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An Intelligent Product Service System for Adaptive Maintenance of Engineered-to-Order Manufacturing Equipment Assisted by Augmented Reality

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Abstract: Under the framework of Industry 4.0, machines and machine tools have evolved to smart and connected things, comprising the Internet of Things (IoT) and leading to the Mass Personalization (MP) paradigm, which enables the production of uniquely made products at scale. MP, fueled by individualization trends and enabled by increasing digitalization, has the potential to go beyond current mass customization. Although this evolution has enabled engineers to gain useful insight for the production, the machine status, the quality of products, etc., machines have become more complex. Thus, Maintenance Repair and Overhaul (MRO) operations should be undertaken by specialized personnel. Additionally, Augmented Reality (AR) can support remote maintenance assistance to handle unexpected malfunctions. Moreover, due to advances regarding Product Service Systems (PSS), manufacturing companies are offering many services to improve user experience. Consequently, in this manuscript the design and development of a method based on the principles of servitization for the provision of an intelligent and adaptable maintenance service assisted by AR are presented. The contribution of the manuscript extends to the provision of an optimization algorithm for adapting the schedules of the stakeholders based on the energy supplier predictions. The developed method was tested and validated on an industrial case study of injection mold maintenance, achieving 11% energy reduction, 50% less time for mold inspection, and a 20% rise in on-time mold deliveries.

Keywords: Intelligent Product Service System; Industrial PSS; Product Service System (PSS); Augmented Reality; Engineered-to-Order; maintenance

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1. Introduction

Companies are attempting to stay ahead of their competitors in the current extremely competitive business environment by implementing the latest manufacturing trends. Thus, we are currently living through the Fourth Industrial Revolution, also known as "Industry 4.0" [1,2]. Industry 4.0 is based on manufacturing trends such as the Internet of Things (IoT), Big Data Analytics (BDA), Cyber Physical Systems (CPS), advanced sensors and networking, intelligent algorithms, and Virtual and Augmented Reality to upgrade the manufacturing process and enable the creation of personalized products [3]. Therefore, two cornerstone principles underlying Industry 4.0 are digitalization and servitization, also known as the Internet of Services (IoS) [4].

The innovative Mass Personalization (MP) paradigm, not fully investigated under Industry 4.0, represents a high-tech manufacturing automation strategy, enabling the better integration and smoother cooperation of hardware devices and machinery (IoT), software systems, and humans in the extended manufacturing value chain. Smart Factories, the core of this new paradigm, are characterized by a high degree of digitalization and data centricity. Jointly cooperative working teams of humans and robots autonomously guided by lights out are collaborative, operating in the so-called Lights-out Factories. Extreme automation until "everything is connected to everything else" creates vulnerabilities that have not been investigated extensively so far. The next industrial revolution, Industry 5.0, is expected to cope with these new challenges by bringing the efficiency of manufacturing systems and supply chains beyond limits. Industry 5.0 aims at democratizing the co-production of knowledge by employing cutting-edge digital technologies, e.g., Big Data and IoT, being supported by three main pillars: (a) human centricity; (b) resilience, and (c) sustainability. One of the main focuses relies on the development of Product Platforms aiming at improving the production efficiency and creating high added value for the customer/end-user [5].

During the last decades, manufacturing systems are undergoing a series of changes in order to transform their business models from craftsmanship towards a more customer-oriented manufacturing approach, in an attempt to tackle the volatility of modern market landscape. By extension, this transformation enables the better alignment to customer demands, as a result of the mass customization and personalization, Business-to-Business (B2B), and Business-to-Customer (B2C) paradigms. Consequently, enterprises require competitive business strategies and powerful engineering tools to enable multi-dimensional knowledge exchange throughout the supply chain [6]. Under the framework of Industry 4.0, companies are increasingly shifting their business models from manufacturing and offering only tangible products to the design and development of complete solutions, which include services. By extension, this move enables the development of more sustainable products [7], making it critical for industrialized countries to shift to the Industrial Product Service System (IPSS) paradigm [8]. The importance of servitization is widely recognized in industry as it moves toward mass customization manufacturing systems [9].

The Product Service System (PSS) [10], the dominant hybrid solution of providing services in addition to or instead of product ownership, promises competitiveness and sustainability through the identification of customer value. The academic community has long recognized the importance of evaluation in the early stages of PSS development, but as indicated by [11], PSS evaluation is still an immature field with few concrete results and approaches. Furthermore, the integration of cutting-edge digital technologies in the design and distribution of PSS can be considered as a cornerstone, based on the findings of Sala et al. in [12]. In this research, the authors focus on the implementation of AR technology as a PSS in the field of Maintenance, Repair, and Training.

Maintenance is a widely offered service because it is regarded as a critical activity throughout the lifecycle of a product. Engineers can now identify faults and malfunctions in products more easily and precisely thanks to recent technological advances in information and communication technologies (ICT) [13,14]. To that end, the three steps listed below can be used towards addressing this problem. To begin, data can be retrieved from Cloud repositories (historical data from previous maintenance procedures). Thereinafter, they will be processed using appropriate algorithms. Finally, they either predict when components will fail (predictive maintenance) [15] or evaluate the health of components (condition-based maintenance).

The Industrial Internet of Things (IIoT) allows businesses to provide more innovative solutions [16]. Among these technologies, AR enables the intuitive visualization of virtual information (of any kind, including data, 3D models, audio, and video) on the user's field of view, thus in modern manufacturing environments, the visualization of insightful data (machine health monitoring, machine specifications, assembly instructions, etc.) is enabled [17]. The combination of AR and maintenance has facilitated engineers to design and develop services (realized as mobile applications) for the provision of remote maintenance support (also known as tele-maintenance) [18]. Furthermore, visualizing the assembly steps of components that lead to the final product clarifies the maintenance process of complex industrial equipment [19]. Similarly, Cloud Computing and Cloud Manufacturing open up new opportunities for enterprises [20], as they can transform traditional business models in such a way that stakeholders not only maintain their competitive edge but also ensure their continued existence in the global market.

To that end, this research is an extended version of the research paper in [21] and presents an Intelligent Product Service System (IPSS) for adaptive maintenance of Engineered-to-Order industrial equipment based on AR. A key contribution of this research work is to facilitate PSS providers to successfully adapt their shopfloor schedule in order to incorporate the maintenance activities required for the repair of equipment, and simultaneously take into consideration the energy demand for the completion of these tasks. Moreover, it is also imperative to achieve more efficient communication between the shopfloor technicians and the engineering department. In order to test and validate the proposed framework, an industrial case study derived from a mold-making Small-Medium Enterprise (SME) was used.

The remainder of the manuscript is organized as follows. In Section 2, the most pertinent literature on the key components of this research work is investigated. Then, in Section 3 the PSS approach and the proposed system architecture are presented and discussed in detail. Then, Section 4 follows a technical discussion about the development of the PSS platform, including details about the software and hardware configuration of this application. Section 5 is dedicated to the description of the industrial case study used for the validation of the developments. Afterwards, in Section 6 a discussion on the validation results is presented. The manuscript is concluded in Section 7, along with the provision of directions for further elaboration.

2. State of the Art

In this section of the manuscript, relevant publications are investigated regarding the key topics of the manuscript. Concretely, in Section 2.1 the concept of Product Service Systems (PSS) is discussed through the prism of Industry 4.0. Then, in Section 2.2 the concept of PSS is extended to what is called Smart and Intelligent PSS, highlighting the key contributions for modern manufacturing and production systems. In Section 2.3 a discussion on a system's resiliency follows, as industry is heading towards a new revolution, also known as Industry 5.0, which will focus on augmenting humans and improving their position within the production/manufacturing environments. In Section 2.4, maintenance as a service is investigated. Similarly, in Section 2.5, energy distribution is investigated as a service. Finally, in Section 2.6, several key characteristics of Industry 5.0 are presented.

2.1. PSS under the Framework of the Fourth Industrial Revolution (Industry 4.0)

The investigation of the academic literature has provided evidence of the potential benefits associated with the digitization and digitalization of manufacturing systems, following the Industry 4.0 paradigm, and the shift to what is also known as intelligent manufacturing. This extends to the integration of IoT devices, including smart sensors, which are in turn integrated with processing units, and capable of performing data processing tasks with high computational speeds [22]. Moreover, engineers are more capable of developing a complete solution towards the PSS business models [23]. The authors in references [24,25] have investigated the potential of the pillar Industry 4.0 digital technologies and techniques such Cloud technologies, as well as Predictive Analytics (PA), in order to fully utilize the vast amount of data produced on a daily basis on the shopfloor level (Big Data). Big Data, however, require further processing by suitable algorithms in order to be transformed to information and by extension (based on the use of Artificial Intelligence (AI) approaches) to become useful knowledge. Afterwards, such knowledge will be useful for the development of novel Product Service offerings. Strozzi et al., in their research work [26], concentrate on Additive Manufacturing (AM), emphasizing the advantages of such technologies. More specifically, with AM, small batch products can be produced, up to one-off production, thus promoting the mass customization and personalization paradigms. As a result, individual customer requirements can be met more easily. Consequently, customized and adaptive PSS can become more feasible for manufacturers. However, since the complexity of modern manufacturing systems as well as the complexity of the products has increased, the authors in [9] have proposed a framework for the collaborative design of highly customized PSSs in order to compensate for the complexity mentioned before and facilitate manufacturers to establish better communication channels with their customers. In addition to that, a common issue that needs further attention from engineers is the setup of the suitable technological infrastructure required for the support the servitization transformation [25].

Taking into consideration the above-mentioned points, the ongoing advances in cutting-edge digital technologies under the framework of Industry 4.0, and the research work of the authors in [27], the key technologies and techniques of the design and development of the next generation of technology-driven PSSs are summarized in Table 1. Furthermore, based on the context of each technological field, the resulting PSSs are presented. For example, the integration of sensing systems and the utilization of the IIoT will enable engineers to develop smarter products, and BDA will enable the analysis of data from the usage of the PSS as a system, i.e., the usage of the tangible product, as well as the utilization of the associated service(s), etc.

Table 1. Correlation of key Industry 4.0 and their contributions to servitization.

Industry 4.0 Technology	PSS Approach	References
IIoT and smart sensors	Smarter products	[28]
BDA and AI	Data-driven services	[29]
Blockchain	Smarter service	[30,31]
AR	Smarter service design and delivery, Training, Maintenance	[32]
Cloud Computing	Flexible computing resources for digital services	[33]
AM	Product customization and adaptation	[34]
Energy Services	Servitization, environmental impact, resource planning, Energy Demand Management, scheduling	[35,36]

2.2. Smart—Intelligent PSS

The definition of a Smart PSS is as follows: "*an IT-driven value cocreation business strategy involving various stakeholders as players, intelligent systems as infrastructure, smart, connected products as media and tools, and their generated e-services as key values delivered that continuously strives to meet individual customer needs in a sustainable manner*." [37] Stakeholders, Service and Performance Checkout System (SCPs) and e-services, and intelligent systems are key elements, according to the definition, while value co-creation with sustainable concerns is the business value proposition. Stakeholders are participants in the value co-creation process who are divided into three categories: users, service providers, and manufacturers and vendors.

- Users: The people who demand or consume the value.
- Service providers: The companies/individuals who are responsible for designing, sharing, and/or performing maintenance of the offered services are designated as service providers.
- Manufacturers and vendors: All parties involved in the SCP manufacturing process are represented by manufacturers and vendors.

Additionally, the authors in [37] have presented the Smart PSS solution design, which is a complex process, with three general hybrid concerns outlined, as illustrated in Figure 1. More specifically, the design and development of a Smart PSS requires the co-existence of three entities, namely the intelligent system, the stakeholders, and the IT providers. The conjunction of the above-mentioned entities in pairs, starting from the top in a clockwise fashion, leads to the "hybrid value" creation, which corresponds to the added value offered by PSSs and the extension of the product lifecycles, as a result of the integration of intangible services to the tangible/physical products. Moving on, the "hybrid design", corresponds to the creation of new services, thus new products, and by extension new a PSS as a result of the cooperation of the stakeholders with the PSS engineers/designers. The two parties have to collaborate closely in order to address existing challenges. Finally, "hybrid intelligence" corresponds to the utilization of data and information acquisition, processing, and transmission through a wide variety of smart and intelligent tools, technologies, and techniques.

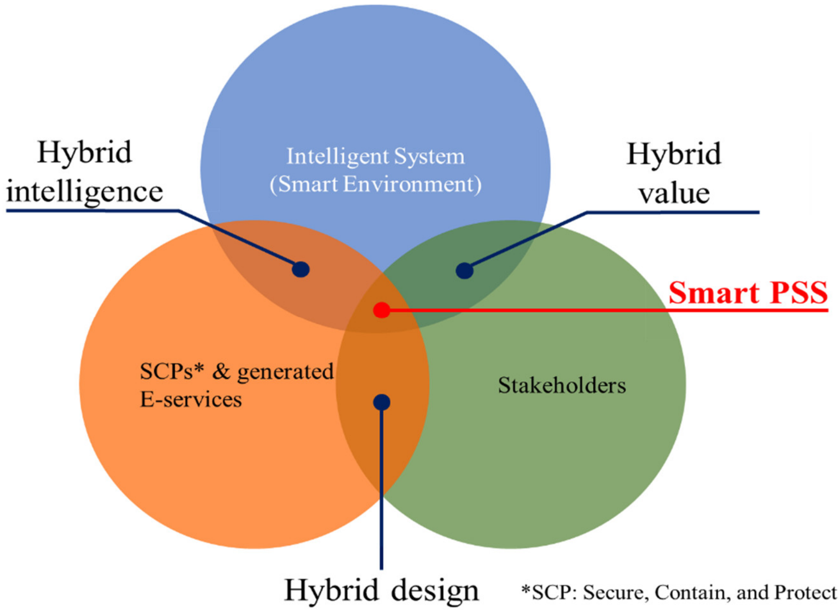

Figure 1. Smart Product Service System Solution, adopted from [37].

2.3. Towards Resilient Manufacturing Systems and Services in Industry 5.0

According to its definition, a resilient manufacturing system is *"A system with the ability to adjust its functioning prior to, during, or after operational changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions"* [38]. The ability of manufacturing activities to withstand and/or quickly recover from operational disruptions that threaten the continued operation of manufacturing operations at the desired level demonstrates their resilience [39,40]. As the Industry 4.0 paradigm develops smart and resilient capabilities in next-generation manufacturing systems, the workforce should also develop smart and resilient capabilities. Thus, the concept of Operator 5.0 has been introduced in the literature [41,42]. The "Resilient Operator 5.0" is defined as a smart and skilled operator who, with the help of information and technology, overcomes obstacles on the way to developing new, cost-effective solutions for ensuring manufacturing operations' long-term sustainability and workforce well-being in the face of difficult and/or unexpected conditions. In order to predict, react, and recover from a disruption, a Smart Resilient Manufacturing System can be defined as an agile and flexible/reconfigurable system that collects and analyzes operational and environmental data in real time using smart sensor systems and descriptive, predictive, and prescriptive analytics techniques. As a result, the degree of resilience of a manufacturing system will be determined by the resilience of its weakest sub-system. This will frequently be the human system due to its (human) frailty. When confronted with new obstacles, it will rely on its most powerful sub-system, which may also be the human system, because of its intuitive abilities to avoid negative outcomes or perform better than predicted [43]. Human technicians will return to factory floors as part of the Fifth Industrial Revolution, or Industry 5.0, which will combine human and machine brainpower and creativity to increase process efficiency by combining workflows with intelligent systems. While automation is the primary concern in Industry 4.0, Industry 5.0 will focus on human–machine collaboration. The autonomous workforce will be able to detect and inform human intention and desire [44].

2.4. Maintenance as a Service

Maintenance, according to the European Federation of National Maintenance Societies (EFNMS), can be defined as the execution of all the required actions leading to the restoration of equipment to its original condition (or near-original condition) following a cost-effective strategy. Thus, taking into consideration the original definition of maintenance, it becomes obvious that it constitutes an important stage of the product's lifecycle. Maintenance consumes a significant quantity of resources (including time and finances) throughout a product's lifecycle [45]. To mitigate its impact, efforts are being made to integrate novel technologies in an attempt to democratize technical knowledge, and facilitate its distribution, especially in remote locations. AR is one of the nine pillar technologies of Industry 4.0, which can be integrated in various aspects of technicians' everyday tasks targeting the reduction in their cognitive load. Consequently, engineers, through AR overlays and in conjunction with other ICT tools, are capable of setting up suitable communication channels with on-site technicians and providing them with remote guidance [19]. Machine breakdown is a common occurrence in an industrial environment, resulting in unexpected failures. However, because machine downtimes can be costly in terms of production, a preventive maintenance model must be implemented in order to improve the reliability of machine tools, i.e., to reduce mainly unexpected downtimes [46]. As a result, opportunities for integrating alternative technologies such as AR are emerging to address complicated maintenance tasks more efficiently. The goal is to provide intuitive 3D/virtual interfaces, aiming at the full digitization and digitalization of paper-based instruction manuals. Specially trained personnel are no longer required with this strategy. This transition relies on the utilization of Mixed Reality (MR) and AR Head Mounted Displays (HMD), Handheld Smart Devices (HHD), and wearable devices [47,48].

In order for manufacturing companies to maintain their competitive edge over the global market landscape, they have concentrated their efforts on the design, development, and provision of PSS [43]. Thus, this provides enough evidence that manufacturers are willing to produce complete solutions rather than solely products as specific artefacts. On the other hand, consumers are more willing to consume/acquire complete solutions rather than simple tangible products. As a result, several types of PSSs have been developed. However, based on their key characteristics, PSSs can be classified into three main categories, according to [49]:

- Product-oriented PSS: This type of PSS is characterized by the transfer of ownership of the tangible product to the customer; however, additional services, e.g., maintenance contracts, are provided.
- Use-oriented PSS: Opposite from the previous type of PSS, this type retains ownership of the product to the manufacturer, i.e., the service provider, who are targeting at selling only the functions of the product. In order to support this type of PSS, alternative solutions regarding the payment are required, such as sharing, pooling, and leasing.
- Result-oriented PSS: The third type of PSS is based on the complete replacement of tangible products by the accompanied services. For example, a common result-oriented PSS is the voicemail service, which by extension has replaced the need for acquiring and setting up a physical answering machine next to the phone. The development of such services has also enabled the further development of services which are offered by default in mobile/smart devices.

Therefore, based on the classification of PSS presented above, in this research work the proposed framework is based on the implementation of a product-oriented PSS approach.

2.5. Energy as a Service

Decarbonization, greater decentralization, and increased digitalization of energy systems are driving rapid changes in the energy sector today. Another facet of this effort is the involvement of larger consumers, such as manufacturing firms, with the goal of achieving more sustainable energy production and consumption systems using service-oriented business models [50]. As a result, energy providers are among the key suppliers making an effort towards shifting their business models to provide IPSSs in order to improve their sustainability, thereby increasing the added value of their offerings [51].

Using cutting-edge digital technologies, namely Cloud systems, IoT, and BDA, energy companies are attempting to combine centralized and distributed energy systems into a more complex system. In addition, Energy Sales Companies (ESCs) are becoming more digitalized to keep the electricity supply competitive and affordable while maintaining the supply of electrical power at adequately high levels. Consequently, stronger synergies between the manufacturing (demand) and energy (supply) sectors are required. In addition to that, innovative solutions are required to make the electricity market fit for distributed energy while also requiring the industrial sector to shift to energy-efficient manufacturing [52]. In the research work presented in [53], the authors analyzed how PSSs have originated. Their work also extends to highlighting the current applications of PSS, and they conclude with providing directions for further research based on the current trends. However, the contribution of Annarelli et al. [53] involves the discussion on the importance of building and maintaining relationships between suppliers and customers. What is more, key PSS drivers will be the reduction in environmental impact as well as the cooperation with authorities. The Product Service System (PSS) value proposition strategy is suggested as part of the mix of innovations necessary to move society toward more sustainable futures, based on extensive research [44]. Additionally, the authors in [50] present a design and development of an Industrial Product Service System (IPSS) business model, aiming for the collaboration between ESCs and manufacturing companies. Moreover, an adaptive production scheduling approach considering the power usage of manufacturers in response to time-varying energy prices is presented. Similarly, the authors in [35] proposed a methodology for conducting resource planning for the production and installation of IPSS, and according to this, the architecture of a Cloud-based tool is developed. The energy provision can be considered as a Product Service, which involves the contract as a product and a set of services. That leads the energy provider and the customers to mutually benefit through the performed collaboration [54,55].

In the literature review performed in the previous paragraphs, it can be highlighted that maintenance is an important aspect to the lifecycle of the products. As a result, the arising challenge is to develop intelligent solutions targeting the reduction in unexpected equipment downtimes, which could affect in a positive manner the reliability of modern manufacturing equipment.

2.6. Additional Features of Industry 5.0

Industry 5.0, as per the authors in Reference [56], is the industrial evolution led by humans, based on the 6R (Recognize, Reconsider, Realize, Reduce, Reuse, and Recycle) principles of industrial upcycling, a systematic waste prevention technique, and logistics efficiency design to evaluate life standards, innovative creations, and produce high-quality personalized products. There are some added features of Industry 5.0, rather than the three pillars (see Figure 2), which are discussed in this subsection.

2.6.1. Smart Additive Manufacturing (SAM)

Sustainable manufacturing is the most popular cost-effective approach for current manufacturing industries, as it helps producers execute development plans, reduce pollution, and maximize resource utilization throughout the development lifecycle [57]. AM, also known as 3D printing, is one of the most prominent features of Industry 5.0, and it is used to make manufacturing products more sustainable. In Industry 4.0, AM prioritized customer satisfaction by incorporating benefits into products and other services. Transparency, interoperability, automation, and actionable insights are also facilitated [58]. SAM has the ability to conserve energy while also assisting in the reduction in material and resource consumption, resulting in pollution-free environmental production. To reap the full benefits of Industry 5.0, SAM is combined with integrated automation capabilities to streamline supply chain management processes and shorten product delivery times.

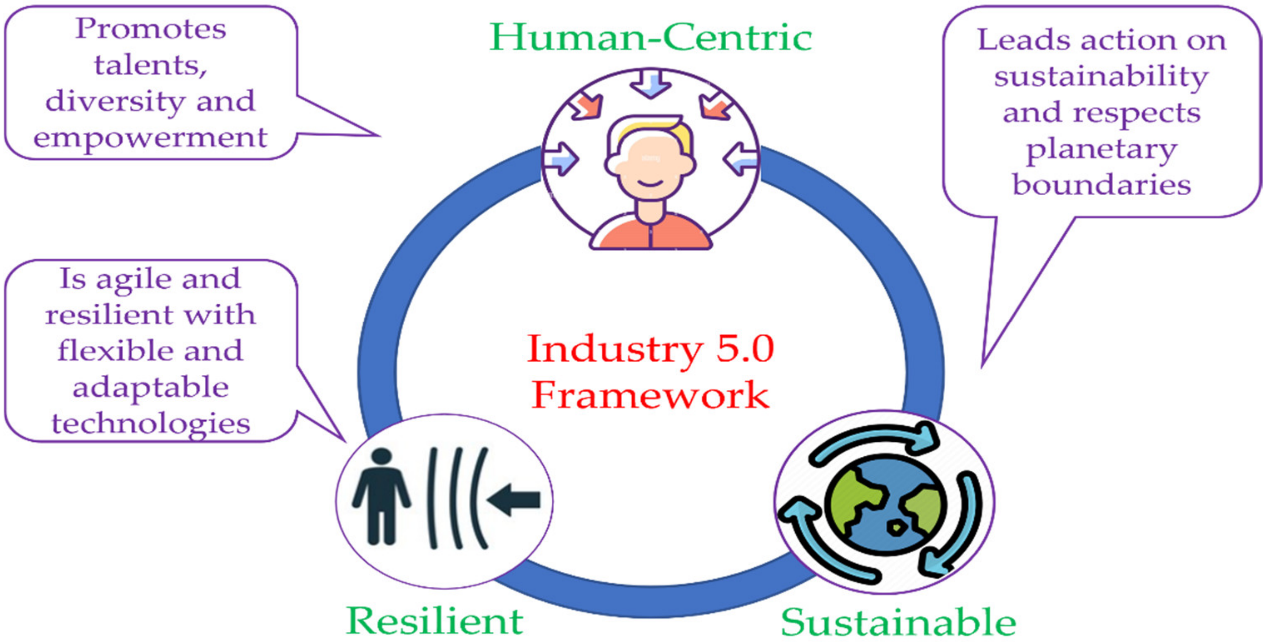

Figure 2. Core values of Industry 5.0 [44].

2.6.2. Predictive Maintenance

The industries are facing many challenges as the global economy moves toward globalization. As a result, manufacturing units are being forced to adopt new technologies such as predictive maintenance (PdM). Manufacturers began utilizing evolving technologies, such as CPS approaches and advanced analytical methods, to improve productivity and efficiency. The ability of industry to uncover and assess uncertainties in order to estimate manufacturing capability and availability is known as transparency [59]. Essentially, most manufacturing schemes assume that equipment will be available at all times. However, in practice, this never occurs in the real world. As a result, manufacturing units should transition to predictive maintenance in order to gain transparency. This transformation necessitates the use of cutting-edge prediction tools in which data are systematically transformed into information and uncertainties are defined, allowing the workforce to make informed decisions. With the use of smart machines and smart sensor networks, the implementation of IoT provides the basic framework for predictive maintenance. The main goal of predictive maintenance is to enable self-awareness in systems and machines. The smart computational agent, which includes smart software to provide predictive modeling functionality, is the key technology for predictive maintenance [60].

2.6.3. Hyper Customization

Industry 4.0 aimed to connect machines, create intelligent supply chains, promote smart product production, and separate manpower from automated industries, among others. However, Industry 4.0 has struggled to keep up with the growing demand for customization, whereas Industry 5.0 does so through hyper customization. Hyper customization is a personalized marketing strategy that employs cutting-edge technologies such as AI, Machine Learning (ML), cognitive systems, and computer vision to analyze real-time data and provide more tailored products, services, and content to each customer. Manufacturers can customize products in bulk thanks to the integration of human intelligence and robots. Many variants of the functional material are shared with other personnel in order to customize the product with different variants for customers to choose from. Industry 4.0 aimed for mass customization with minimal cost and maximum accuracy, whereas Industry 5.0 aimed for large-scale production with minimal waste and maximum efficiency. The collaboration of operators and robots, as well as cognitive systems, allows industries to coordinate manufacturing processes in order to meet customer needs and market changes. The transition to an agile manufacturing process and supply chain is the first step in hyper personalization. Human intervention, a production team, and customer preferences are also required. Hyper customization's applicability is also heavily reliant on the cost-effectiveness of the developed products [61].

2.6.4. Cyber Physical Cognitive Systems

Cyber Physical Systems (CPS) have gained popularity in recent years as a result of advancements in technologies such as Smart Wearable Devices, IoT, Cloud Computing, and Big Data Analytics. The communication between CPS with the help of IoT is the foundation for Industry 4.0. Cloud technology is used to store and exchange a large amount of data in an efficient and secure manner. Additionally known as a Cyber Physical Cognitive System (CPCS), cognitive methods are used in a variety of applications such as surveillance, industrial automation, smart grid, vehicular networks, and environmental monitoring to improve the performance of the system. In CPCS, learning and knowledge are the most important factors in making decisions. For Human Robot Collaboration (HRC) in manufacturing, the CPCS has been introduced. In collaboration with a robot and a human, the HRC completes component assembly in the manufacturing division. The integration of machine–human cognition is modeled and applied for this real-time collaboration work. In Industry 5.0, robots and skilled laborers are allowed to collaborate to produce customized products and services in a more effective manner [62].

3. System Architecture of the Proposed IPSS Maintenance Assistance Platform

The proposed methodology aims to build an Intelligent PSS (IPSS) solution that will improve maintenance throughout its lifecycle, taking into consideration the Energy Demand Management of the provider. As such, by improving and expanding existing services, businesses contribute to aspects such as customer satisfaction and loyalty, as well as financial and environmental sustainability by producing a limited number of high-value products. PSS can also be considered a dematerialized solution due to the reduction in the environmental footprint [63].

The proposed IPSS maintenance assistance platform will facilitate manufacturers in increasing the added value of their tangible products through the provision of a product-oriented PSS. Both the company and the customer will benefit from this approach. Customers will benefit from robust and high-quality maintenance support, and the company will gain a significant competitive advantage over competitors.

The main module of the proposed system architecture is the AR module. This module is based on the implementation of a precedence algorithm, which in turn facilitates engineers during the development of user-interactive AR instructions for both assembly and disassembly, and guidance steps for performing inspection tests on the manufacturing equipment based on suggestions from a knowledge repository which is saved and updated on a Cloud Database [64]. Further to that, data acquired from sensors which are integrated on the manufacturing equipment are also saved to the Cloud Database and are retrieved in order to facilitate shopfloor technicians and engineers in performing the diagnostic tests on the equipment. Four parties are involved in maintenance:

- The customer, who retains the ownership of the tangible product and uses the maintenance service;
- The engineer department, which consists of the expert engineers who are responsible for tracking the progress of the maintenance activities as well as to generate the shopfloor schedule;
- The energy supplier, who can predict energy consumption and provide suggestions for improving the schedule of the mold-making industry;
- The shopfloor technicians, who are in charge of the maintenance tasks.

Taking into consideration the people involved in the maintenance of the manufacturing equipment, in the proposed system architecture the following five (5) teams/user groups have been formalized. The formalization of the people facilitates the creation of the different functionalities of the framework and is used to regulate the type and level of information to be displayed on each group.

- Customer: The people of this group are capable of sending and receiving information about the operating parameters of the equipment. In addition to that, they can also request to plan the maintenance of their equipment in collaboration with the service provider and receive quotations regarding the maintenance activities/spare parts required for repairing/restoring their equipment.
- Engineer: This team/user group is responsible for keeping track of the progress of the maintenance processes; they gather feedback from 3D annotations and create the Bill of Processes (BOP) and the Bill of Materials (BOM).
- Shopfloor technician: Diagnoses faults, determines product code, creates annotations, and has access to the AR tool and database.
- Energy supplier: Obtains data regarding the processes involved in the MRO operations and provides alternative schedule solutions.
- Administrator: The administrator is a supporting team, with rights and access to the whole system, in order to ensure the seamless operation of the framework.

A detailed representation of the system architecture, including the steps, and the information flow in each step are illustrated in Figure 3. The first step in the framework presented in Figure 3 is the collection of data from the integrated sensing system on the manufacturing equipment (please refer to Step 1 in Figure 3, in the layer denoted as customer side). The processed data are displayed on the engineer's dedicated GUI (Step 2, engineer side), which includes a list of all products as well as an estimation of the remaining time in which a specific manufacturer's equipment will arrive at the manufacturer's facility for maintenance.

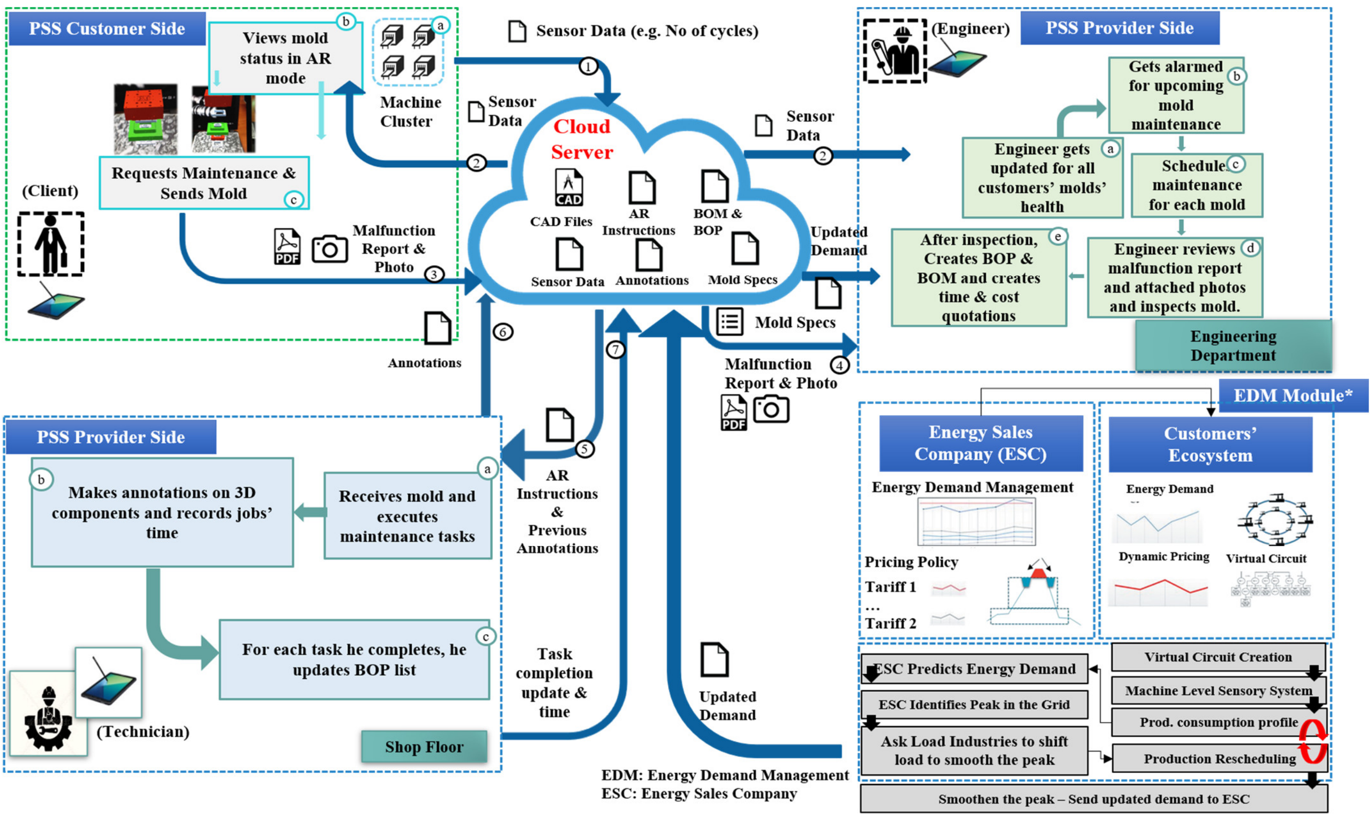

Figure 3. Proposed system architecture derived from [21].

In an attempt to further facilitate the engineering department of the equipment manufacturer, a Graphical User Interface (GUI) for monitoring the status/health of the online customer equipment is utilized. This can be realized in Figure 3, in the engineering layer, Steps a through c. A similar GUI is also provisioned for the clients, from which the customer can quickly scan their equipment with a smart device and visualize their status. In the case that the equipment health is low, through the proposed AR interface, the client can send snapshots of the equipment and send them via the Cloud Database to the engineering department of the OEM in order to initiate the scheduling process of the maintenance (please refer to Figure 3, customer layer, Step 2). Further to that, customers can send media files (e.g., images, video) via the Cloud platform when the manufacturer's equipment is delivered for maintenance (Step 3). The aim of this functionality is to fully digitize the process of equipment maintenance, by gathering a wide variety of data that can be later used by the manufacturer in order to further reduce the equipment inspection time as well as to facilitate communication of the two involved parties.

Following the initial communication of the two parties, the customer is responsible for delivering the equipment to the premises of the maintenance contractor, i.e., the PSS provider, where the manufactured equipment is inspected in detail by the engineering department. Afterwards, the engineering department is responsible for composing BOM BOP, as indicated in Figure 3, in Step 4. The result of this process is the generation of a report including an estimation of the time and cost maintenance processes and spare parts. This functionality supports sending the report to the customer, in order to approve it and therefore grant the maintenance contractor permission to proceed with the maintenance of the equipment.

As discussed in previous paragraphs, the maintenance process is supported by AR instructions which are generated by a smart precedence algorithm (please see Step 5 in Figure 3 [65]). The precedence algorithm accepts the CAD assembly of the equipment as the input and the output is an XML file with the sequence of assembly or disassembly of the equipment. Likewise, the algorithm also outputs the axis and direction in which each part should be removed or inserted. In the AR GUI, additional functionalities are also provisioned, such as manipulation of the virtual augmentations, in an attempt to improve the users' perception about the assembly, the parts involved, and other geometric features of interest.

As far as the Energy Demand Management (EDM) Module, its functionality is based on creation of an ecosystem between the Energy Supply Company (ESC) (I) and the customers (II). The ESC has a specific pricing policy with individual tariffs and aims at the creation of an ecosystem to provide Dynamic Energy Pricing. To accomplish this, an Energy Demand Management service (EDM) is required, which is fed with the "production-consumption profiles" of each of the ecosystem's individual industries. The visualization and monitoring of the manufacturers' infrastructures is an innovative feature of the proposed methodology. Wireless data acquisition devices are connected on production equipment and transmit data to a Cloud server. This part aims to provide insights into machine energy usage and to link that information to the energy consumption profile of the corresponding customer. As a result, future energy demand can be forecasted using data from the machines of the company, allowing for peak identification in the energy grid. When a peak is detected, an alert is sent to a select group of high-load industries, asking to shift their load to smoothen the estimated peak. As a result, on the side of the manufacturer, an adaptive scheduling algorithm is triggered to ensure grid stability and reduce required energy consumption during peak demand periods. To summarize, EDM has a great deal of potential for ESC. Moreover, customers' information not only helps Energy Sales Companies save money by directly managing energy demand, but it also helps them better predict customer needs and improve the efficiency of their systems. Finally, as soon as the demand peak is smoothed, the updated demand is sent to the Cloud and then to the PSS provider side.

4. Platform Development

This section of the manuscript is dedicated to the discussion of the software and hardware tools that were used to develop the proposed application and discuss the development workflow. The AR scenes were created using the CAD files of the equipment. Next, in order to develop the interfaces required for the application, the MS® Visual Studio Community 2017 (Version 15.9.43, Microsoft, Redmond, WA, United States) IDE (Integrated Development Environment) has been utilized. As regards the development of the AR module and its functionalities, the Unity 3D™ (version 2018.4.36f1, Unity Technologies, San Francisco, CA, USA) game engine was used in conjunction with the Vuforia plugin. For enabling the build/publishing of the mobile application in Android-based devices, JDK (Java Development Kit) was also implemented in Unity 3D™ (Java version 1.8.0_333-b02, Open JDK 1.8.0_152, Oracle Corporation, Austin, TX, USA). Regarding the development of the scripts, C# was used for the scripts related to the operation of the mobile application. As regards the communication of the clients (i.e., mobile application instances) with the server (i.e., Cloud platform), PHP (Hypertext Preprocessor) was utilized. Essentially, PHP is used in order to interface the mobile application with the Cloud platform. Although the proposed application is aimed at mobile devices, it can be implemented on other types of hardware (for example, HMDs) as long as they host a camera and a display. The proposed framework also requires a Cloud Database, supporting the File Transfer Protocol (FTP) and SQL (Structured Query Language) databases. For the development of the Cloud platform, phpMyAdmin (version 5.2.0) was used, which is a PHP-based free software tool providing functionalities for handling the administration of MySQL and MariaDB. In addition, the MySQL (version 8.0, Oracle Corporation, Austin, TX, USA) open-source database management system was also implemented. In order to host the Cloud platform, the MS® Azure was implemented. It is stressed that MS® Azure according to the official site is defined as a *"cloud computing service for application management"* [65]. In terms of hardware, an Android-based tablet PC and a Smart phone were used to implement the proposed system, which is connected to the databases and hosts the user interface. For the development and the management of the mobile application and the Cloud platform, a desktop PC was used, equipped with an Intel Core i7—8750 CPU, 16 GB RAM, and NVIDIA GeForce GTX 1060 GPU (8 GB dedicated RAM). Finally, a network connection, either local or global, is required for communication between the two parties. A collection of the AR user interfaces of the developed application is presented in Figure 4.

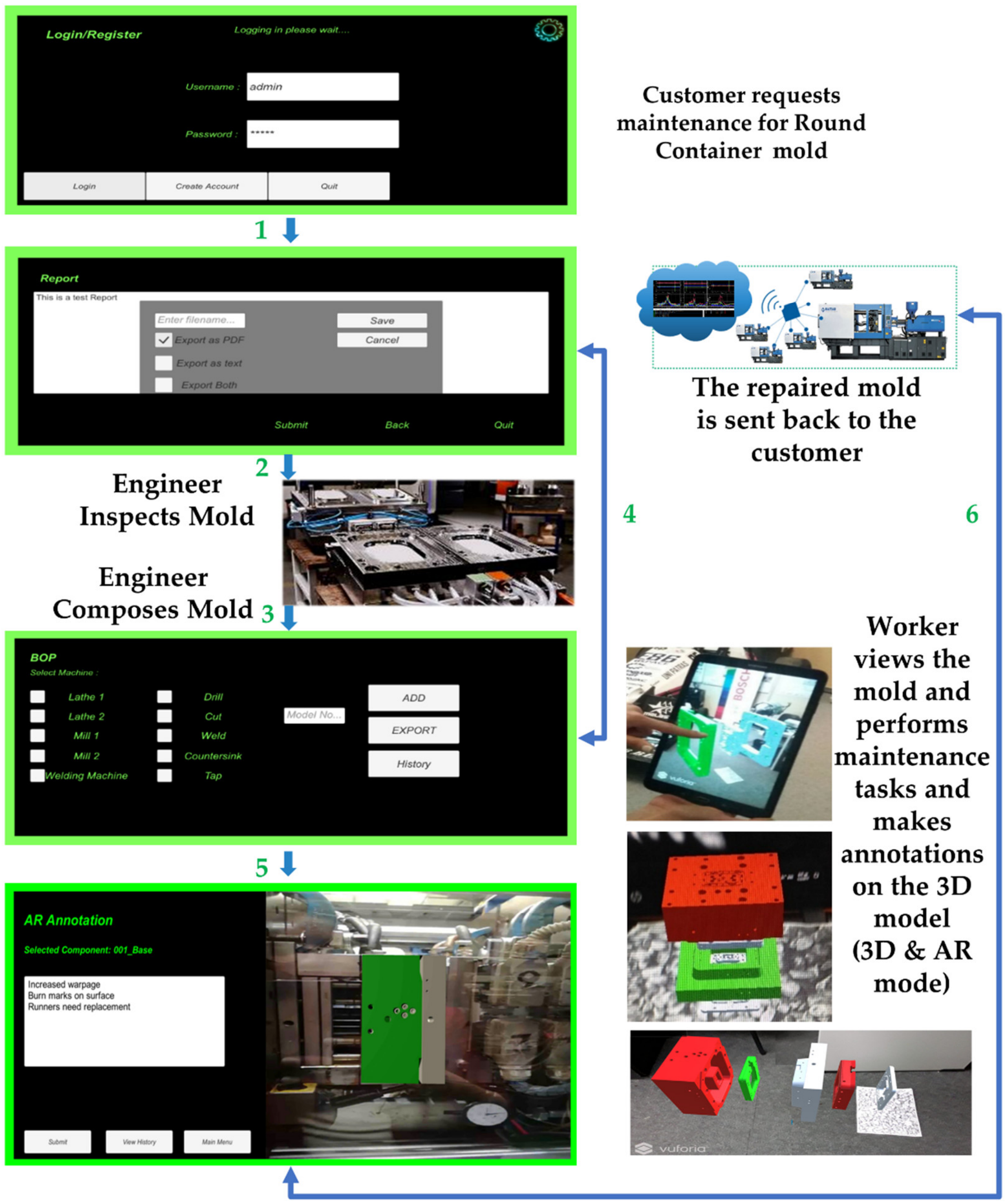

Figure 4. Graphical User Interfaces (GUI) of the developed AR application.

5. Case Study

The validation of the EDM module and the AR application is based on a real-life case study derived from the mold-making industry. The shopfloor of the mold-making industry consists of 7 job shops, each with 13 work-centers and a total of 40 individual resources. The hierarchical model of the mold-making industry based on the workload and the available resources is illustrated in Figure 5.

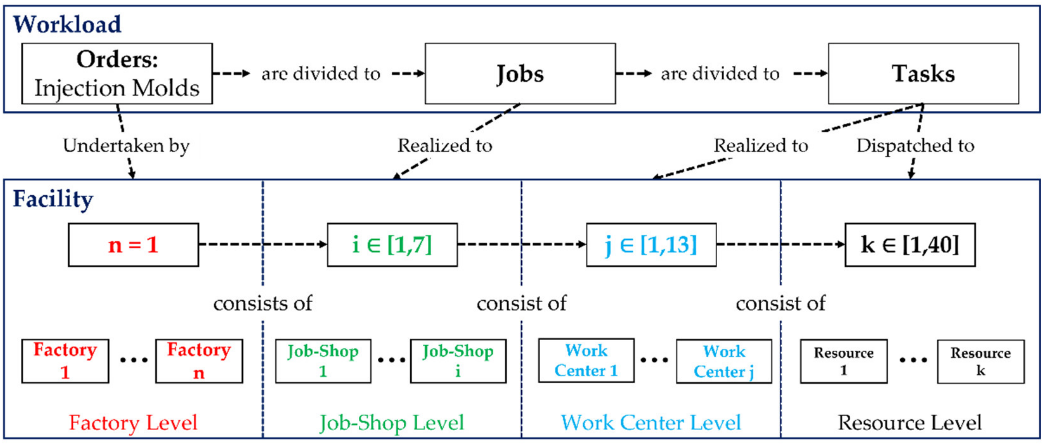

Figure 5. Hierarchical model for workload and facility model.

The mold company selected as the test case is an SME which manufactures and performs MRO on injection molds. In the present, mold maintenance is manually documented. Therefore, maintenance monitoring, maintenance history of sold molds, historical data about mold assemblies, and the scheduling are performed manually by the mold-maker engineering department and are difficult to track/monitor/retrieve. If a customer requests mold maintenance, the physical product is sent to the company's premises along with a report about the mold specifications. Upon mold arrival, the company's engineering department receives the mold and in conjunction with the technicians, the mold inspection is performed. During this process, the engineer prepares a report of the points/components that need to be repaired, so that the process planning can be completed, and the maintenance quotation is sent to the client as well. The time and cost quotation is sent to the customer as a PDF, through the Cloud platform, for approval. If the customer's approval is granted, then the actual maintenance procedures take place. Finally, the repaired mold is tested and is shipped back to the customer. The proposed framework has implemented an alarming tool, accessible from both stakeholders (i.e., client and service provider). For the alarming tool, the installation and setup of a Wireless Sensor Network (WSN) is required in order to monitor the operation of the injection mold machines. Currently, the mold manufacturer receives no input from their customers about the mold's health during their operation. Thus, the production of the mold company cannot be scheduled effectively, creating delays in the maintenance of the mold as well as the production of the client. At this point, AR is used as a visualization tool for monitoring the status of the mold components. With this functionality, the clients are capable of scanning their molds with the use of unique QR codes and view the mold status. A unique QR code is used for each mold, corresponding to its model, ID, and specifications. A color-coding system has been implemented (green, yellow, and red), indicating the health of the components to quickly notify the users.

The engineering department, through the implementation of the ESC module, targets gathering useful insights regarding energy consumption, i.e., when, where, and why energy is consumed, so that the company can enter the energy trade market with knowledge. The SME customer, on the other hand, must be persuaded of the benefits of participating in such an ecosystem. By default, energy provision is a PSS, which involves the contract as a product and a set of services that go far beyond the sole provision of energy and benefit both the energy provider and the customers. The energy provider can design more suitable energy plans by tracking the customers' energy demand, whereas the clients can constantly monitor the amount of energy used as well as peak demands within workdays and workhours, resulting in more cost-effective and environmentally friendly production plans. The business problem that needs to be solved can be defined as an industrial customer's need to reschedule the production in order to avoid excessive energy consumption within a predetermined time frame. It is emphasized that the specific ESC industrial customers are covered by a fixed sales tariff, which means a fixed price for peak energy periods and a different price for non-peak energy periods.

One theoretical scenario that serves as a starting point for the adaptive scheduling algorithm is presented in Figure 6. The energy peak is identified on the ESC side, considering the energy requirements of the companies. The ESC then specifies two specific periods with energy consumption thresholds. In the case that the above-mentioned thresholds are not exceeded, the industry's pricing tariff remains the same.

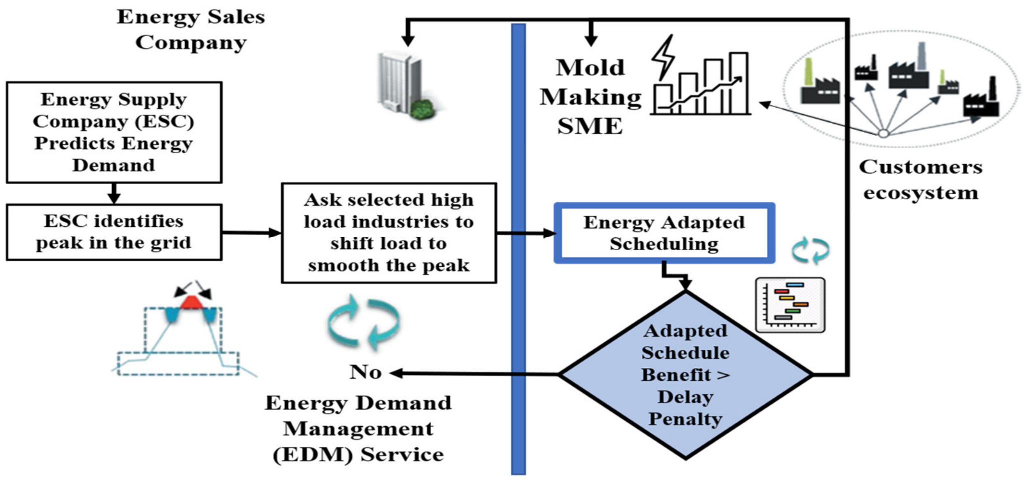

Figure 6. Scenario for the consideration of the energy-supplier to the adaptive scheduling algorithm.

In order to implement and validate the developed system, a use case of a mold-manufacturing SME undertaking both the construction of new molds as well the maintenance of older molds was chosen. The current situation is not digitalized and the communication between the customer and the manufacturer is based on the exchange of written reports. In addition to that, the mold manufacturer is not aware of the malfunctions of the mold until it has been delivered to their premises by the customer. For the testing and validation purposes, the following scenario was set up. Initially, the customer had to create a digital form using the developed mobile application in order to request a maintenance schedule and to describe the malfunction observed. Then, the customer delivered the injection mold to the premises of the manufacturer. At this point, the engineering department is assigned with the task of mold inspection. During this step, the engineers physically inspect the mold and with the utilization of the mobile application functionalities, they create textual annotation on the virtual counterparts of the mold, which are then saved automatically on the Cloud Database. In case that there are no data about the operating parameters of the mold, the customer is requested to upload them using the Cloud Database. It is stressed that these data will be used at the final stage of the maintenance procedure in order to test it under real circumstances. As soon as the physical inspection of the mold is completed, the engineer using the application composes an analytical quote about the maintenance activities required. Simultaneously, the BOM and the BOP are created in order to proceed. In order to facilitate the engineers creating an accurate quote, similar past cases are examined in order to provide time and cost estimations which have been saved in the Cloud repository.

At this point, the engineer consults the energy supplier in order to obtain the necessary energy consumption and pricing predictions. Further to that, the scheduling of the mold maintenance company is adapted to the predictions of the energy provider, taking into consideration the MRO operation that needs to be undertaken. As a result, the maintenance engineer has a clear perspective on the delivery date of the mold from the customer. By extension, the customer can adapt their production schedule based on the report received from the maintenance engineer. Consequently, with the integration of the proposed framework, as part of the PSS provided by the mold maker, disruptions in the production and the supply chain can be further minimized. In Figure 7, a typical example of three different injection mold maintenance BOPs are illustrated.

Figure 7. Bill of Processes (BOP) for three different injection molds.

The technicians are in charge of the maintenance. Through the interactive 3D GUIs, the shopfloor technicians are provided the functionality to record the duration of each maintenance task. As long as a maintenance task is completed, the time recording is automatically uploaded to the Cloud Database and the knowledge database is updated.

There are two (2) demand periods (DP) in which "smoothen the peak requirement" exists, with the following targeted thresholds: 50 KWh (DP1) and 0 KWh (DP2). Finally, a balanced change has been accomplished. Even though the processing time has increased by 3% overall, energy consumption has decreased by 11%, achieving the desired consumption shift. Likewise, the adapted schedule reduces energy costs while increasing time. Finally, a balanced change has been accomplished. The most important finding that summarizes the added value of the proposed approach is that energy costs have been reduced by about 47 percent. The company has been given a special tariffing plan based on their flexibility, which has resulted in this reduction. While it was previously necessary to pay a higher-cost tariff for high-demand periods, it now receives a fixed lower-cost tariff for their demand periods. The tariffing for the high-demand period is currently only 31.82% higher than the default tariff. As a result, even if the production cost increases by 2% over the course of a year, it is safe to assume that the company will earn a net profit of more than EUR 10.000, taking into account the customized tariffing that will be provided as a reward for the company's flexibility in terms of energy demand. In Figure 8, a comparison of the additional production cost of this solution with an estimate of energy cost savings over a year (with the achieved solution precision) is presented. There was a reduction in energy consumption for the two cases, Mold 1 and Mold 3.

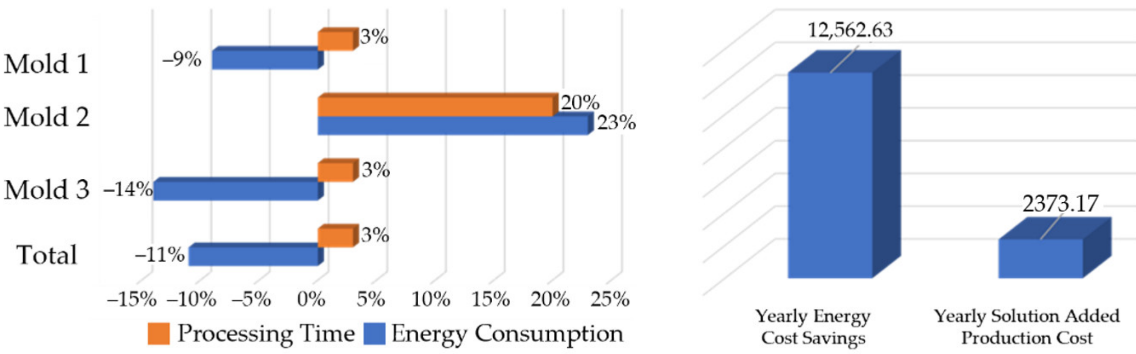

Figure 8. Results: processing time and energy consumption comparison—financial savings.

In contrast to the previous situation, energy consumption and processing have increased for Mold 2. Mold 2 required the least amount of machining processes, which supports this assertion. As a result, the intelligent algorithm has determined that it should be processed by non-optimal resources, resulting in increased energy consumption and processing time. As a result, it becomes obvious that overall energy consumption has been reduced by approximately 11%.

6. Results

The applicability of the proposed framework was tested through a series of experiments. More specifically, the validation focused on two main dimensions. Firstly, the achieved performance was evaluated versus the performance before implementing the proposed framework. Secondly, the evaluation of the main interface for providing PSS functionalities was carried out.

For the validation of the developed IPSS platform, the AR mobile application and the supported functionalities, a set of Key Performance Indicators (KPIs), was set. These KPIs are illustrated in Figure 9 and are relevant to the "Processing Time" and the "Energy Consumption" (see Figure 8). Likewise, the "Energy Cost Savings" as well as "Added Production Cost" per year (see Figure 8) were calculated. From the results, it becomes obvious that a significant reduction in energy consumption is feasible for Mold 1 and Mold 3. On the contrary, for Mold 2 both values have risen as a consequence of less demanding maintenance activities. Despite that, the overall performance of the proposed PSS framework appears to be beneficial for the mold-making industry, resulting to an energy reduction equal to 11%.

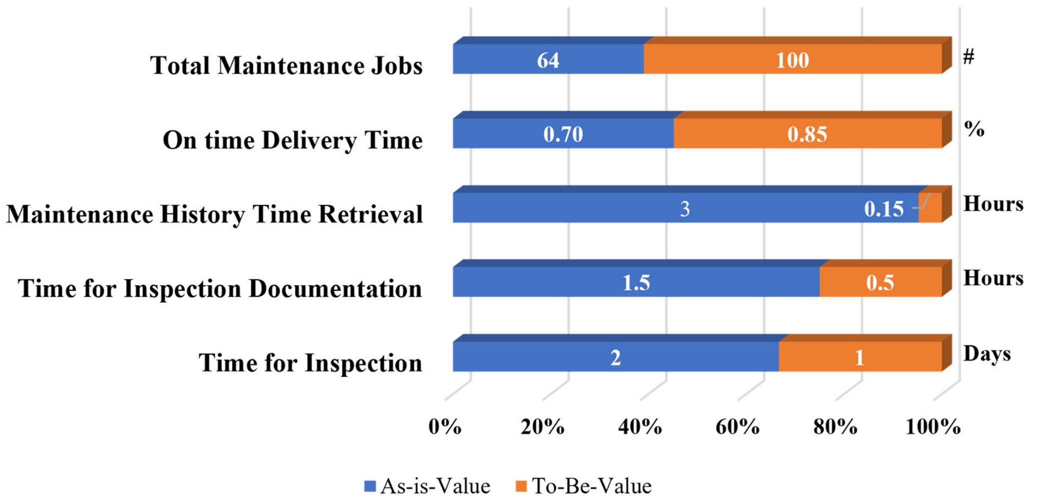

Figure 9. Validation results. Comparison of metrics before the implementation of the framework versus after the implementation.

In particular, it can be concluded that the use of the mobile AR application on the shopfloor level facilitated shopfloor technicians in reducing mold inspection time by up to 50%. Further to that, it has also been observed that the malfunction documentation, due to the annotation creation on the 3D component of the mold, has been reduced by approximately 70%. Finally, one of the findings of this research is that the mold maker had issues with the on-time delivery of the repaired molds, as illustrated in Figure 9.

Participants were also given questionnaires to fill out in order to record their opinion regarding the functionalities provided with the mobile tool. Moreover, several webinars and workshops were held during the development phase of the tool, which helped to improve its status. The method presented in this research work is part of an EU research program, therefore, the end-users (i.e., the mold-making industry) participated in the design, testing, and validation phases of the method. Concretely, discussions and physical meetings were organized in order to establish the key requirements, which led to the creation of the KPIs (Key Performance Indicators). Then, the research team proceeded with the development of functional mockups in order to present and discuss the application (Augmented Reality application) functionalities and agree on the information content.

As soon as the fully functioning application was developed, the research team, in close cooperation with the mold-making industry, performed several tests, and the results were compiled and presented in Section 6 of the revised version of the manuscript. It is stressed that several application test meetings were organized in order to calibrate the AR application (calibration of the visualizations with respect to the physical environment).

Regarding the on-time delivery of the molds, an approximate 20% rise has also been observed, indicating that the shopfloor of the mold-making industry was more efficient, thus more capable of meeting the deadlines. As a result of the implementation of the proposed IPSS, an approximate 20% rise in on-time mold deliveries has also been observed. This is justified by increased and more efficient communication between the OEM and the client, as well as between the OEM and the energy supplier. Consequently, the three parties could efficiently collaborate with each other in order to build an appropriate maintenance plan that could be followed more easily and accomplished in a timely manner.

7. Conclusions

To sum up, the purpose of this research work is the design and development of an Intelligent Product Service System for improving the remote maintenance support, taking into consideration the energy demands and adapting the shopfloor scheduling. Ultimately, the purpose of the IPSS is the creation of suitable communication channels between the OEM, the customer/end-user, and the energy supplier. Consequently, as a result of the data exchange between the above-mentioned parties, the MRO operations can be adaptively introduced to the schedules of the customer and the OEM, thus decreasing disruption of the production line. Further to that, an additional service is provided, in order to utilize the big amount of data produced at the shopfloor. The purpose of this service is to calculate a near-optimum schedule for the maintenance and manufacturing activities, in an attempt to reduce the energy expenditures of the manufacturing companies, as well as to reduce the load of the power grid during peak days.

The applicability of the proposed IPSS has been tested in Engineered-to-Order (ETO) products, such as injection molds. However, given that minor amendments are applied to the framework supporting the IPSS, it can be applied in a variety of other industries/products. One of the key findings of the research is that by establishing sufficient communication channels between the nodes of a supply chain, i.e., the end-user, the OEM, and the energy provider, the efficiency of manufacturing processes can be improved. Therefore, in the future, the framework developed as part of the IPSS can be further improved to include more nodes of the supply chain. With the utilization of the alternative generation algorithm, a wider set of criteria can be examined, thus providing more accurate solutions.

Taking into consideration the latest developments in the industrial and market landscapes, and the recent acts towards the environmental impact of manufacturing activities, the proposed PSS-based framework will also be further elaborated in order to calculate the CO_2 emissions of the manufacturing and maintenance activities. Likewise, besides the calculation of the emissions, the implementation of an optimization algorithm for facilitating engineers to adapt the production schedule targeting the reduction in the environmental footprint of manufacturing processes is necessary.

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