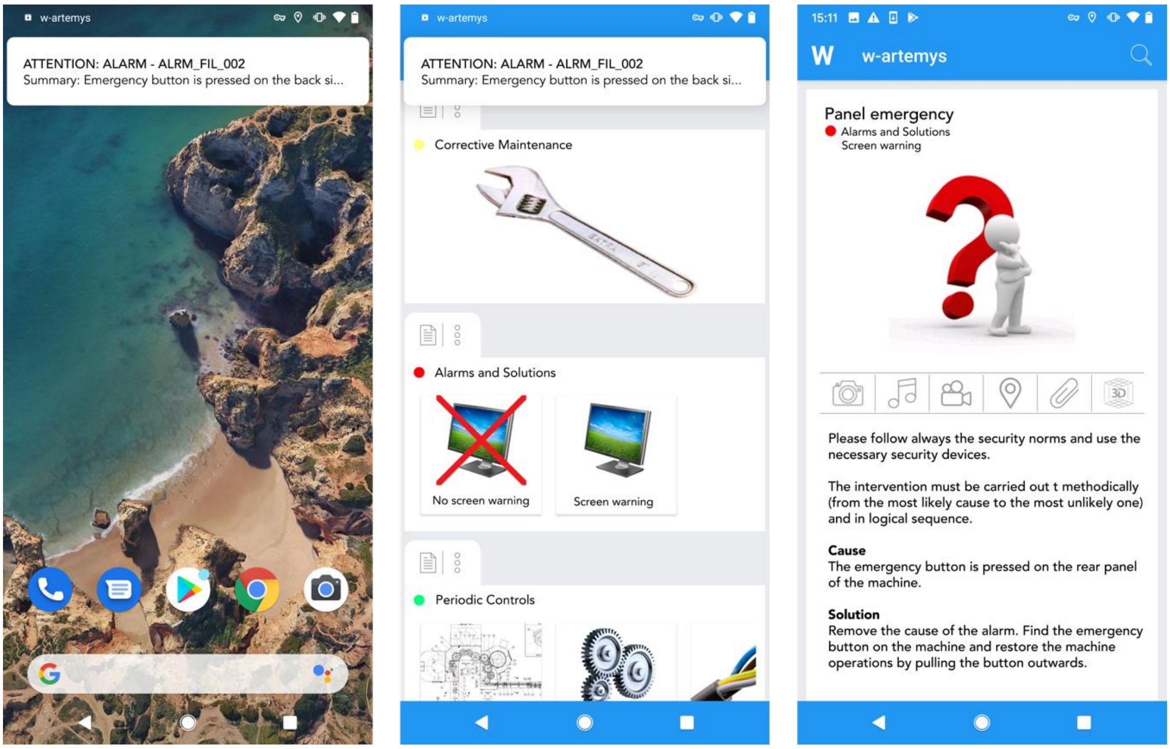


Figure 5: Digital mockup of the list of active alarms and alarm info in the virtual environment.

The application does not use tags (marker-less), which means that it can locate the asset with the alarm based on the location of the asset determined *a priori* in the plant. This choice was motivated by the need for developing flexible solutions that can be easily adapted to any manufacturing environment, including scenarios where markers cannot be used because of the characteristics of the plant or of the production process. To do so, the system's coordinates (reflecting the layout of the plant and components involved) can be directly implemented in the application, thus making it capable of recognizing the point where it is located without using markers or other technologies. Moreover, marker-less solutions are particularly useful for the user experience with the usage of the HoloLens MR application. Indeed, the user can move within the production system and reach the machine where the alarm has been detected by following the red arrow as showed in the mock-up on the right in Figure 5. The green arrow points at the exact location the employee should reach to solve the alarm according to the provided guidelines.

4.3 Empowering the operator: the mobile and the MR-based applications

Once the notification is received on the mobile device – both when the app is closed (see Figure 6a) and open (see Figure 6b), the user (e.g. the employee on the shop floor) can access detailed information about the alarm (see Figure 6c), reach the machine where the alarm has been detected and follow the restoring procedure. Vocal interaction with an intelligent digital assistant represents an innovative interface for the field operator to the cyber world (i.e. the digitalized information), so that information can be retrieved rapidly and intuitively, thus avoiding long information searches and idle times. Typical questions the user can ask are based on the "What-When-Where-Who-Why-How" paradigm. Examples include "What does Alarm 002 means?", "How can I solve the Alarm 005 on the rinsing machine?", "Where is the damaged component located?", "When did the alarm appear?", "Who is responsible to operate on the machine?". Additional information about the intelligent voice assistant and the benefits deriving from its use with a Digital Twin application in manufacturing systems can be found in Longo et al. (2019).



(a) (b) (c)

Figure 6: Alert on smartphone and alarm information on the mobile application.

Similarly, the operator wearing the Microsoft HoloLens on the production floor may immerse into the cyber-physical manufacturing environment. A picture of how the alarm is displayed on the Microsoft HoloLens MR Application (i.e. what the operator sees) concerning a real industrial machine is showed in Figure 7. Even in this case, the alarm notification continues to appear and be signaled to the user also with sound chimes until he/she “opens” the notification and checks the ongoing issue.

Figure 7: Digital mockup of the alarm notification in the MR app

5 Case study

Case studies are a recognized methodology for explaining contemporary circumstances, such as the “how” or “why” of specific phenomena, and to deeply investigate new phenomena in their real conditions (Yin, 2018). These considerations form the basis for testing the two devices, HoloLens and mobile phone, through a real case, thanks to a partnership built with a company based in the North of Italy and operating in the beverage area, the renowned Parmalat.

Specifically, an aseptic bottling line was selected, consisting of five machines, i.e. bottle sterilizer, bottle rinser, cap sterilizer, filler, and capper; this line is exhaustively described in (Rosi, Vignali, & Bottani, 2018). These authors have also developed and applied a framework for selecting the most suitable “Industry 4.0 application” to enhance operators’ safety to the line in question. Without repeating the whole study here, it is worth mentioning that the authors concluded that AR was the best solution for the plant under examination, as the technology can actively support the employees avoiding errors during the execution of their tasks. This is the reason why this specific system was selected for implementation in this study.

To be more thorough, Figure 7 below illustrates the production flow (Vignali, et al., 2019), while Figure 8 shows a part of the real plant.

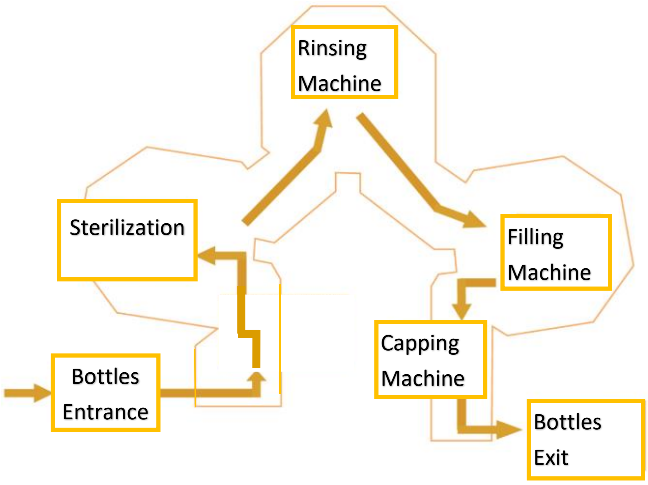


Figure 8. Production flow of the aseptic filling line.

Figure 9. some of the machines in the aseptic filling line.

5.1 System installation and experiment set-up

As mentioned, the W-Artemys system is based on the integration of three main parts: (i) the web application; (ii) the mobile app; and (iii) the MR app (this latter based on the use of Microsoft HoloLens). In order to be used to support operations in a real context, the W-Artemys system requires a preliminary *ad-hoc* set-up procedure, briefly described as follows.

1. Installation of the web application. The web application can be installed locally – e.g. on the company servers – or on servers provided by third parties. Data related to alarms or warning in a plant, as well as data related to the machine working conditions, are typically sensitive information for a company; thus, there is often the need to avoid the dispersion of these data outside the company or their misuse by hackers, which could compromise the worker's safety conditions. Hence, the preferred scenario for implementing and using the solutions developed is the first option, i.e. building a local connection, which is more suitable whenever data sharing outside the company may put at risk the company know-how, or when the internet connection is not available at the machine level. The web app installation includes the web-server installation (the web server Apache has been used for the W-Artemys system), the database installation (MySql for the W-Artemys system), and the framework installation (Laravel), including the proper integration of the W-Artemys programming code and DB configuration;
2. Installation of the mobile app on the devices, including the push notification system;
3. The set-up of the zero position for the MR app. Indeed, the W-Artemys system does not make use of tags (marker-less), which means that it can locate the machine with the alarm based on the location

of the machine determined *a priori* in the plant. This is done by using a reference system and locating on this reference system all the company machines and assets. Then, in correspondence with each machine, a HoloLens wearing position can be defined; this is the position where the operator is required to start the W-Artemys MR application.

Before testing the solution, it is always required to connect the W-Artemys system with the machine embedded system; creating such connection was another "syntactic" interoperability problem. Indeed, our designing effort was directed toward the development of an interoperable and reusable system. Nevertheless, each production system has its own informative system and each machine can have its own embedded system. Even if properly working, sometimes informative and embedded systems are quite old and information about the way they work, versions and user's manuals are no longer available. This makes the syntactic interoperability even more complex and trial and error approaches are often required. In the case study carried out, this happened at the time the connection between the MySql W-Artemys database and the machine database was established for the first time. Obviously, this aspect is strongly linked to the choice of the company involved in the real case implementation, since the IoT infrastructure might require dedicated connections to the company's information system and to the sensors/actuators located in the plant for data collection.

5.2 Testing procedure

According to a recent analysis by (Bottani & Vignali, 2019) and (Egger & Masood, 2020), who reviewed the last ten years of literature related to AR implementation in the manufacturing context, key performance indicators (KPIs) for the evaluation of AR solutions can be either technical, i.e. aiming at evaluating technical characteristics of given technologies, such as its correct functioning, the response time of the device or the number of devices on which the solution works, or related to the performance resulting from its usage. In this specific case, the tests aimed to evaluate the usability, effectiveness, and acceptance of both the AR solution prototype and the mobile app perceived by exactly eight operators during a normal workday with the system in function (see Figure 10 for an example of usage of the HoloLens). The number of users involved in the testing phase was determined as a compromise between the need for having a sufficient amount of data and the need for not suspending for a too long time the activity of the company where the tests were carried out. Nonetheless, this number is in line with several previous studies that developed "in the field" user tests for evaluating the effectiveness of AR solutions in industrial contexts (e.g. (El Kabtane, Sadgal, El Adnani, & Mourdi, 2016); (De Crescenzio, Fantini, Persiani, & Di Stefano, 2011)).

After having been shortly introduced to the technologies, the operators involved were asked to respectively wear/handle the two devices they have never seen before for 15 minutes. The order by which the technologies were tested was randomized across the employees. Users were not preliminarily trained about the usage of the devices and solution, and were not experts in this field; this choice was made in order not to bias the evaluation of the solutions' usability, which relies on different people being able to use it efficiently and achieve a set of specific functional objectives (De Crescenzio, Fantini, Persiani, & Di Stefano, 2011).

In previous studies testing AR solutions in real contexts, no specific information was provided as far as the minimum test time, since it was supposed to be the time needed for completing the tasks (Kluge & Termer, 2017); in many user tests, however, the testing time is limited to some minutes (e.g. (Webel, et al., 2013); (El Kabtane, Sadgal, El Adnani, & Mourdi, 2016); (De Crescenzio, Fantini, Persiani, & Di Stefano, 2011)). The testing time of 15 minutes was therefore determined based on a preliminary test carried out by the researchers of the University of Parma in November 2019 (Tancredi, Tebaldi, Bottani, Longo, & Vignali, 2019); this laboratory test showed that 15 minutes is a reasonable time for assessing the usability of the technologies and for answering the questions submitted for the evaluation (see section 5.3). This time was also sufficient for a user to complete the task with the two technologies. Indeed, each participant was required to: 1) wear/handle the device; 2) detect the alarm message sent by the machine and appearing on the device; 3) search for the solution procedure using the functionalities offered by the two devices; 4) restore the normal working condition of the machine. Equally important, the timing for testing the technologies was compatible with the availability of the operators, as they all were working in the two testing days.

Tests were carried out *in situ* on January 8th and 9th, 2020. Six workers from Parmalat were involved, and two from the company producer of the whole line, GEA Procomac S.p.A., since it was preferable to get more feedbacks from the company which is supposed to concretely deal with the two solutions.

Figure 10: example of usage of the HoloLens during the testing phase.

5.3 Evaluation procedure

The evaluation of both technologies was made based on 14 statements, to which the employees were asked to express their degree of agreement on a five-point Likert scale, from 1 (complete disagreement) to 5 (complete agreement). Ten statements were taken from the System Usability Scale (SUS) (Brooke, 1986), whose usage for evaluating wearable solutions in AR is not new; for instance, Wang et al., (2019) (Wang, Tsai, Lu, & Wang, 2019) or Helin et al., (2018) (Helin, Kuula, Vizzi, Karjalainen, & Vovk, 2018) already adopted this tool for their assessment. These statements, listed below, were properly translated in Italian language:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think I would need the support of a technical person to be able to use the system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with the system.

These statements were treated from a mathematical point of view applying the computational procedure described by (Brooke, 1986); the final score obtained returned a global view of the subjective assessments related to the usability of the technology.

The additional list of four statements, rated again on a five-point Likert scale, is provided below:

a. I think the solution was easy to use.
b. I think the solution is useful for carrying out tasks.
c. I learned something from the instruction provided.
d. I appreciated the solution.

From a practical point of view, it is reasonable to assume that there are different types of possible intervention on the plant. For the purpose of this study, interventions were categorized as simple, medium or complex, mainly as a function of the number of tasks they require, their total time, or the need for a specialized employee for carrying them out. The level of complexity of interventions could somehow affect the perception about the usefulness of the solutions or the possibility of learning something from the usage of the solutions; hence, the response provided to the statements used for the evaluation could vary depending on the complexity of the intervention, as well. In line with this consideration, for some statements (i.e. statement 1 of the SUS and statements b, c, and d of the additional list) the respondents were asked to provide three answers taking into account the case of simple, medium, or complex intervention on the plant. In the calculation of the final score, the average value was considered. In case no answer is provided, the survey is considered valid anyway; simply statistics are applied on the results provided, excluding the missed values.

Respondents were also profiled with respect to their gender, age, educational level, role, and company they belong to.

5.4 Results and discussion

5.4.1 Users profile

The profile of the subjects involved in the study is shown in Table 1; general information about the users, useful for interpreting the results, are also included. As can be seen from the table, three subjects from Parmalat were selected as being representative of the management (in other words who should finance the investment), while the remaining three were line operators, i.e. those subordinates who are expected to handle and make use of the devices; their opinion about the usability is therefore particularly important.

Table 1: users' profile and personal details.

	User 1	***User 2***	***User 3***	***User 4***	***User 5***	***User 6***	***User 7***	***User 8***
Gender	Female	Male	Male	Male	Male	Female	Male	Male

Age	43	42	31	46	48	35	50	51
Educational Level	PhD	High School Diploma	High School Diploma	High School Diploma	High School Diploma	Master's Degree	High School Diploma	High School Diploma
Company	GEA Procomac S.p.A.	GEA Procomac S.p.A.	Parmalat	Parmalat	Parmalat	Parmalat	Parmalat	Parmalat
Role	R&D Responsible	Computer Technician	Line Operator	Line Operator	Line Operator	Product Unit Responsible	Maintenance Supervisor	IT Manager

5.4.2 HoloLens results

5.4.2.1 SUS scores

As far as the HoloLens SUS scores, they are shown in detail in Table 2. The procedure for computing the scores (last row in the Table) is illustrated in (Brooke, 1986), while the overall final outcome for the technology was deduced as the mean of the users' scores. Looking at the numerical results in Table 2, what stands out is that the HoloLens got a sufficient result overall, i.e. 71.74, which is above the threshold of 70 suggested by Bangor et al., (2009) (Bangor, Kortum, & Miller, 2009) and Brooke (2013) (Brooke, 2013) for considering a technology acceptable; however, for three users this innovation is not positively assessed.

In general terms, it is interesting to note that the two highest scores came from two of the three line operators; the third, who is also the oldest among them, got a lower value compared to them, more specifically one of the three insufficiencies. Note also that the highest value corresponds to the youngest user, who is probably the closest to the technology in question. Another point where to draw the attention is that the lowest scores (insufficiencies) are gained by the users who act as supervisors in Parmalat, in addition to the abovementioned line operator; probably, these users are more unbiased and conscious of possible implementation problems thanks to a broader view of the system.

Table 3 details the scores against the SUS statements as a function of the respondent's role. As mentioned, what is paramount is that the line operators, as the real users of the solution, find it useful and easy to use. From the results in the table, it is easy to see that the line operators actually found the solution very easy to use (statement 3) and to understand (statement 5); they also expressed a positive judgment about the likelihood of the system being used frequently (statement 1). The reason for these results could be the fact that due to their low level of education, line operators are attracted and excited by innovations and new technologies they usually do not deal with.

Table 2: HoloLens SUS results.

Statement	***User 1***	***User 2***	***User 3***	***User 4***	***User 5***	***User 6***	***User 7***	***User 8***
1	2.67	2.3	4.67	3	4.3	4	3	3.33
2	2	2	1	1	3	1	4	2
3	3	4	5	5	4	3	4	4
4	2	1	2	2	1	4	3	4
5	4	4	4	4	3	3	3	3
6	1	2	1	1	3	1	3	1
7	4	3	4	5	4	3	4	4
8	1	3	2	2	3	2	3	2
9	4	4	5	2	3	4	4	5
10	1	1	1	1	1	2	5	2
SUS SCORE	76.675	70.75	89.175	80	68.25	67.5	50	70.825
HOLOLENS SUS SCORE: 71.74								

Table 3: HoloLens SUS scores vs. respondent's role.

SUS statement	Respondent's role		
	Technician	Line operator	Responsible
1	2.0	4.0	3.3
2	2.0	1.7	2.3
3	4.0	4.7	3.5
4	1.0	1.7	3.3
5	4.0	3.7	3.3
6	2.0	1.7	1.5
7	3.0	4.3	3.8
8	3.0	2.3	2.0
9	4.0	3.3	4.3
10	1.0	1.0	2.5

5.4.2.2 Statements a-d scores

Table 4 presents results from the statements a-d listed in the previous sub-section, including their mean score (μ) and standard deviation (σ).

Table 4: HoloLens a-d statements results; Note: "-" means the user did not provide any answer.

Statement	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	μ	σ
a	5	4	5	4	4	3	5	4	4.25	0.71
b – Simple	3	1	5	1	2	3	1	3	2.38	1.41
b – Medium	4	2	5	3	3	3	4	3	3.38	0.92
b – Complex	4	4	4	4	4	3	5	2	3.75	0.89
c – Simple	-	5	4	4	-	3	-	4	4	0.71
c – Medium	-	5	4	4	-	3	-	4	4	0.71
c – Complex	-	5	5	3	-	3	-	4	4	1
d – Simple	4	2	5	4	5	4	-	3	3.86	1.07
d – Medium	4	3	5	5	5	4	-	3	4.14	0.9
d – Complex	4	4	5	5	5	4	4	2	4.13	0.99

About these additional statements, in general, all the users agree on the ease of usage of HoloLens, and more specifically they think this solution can be helpful for complex interventions, which got the highest mean scores and the lowest standard deviation among the three levels of complexity. Three users out of eight did not reply to statement c; specifically, these users were one of the supervisors from Parmalat, one of the line operators, and the R&D responsible from GEA Procomac S.p.A. The reason is that workers from Parmalat argued they did not feel able to express any opinion about the possibility of learning something from the usage of the application since they were already familiar with the procedures (and therefore, they did not actually learn anything new in practice). The user from GEA, instead, was more interested in evaluating and understanding the functioning of the device itself, rather than the instruction to intervene on the machine, which is not properly her task as an R&D manager.

In line with that, Table 5 deepens the relationships between the scores of the statements and the respondent's role. From this table is can be seen that the judgments expressed by the line operators are higher than the remaining categories of employees when looking at the ease of usage of the solution (statement a), its usefulness (statement b), and the level of appreciation for the application developed (statement d). It is also interesting to note that line operators (all from Parmalat) expressed a lower judgment about the possibility of learning from the solution developed, compared to the technicians (from GEA Procomac), which confirms the previous findings.

Table 5: HoloLens a-d statements scores vs. respondent's role.

	RESPONDENT'S ROLE		
Statements a-d	**Technician**	**Line operator**	**Responsible**
a	4.0	4.3	4.3
b – Simple	1.0	2.7	2.5
b – Medium	2.0	3.7	3.5
b – Complex	4.0	4.0	3.5
c – Simple	5.0	4.0	3.5
c – Medium	5.0	4.0	3.5
c – Complex	5.0	4.0	3.5
d – Simple	2.0	4.7	3.7
d – Medium	3.0	5.0	3.7
d – Complex	4.0	5.0	3.5

5.4.3 Smartphone results

5.4.3.1 SUS scores

Regarding the mobile app installed on the smartphone, instead, the SUS results are proposed in Table 6. Note that in this case, the number of users involved is seven as user 7 could test the HoloLens technology only for reasons of time and work. From this table, it can be seen that SUS scores for the smartphone solution are very high (>90); the only exceptions are the judgment expressed by the IT responsible from Parmalat (whose score is 70) and the "insufficiency" obtained by the product unit responsible (user 6).

In general terms, the users all agree on the fact that the solution was not complex to use and to understand (statement 2) and that the system was linear and there were no inconsistencies (statement 6). This positive result is in line with a previous test carried out in a simulated environment to evaluate the same device used by a group of researchers (Tancredi, Tebaldi, Bottani, Longo, & Vignali, 2019). In that test, the SUS score was 84.375; actually, the in-field application got even a more satisfactory result, and this is even more meaningful since the users, in this case, are those who should operatively use the solution and are more aware of an eventual industrial application.

Again, to evaluate the judgments expressed on this technology by the real users, i.e. the line operators, Table 7 details the scores against the SUS statements as a function of the respondent's role. From the outcomes in the table, it is easy to see that the line operators expressed a very positive judgment about the ease of usage (statement 3) and understanding (statement 5) of the solution; they are also confident about the likelihood of the system being used frequently (statement 1). This positive evaluation can be easily justified taking into account that the mobile app installed on a smartphone is a quite common technology: nowadays, everybody owns a smartphone or at least is able to use it, which enhances its likelihood of being used and understood by employees.

Table 6: Mobile app SUS results.

Statement	***User 1***	***User 2***	***User 3***	***User 4***	***User 5***	***User 6***	***User 8***
1	5	5	4.67	5	4	4	3
2	1	1	1	1	1	1	1
3	4	5	5	5	5	3	3
4	1	1	2	1	1	4	3
5	4	4	5	5	5	3	4
6	1	1	1	1	1	1	1
7	4	5	5	5	5	3	4
8	1	1	1	1	1	2	3

9	5	5	5	5	5	4	4
10	1	1	1	1	1	2	2
SUS SCORE	92.5	97.5	96.675	100	97.5	67.5	70
MOBILE APP SUS SCORE: 88.81							

Table 7: Mobile app SUS scores vs. respondent's role.

	Respondent's role		
SUS statement	**Technician**	**Line operator**	**Responsible**
1	5.0	4.7	4.0
2	1.0	1.0	1.0
3	5.0	5.0	3.3
4	1.0	1.3	2.7
5	4.0	5.0	3.7
6	1.0	1.0	1.0
7	5.0	5.0	3.7
8	1.0	1.0	2.0
9	5.0	5.0	4.3
10	1.0	1.0	1.7

5.4.3.2 Statements a-d scores

The detailed scores of the mobile app against statements a-d are shown in Table 8, while their share as a function of the respondent's role is shown in Table 9. From a general perspective, all the users appreciated the solution, as can be deduced by the average scores (which are always >3). The lowest score was expressed about the possibility of learning something in the case of simple interventions (statement c-1); probably, being the intervention simple and the device known, the user has low opportunities to learn something new.

Looking at Table 9 it can also be seen that both line operators and technicians expressed very positive judgments about the mobile app. It is also interesting to note that compared to the remaining categories of employees, line operators expressed lower judgments about the learning potential (statement c), regardless of the complexity of the task. This is probably due to the fact that line operators have a more complete knowledge about the tasks to be carried out to restore the machine functioning in the case of alarms or warnings and therefore, they actually do not learn these instructions from the usage of the mobile app (which, on the contrary, could be the case for technicians or responsible). Despite this, line operators appreciated the solution very much (statement d) and found it useful as a support for carrying out the required tasks (statement b).

Table 8: Mobile app a-d statements results; Note: "-" means the user did not provide any answer.

Statements a-d	*User 1*	*User 2*	*User 3*	*User 4*	*User 5*	*User 6*	*User 8*	*μ*	*σ*
a	1	5	5	5	5	4	4	4.14	1.46
b – Simple	5	5	5	5	4	3	4	4.43	0.79
b – Medium	5	5	5	5	4	3	4	4.43	0.79
b – Complex	5	5	4	5	4	3	2	4	1.15
c – Simple	4	5	4	1	4	3	3	3.43	1.27
c – Medium	4	5	5	2	4	3	3	3.71	1.11
c – Complex	4	5	5	2	4	3	2	3.57	1.27
d – Simple	5	5	5	5	5	3	4	4.57	0.79
d – Medium	5	5	5	5	5	3	4	4.57	0.79
d – Complex	5	5	5	5	5	3	2	4.29	1.25

Table 9: Mobile app a-d statements scores vs. respondent's role.

	RESPONDENT'S ROLE		
Statements a-d	**Technician**	**Line operator**	**Responsible**

a	5.0	5.0	3.0
b – Simple	5.0	4.7	3.7
b – Medium	5.0	4.7	3.7
b – Complex	5.0	4.3	3.3
c – Simple	5.0	3.0	3.7
c – Medium	5.0	3.7	3.7
c – Complex	5.0	3.7	3.7
d – Simple	5.0	5.0	3.7
d – Medium	5.0	5.0	3.7
d – Complex	5.0	5.0	3.3

5.4.4 Comparison of the technologies

A comparison of the results obtained by the two devices against the SUS statements (Table 10) shows that the smartphone is generally perceived as more user-friendly and complete than the HoloLens, regardless of the role or education level of the respondent. Indeed, it is easy to see that in all the "positive" SUS statements (i.e. statements 1, 3, 5, 7, and 9) the difference in the scores is positive as well, which means that the smartphone got higher scores than the HoloLens. Similarly, in all "negative" SUS statements (i.e. statements 2, 4, 6, 8 and 10), the difference is negative, meaning, once again, that the smartphone was preferred.

Table 10: comparison of the average scores of the two devices – SUS statements.

SUS statements	HoloLens	Smartphone	Mean difference (smartphone score – HoloLens score)
1	3.38	4.43	1.05
2	2.00	1.00	-1.00
3	4.00	4.29	0.29
4	2.38	1.86	-0.52
5	3.50	4.29	0.79
6	1.63	1.00	-0.63
7	3.88	4.43	0.55
8	2.25	1.43	-0.82
9	3.88	4.71	0.84
10	1.75	1.29	-0.46

The same comparison, carried out on statements a-d (Table 11) shows that the HoloLens was perceived as a slightly easier technology to be used compared to the smartphone; this is probably because the HoloLens allows the user to receive instructions that can be immediately displayed, thus avoiding the need for searching for these instructions on the device. At the same time, however, the smartphone appears to be more useful for carrying out the task (no matter its level of complexity) compared to the HoloLens. It could be argued that this result depends upon the need for the employees to wear the HoloLens, which could become cumbersome when worn for the whole work shift. The solution implemented on the smartphone is also more appreciated than the solution installed on the HoloLens. This is in line with the outcomes in Table 12, which summarizes the respondents' opinions about the device they preferred during the testing phase (user 7 is excluded from the comparison of the two devices). According to these findings, the reasons for preferring the smartphone mainly rely on the more mature, more user-friendly, and less cumbersome technology. Interestingly, the results also indicate that the respondents learned more when using the HoloLens than when using the smartphone, regardless of the type of task carried out. Probably, this is due to the fact the HoloLens is a newer device, which was probably unknown to most of the respondents, while the smartphone is a known device; a new device is indeed likely to enhance motivation and knowledge gain (i.e. cognitive learning – (Schmitz, Specht, & Klemke, 2012)).

Table 11: comparison of the scores of the two devices – statements a-d.

Statements a-d	HoloLens	Smartphone	Mean difference (smartphone score – HoloLens score)
a	4.25	4.14	-0.11
b-1	2.38	4.29	1.91
b-2	3.38	4.29	0.91
b-3	3.75	4.00	0.25
c-1	4.00	3.57	-0.43
c-2	4.00	3.86	-0.14
c-3	4.00	3.86	-0.14
d-1	3.86	4.43	0.57
d-2	4.14	4.43	0.29
d-3	4.13	4.29	0.16

Table 12: Favorite device and general reason. Note: "-" means the user did not provide any answer.

User	*Favorite device*	*Reason*
1	-	HoloLens is useful to identify the exact position where to intervene; the smartphone is comfortable to handle and easier to understand.
2	Mobile App	Technologically mature, easy to use for everybody; at present, HoloLens is useful for complex interventions, but in the future, they could reach the maturity smartphones own today.
3	Mobile App	Less cumbersome.
4	Mobile App	Quicker and more comfortable.
5	Mobile App	Less cumbersome.
6	HoloLens	Useful for complex interventions, allowing hands-free.
8	Mobile App	More user-friendly; HoloLens would be too difficult to be managed from a line operator.

Looking again at Table 12, it is immediate to see that the preferred solution was almost unanimously the smartphone app, no matter the level of instruction or the age of the respondents; for sure this solution is easier to understand and to be implemented, and people are more confident and practical with the technology. The device is also easy to be handled, as well as to keep in a pocket. On the contrary, the HoloLens were perceived as less usable; this could be a logical consequence of the newness of the technology, which has certainly potential, but is still less widespread and probably turns out to be unknown to many operators. Interestingly, one employee indicated the HoloLens as the preferred device in the light of its usefulness for complex interventions, confirming the potential of this technology.

5.5 Implications

At present, it is likely that production plant machines are sometimes not "Industry 4.0 ready"; therefore, an additional "step ahead" should be done by the Industry 4.0 technologies. In line with that, the testing phase carried out allows for some considerations to be drawn when pondering the implementation of Industry 4.0 solutions. To be more precise, results from the tests indicate that HoloLens is less appreciated than the mobile app, which could suggest that this technology still has some limitations for a practical application. Examples of these limitations include the imperfect working of the spatial mapping (which needed to be restarted at every launch of the application), the limited field of view and wearability, the battery duration. Some of these issues could be improved by the newly released Microsoft HoloLens 2.

It follows that the appropriate device for the technical implementation of the solution should be carefully chosen. This choice is typically a compromise solution between different aspects, such as:

1) The cost of the device. Innovative “cutting-edge” devices will be more interesting to test from a scientific point of view, but their cost will be generally higher; this is for instance the case of wearable devices (e.g. smart glasses). At the same time, it is worth mentioning that the cost of these devices typically drops considerably in 12-24 months; hence, the wearable devices tested in this study could become usable after the completion of the W-Artemys project;

2) The need to ensure the (almost continuous) usage of the device by the operators in the real working conditions, taking into account convenience of use and ergonomics characteristics of the device, as well as ambient conditions (e.g. noise or dust), which could force the operators to also wear specific personal protection equipment;

3) The technical characteristics of the devices, which vary as a function of the device considered.

6 Conclusions and future research

Implementing fault detection and early warning systems in manufacturing plants may remarkably impact positively on productivity, reduce downtimes and enhance the employees’ safety. Benefits would be even higher if such systems are integrated with technologies enabling more efficient information fruition and interaction by the field operator, such as Mixed Reality and Intelligent Digital Assistants with vocal interaction.

This research study fills the gap of the industrial domain with other sectors (e.g. construction, healthcare) where MR has been successfully tested and implemented. A fault detection and early warning system based on wearable and interactive MR has been designed, developed, deployed, and tested in a real aseptic bottling line consisting of five machines owned by one of the most important companies operating in the beverage field. The testing objectives were to ascertain the usability and level of acceptance of these solutions by the line and field operators (who are those employees that will be using these tools on the shop floor). The results of the testing phase showed that the usability of the mobile and MR-based devices was positively rated by all users involved. In general, the users appreciated the mobile app, which is probably a more familiar technology, while the HoloLens were perceived as less usable, although one employee indicated this technology as the preferred one for complex interventions on the plant.

Besides testing, the case study also allowed to identify the main criticalities for the practical implementation of these technologies and the next actions for companies and researchers. To be more precise, the major issue in deploying Industry 4.0 solution in real manufacturing/production systems is the limited current level of digitalization of shop floor machines and assets, which need to be properly equipped with external systems/sensors to collect real-time health data and exchange them over a network. This consideration, as well as the remaining lessons learned from the case study, can be very useful for companies willing to implement this kind of solution in their working environment and for researchers to advance the state-of-the-art in the field of fault detection and early warning systems in the Industry 4.0 era.

For instance, from what has been the experience in this specific case study, the machine embedded system, as well as the company’s information system, were not able to redirect a call on the W-Artemys system API devoted to receiving (and sharing with the mobile app and with the MR app) an incoming machine alarm. This step was required to let the W-Artemys user know about the presence of a new alarm on the machine, and despite the problem has been solved by programming and adding an ad-hoc time-out trigger within the machine alarm database, it has been a resource-consuming approach. It is therefore paramount that the companies willing to deploy solutions such as that described in this paper ensure the availability of a system (i.e. a set of machines) equipped with sensors and actuators that allow exploiting the functions of the Industry 4.0 technologies in the most effective way. Also, the companies involved must have information technology experts available for supervising the implementation process and should are willing to test the technical solutions following a scientific approach.

Another fundamental aspect is that, as most of the web applications are nowadays installed over the cloud provided by third parties, it is required that each machine of the manufacturing system is able to access the internet to share data with the W-Artemys system. As in the previous case, machines are often not equipped with internet access, which is why a local installation of the entire W-Artemys system should be considered. The lesson learned in this case is that the deployment of Industry 4.0 systems (like W-Artemys) could be done in different steps; to be more precise, the first step is the installation of a local instance of the W-Artemys system, then the system can be migrated over the cloud once all the machines and assets involved have their own internet access.

Among the future research activities, it would be appropriate to allow the operators to use any innovative solution for a sufficiently long time horizon, with the purpose of evaluating their real attitude to accept the technological change and to really use the solution developed, as well as for collecting their suggestions for improving that solution. This implicitly means that for each application developed, it will also be important to carry out technical tests, to evaluate their functionality and improve it. As a further point, the active use of wearable technologies could allow for collecting additional data, which could help improve the worker's safety conditions (e.g., smartwatches can monitor the heartbeat and alert in case of anomalous situations) or to verify the effectiveness of the training received (e.g., HoloLens could record the actions of the operators, thus verifying the correctness of the task carried out). However, the possibility of using wearable technologies for these additional purposes must be verified in accordance with the applicable legislation on operator's privacy and is therefore left for future studies.

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