Article

A Reference Framework to Combine Model-Based Design and AR to Improve Social Sustainability

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Abstract: Product and process digitalization is pervading numerous areas in the industry to improve quality and reduce costs. In particular, digital models enable virtual simulations to predict product and process performances, as well as to generate digital contents to improve the general workflow. Digital models can also contain additional contents (e.g., model-based design (MBD)) to provide online and on-time information about process operations and management, as well as to support operator activities. The recent developments in augmented reality (AR) offer new specific interfaces to promote the great diffusion of digital contents into industrial processes, thanks to flexible and robust applications, as well as cost-effective devices. However, the impact of AR applications on sustainability is still poorly explored in research. In this direction, this paper proposed an innovative approach to exploit MBD and introduce AR interfaces in the industry to support human intensive processes. Indeed, in those processes, the human contribution is still crucial to guaranteeing the expected product quality (e.g., quality inspection). The paper also analyzed how this new concept can benefit sustainability and define a set of metrics to assess the positive impact on sustainability, focusing on social aspects.

Keywords: augmented reality; social sustainability; quality inspection; model-based design; human-centered design; product development

1. Introduction

Sustainability is one of the main drivers of competitive industrial development and European and global strategies, as stated by the 2030 Sustainable Agenda [1]. The sustainable strategy is to boost ecological, economic, and social innovation, as well as to ensure prosperity, environmental protection, and social cohesion [2]. In industry, such results can be achieved thanks to the integration among environmental, economic, and social aspects of the design and development processes [3].

Digital transformation is changing habits and procedures within modern factories. According to the digitization trend, digital models are pervading the product development process. Model-based design (MBD) represents a way to convey every product's lifecycle information into a unique, single source that can drive manufacturing processes [4]. MBD is based on enriched 3D product models, with annotations and notes, which are able to store data on non-geometric attributes and procedures, also known as product manufacturing information (PMI). As a consequence, digitization is changing the manner in which goods are produced and, thus, the role of the operators, which are increasingly called to manage and supervise production systems to enhance flexibility and adaptability. This presents a special opportunity for organizations to develop smart workspaces, improve the working conditions and workers' wellbeing, and to benefit sustainability from multiple viewpoints [5]. However, the digital transformation does not only imply an advancement

in technology but also a renovated attention to sustainability and user experience. Indeed, in order to make operators properly interact with digital contents, new interfaces have to be defined and developed, innovating the traditional way of content access (e.g., paper-based instruction, desktop-based reading). In this direction, augmented reality (AR) technologies can help to find novel and personalized ways of interaction.

AR was established as one of the nine pillars of industry 4.0, dealing with the display of digital contents in the real-world through a device, such as a mobile phone, tablet, or special eyeglasses [6]. There is a lot of different uses for AR in the manufacturing industry, i.e., training (e.g., AR helps to become familiar with protocols, equipment, and procedures on the plant floor, dedicated training to prevent safety instances) real-time process monitoring (e.g., AR overlays text or other digital information to help people understanding what is happening on the floor without requiring additional resources or production stops), logistics (e.g., AR helps shift from manual checks for orders or shipments to automated check, which reduces errors and saves time, money, and resources), and maintenance (e.g., AR provides ad-hoc digital information about equipment and procedures to support preventative maintenance schedules, potential maintenance issues, and maintenance service history of a certain machine). A large part of AR research focuses on introducing AR technologies in industry [7] or the application to specific processes such as maintenance, assembly, and inspection [8–10]. Some studies also deepened the impact of AR applications on the industry, focusing on process performance [11]. However, a precise methodology to evaluate how AR technologies can benefit sustainability is still missing. While the AR impact on environmental and economic sustainability can be easily inferred (e.g., reduced paper documents, reduced travels for onsite installation, and training thanks to remote assistance), the impact on social sustainability is usually unexplored, and on the contrary, is of huge importance. Social sustainability in production sites considers the quality of working activity, workers' empowerment, individual/collective learning, employee participation, and work-life balance. All these concepts aim to preserve or build up human capital and represent a conscious way to deal with human resources [12]. In this sense, AR can positively affect social sustainability in reducing time spent for operations, making worker conditions safer, improving workers' wellbeing and motivation, building up user skills and raising global job satisfaction.

In this context, this paper proposed a workflow to exploit the potentials of MBE and AR to develop human-centered industrial applications and to reuse existing design knowledge for process optimization. The research also defined a set of key performance indicators (KPIs) to assess the impact of AR-supported operations on social sustainability. The proposed approach was deployed on an industrially relevant case that focused on quality inspection, providing a preliminary qualitative assessment on social sustainability. A workflow described how to move from 3D models to AR-supported applications by making the most of industrial knowledge, already embedded on 3D models to display relevant information in an automatic way, to be used for different purposes. The workflow includes several steps, from model-based design to manufacturing/inspection process plan, to operations checklist, until AR application development and final sustainability assessment. KPIs are defined as general parameters for sustainability assessment and are specifically adopted in the industrial case for a preliminary qualitative analysis.

In summary, the main contributions of this study are as follows:

- We proposed an innovative approach to integrate 3D model design annotations in AR applications and develop human-centered AR-supported operations in industry.
- We defined a set of KPIs to assess the impact on social sustainability.
- We provided a preliminary, qualitative assessment of the positive impact of AR applications on social sustainability for quality inspection.

The paper is organized as follows. Section 2 describes the research background on AR and its industrial application, as well as on the evaluation on sustainability in industry. Section 3 describes the research approach including both the adopted tools and strategy to develop the AR applications reusing existing industrial knowledge, and the indicators to

assess the related impact on social sustainability. Section 4 describes the industrial case and discusses the results obtained by the assessment of social sustainability, focusing on pros and cons of the proposed approach. Section 5 contains conclusions and future works.

2. Research Background

2.1. Augmented Reality in the Industrial Product Life Cycle

The concept of AR was first introduced by Azuma who defined this technology as a system " . . . that supplements the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world" [13]. This general definition needs to be translated into three main conditions: (a) something which is able to blend real and virtual content in a real environment; (b) something that is real time and interactive; (c) something which can register virtual content in 3D environment [14]. In a nutshell, AR introduces a new idea of ubiquitous, personalized interfaces that use accessible mobile technologies such as tablets and smartphones [15]. Among emerging technologies, AR can also bring valuable improvement in the design evaluation by enabling interactive changes of shapes of products as well as colors, textures, and user interfaces [16]. In any case, the introduction of digitized contents into the real-world workspace through AR can help workers correctly perform their tasks with improved accuracy and reduced error rate. Recent scientific studies demonstrated these outcomes on different application areas: assembly [17,18], disassembly [19], maintenance [20], and training [21]. On the maintenance side, Siew et al. [22] highlighted how AR can play an important role in sustainable manufacturing, acting as a reliable feedback system of monitoring and validating if maintenance operations are being correctly and timely performed. As for training purposes, Eder et al. [23] underlined how AR can improve the operators' skill acquisition in an interactive and engaging way where instructions or machine data can be selectively displayed to address the user's attention. With these implications, AR can support a paradigmatic shift from conventional manual labor on the factory floor to new augmented, smart processes and procedures under the industry 4.0 umbrella, promoting digital conversion of the future intelligent factories [24].

Devices for augmented applications can be fixed like projection-based systems, wearable like head-mounted display or AR glasses, or hand-held like tablets or smartphones. Projection-based systems are not helpful for dynamic, variable working conditions nor for real process operations, yet they are applicable for training. Wearable systems are particularly suitable for industrial applications, leaving the operator's hands free, but they can be non-compatible with specific personal protective equipment [25]. The use of tablets can be easier and more robust for industrial applications, even if it could limit the operators' actions and hand movements [26]. Nonetheless, technology usability and flexibility, as well as the importance of the user experience in the design of augmented applications, are the key points in the success of AR applications [27]. Moreover, a successful digital transformation requires an effective performance measurement system, which could facilitate data management and support task identification [28].

Despite the progress of industrial automation, procedures at crucial stages of the product development process are still under human responsibility, including quality control. In this direction, AR can be used to accelerate, modernize, optimize, and unify the inspection process. It allows for the inspection time to be shortened and errors that may occur to be avoided, especially if some elements are overlooked. Further, it can reduce the operators' mental workload [29]. Specifically, instructions are usually generated in the form of procedural manuals and inspection notes, but their consultation is generally time-consuming and stressful. Moreover, manuals could not support users in timely ways nor properly recognize or solve hidden anomalies [30]. Runji and Lin demonstrated how AR can support an operator manually inspecting a product (previously automatically inspected) to better identify existing defect locations in an intuitive and efficient manner; additionally, interactive information can help to monitor task progress, thus promoting safety [7]. Furthermore, AR tools could support users via apparatus or parts identification,

inspecting them correctly with self-localization and 3D object recognition technology and guiding users through judgment of the object conditions [31].

2.2. Model-Based Design to Create Reliable Product and Process Data

MBD is a shift from traditional textual instruction and bidimensional representations to holistic 3D product representation, including manufacturing, quality, usage, and maintenance data [4]. To achieve this objective, ISO and ASME standards embed the MBD view into 3D geometry, adding 3D annotations such as views, product manufacturing information (PMI), text annotations, dimensioning and tolerancing notes, surface finishing, and material specifications. Relevant manufacturing data are conveyed through extended and standardized geometric formats used for data interchange. Among them, STEP AP 242 allows to merge highly specific engineering data within geometrical data such as colors or particular geometric entities. STEP AP 242 is one of the most diffused file format protocols for mechanical design used to exchange geometric and non-geometric data between engineering domains. It also merges previous versions, i.e., AP 203 and AP214.

Such a trend leads to few advantages. The first regards an overcome of the duality represented by 3D and 2D models, concentrating all the relevant data on just one representation of the product [32]. The second one is given by the intrinsic capability of leveraging a more usable data representation (i.e., the three-dimensional representation), which is the basis of many engineering numeric simulation systems known as CAE and CAM systems, up to manufacturing cost estimation systems and fruition of the data by virtual and augmented reality technologies. Additionally, it supports a more collaborative design environment, allowing the designer to set in formal annotations his design intent, especially regarding tolerancing and the related inspection process [33,34].

In this context, it is mandatory to identify new conveying means of this extended set of information [4]. Simultaneously, as emerged from a scrupulous literary review, the increasing perception of the decisive impact of new emerging technologies, such as AR, on productive systems has led to an organic revision of working procedures. MBE and related 3D model metadata can be successfully integrated within handheld device application to provide a more effective work rendition, ensuring that activities (such as design, planning, and machining) are correctly performed the first time without the need for subsequent re-work and modifications [35]. Undoubtedly, AR systems are changing how data is viewed, especially on 3D models, which allow the user to understand different product perspectives in a more comprehensive way [36]. As a result, there is an urgent need for proper approaches involving AR, enabling the user to effectively verify solutions relative to real scenes/objects when provided with a complete set of functional information (e.g., PMIs, dimensions, surface finish). The aforementioned digital transformation of modern industrial contexts is based on radical changes in the company communication protocols and paved the way to the idea of displaying a wide set of digital annotations and information throughout the different stages of the product life cycle [37].

2.3. Social Sustainability and Digital Technologies Acceptance

Social sustainability in production sites requires us to consider preventive occupational health and safety by promoting human-centered design of workstation, working activity, workers' empowerment, individual/collective learning, employee participation, and work-life balance. It finally results in higher wellbeing, motivation, and global job satisfaction. Modern companies are forced to merge profit-focused issues with sustainability-focused issues, including the social dimension [38]. In this context, ergonomics and human factors play a key role in designing new manufacturing systems and processes [39]. Social sustainability considers all areas of ergonomics (i.e., physical, cognitive, and organizational) as main requirements to create safe and healthy processes. Promoting socially sustainable in product/process design and development can create safer and healthier workplaces, as well as better working conditions. Recently, several papers have focused on the promotion of social sustainability in smart factories [40,41], which basically proposed methods to

stimulate the adoption of a social sustainable plant model. They paid particular attention to the operators' needs within the workshop, exploiting advances in Internet of Things (IoT) infrastructures to acquire human-related parameters from the plant in order to evaluate and improve the workers' wellbeing, as well as the company performance. The final scope promotes factory social sustainability as the best trade-off between production objectives and the physical-cognitive needs of workers.

Only a few recent works have analyzed how to assess social sustainability in the industry. For instance, Scafà et al. [42] proposed a method to help companies to evaluate workers' experience during industrial processes and identify the optimal solution to improve workers' well-being and company performance on the basis of social indicators to identify ergonomics problems. In particular, following the literature review from [43], they defined five classes of indicators: factory performance (containing the most common objective indicators evaluating productive benefits and resources management), perceived workload (considering the workers' perception of work), work-related diseases (monitoring chronic health problems caused by work context), knowledge (analyzing the workers' awareness and skills about health and safety risks, operations, and technologies), and workplace (including indicators concerning workplace aspects and collaboration between humans and machines).

Another important social aspect to consider is the employee's acceptance of digital technologies (including AR) in industry. The correct handling of new devices require a change in the employees' behavior, a revision of working routines, as well as new skills [44]. Visual and simulation technologies, such as AR and virtual reality (VR), provide one the most effective and safe ways of industrial training experience [45], enhancing the worker's role. Moreover, Nara et al. [46] underlined the key role of virtual reality (VR) and AR in industry 4.0 as drivers for sustainable development, evidencing the substantial positive impacts on social, economic, and environmental sustainability. Nonetheless, as noted by Hallstedt et al. [47], there is a need to define a mature decision support method able to combine qualitative sustainability assessment techniques with quantitative analysis. Similarly, Jetter et al. [11] proposed a set of indicators for AR system evaluation in order to benchmark the impact of ready-for-market tools.

3. The Research Approach

The present research focuses on the definition of a formal procedure to introduce AR tools in human intensive industrial processes and to assess the significant improvements on social sustainability, highlighting the impact on operators' well-being, knowledge valorization, and overall process efficiency. For this purpose, it defines a six-step procedure to guide the implementation of advanced digital techniques, such as AR, in the companies' life cycle for supporting human intensive activities. Figure 1 describes the proposed procedures to successfully implement the AR digital thread in industrial processes. The six steps move from the definition of enriched product models by MBD (step 1) to the human intensive process planning (step 2), the creation of a proper operation checklist (step 3) until the development of the AR application setup (step 4), the implementation of the dedicated AR application supporting operations (step 5), and the final assessment of social sustainability (step 6).
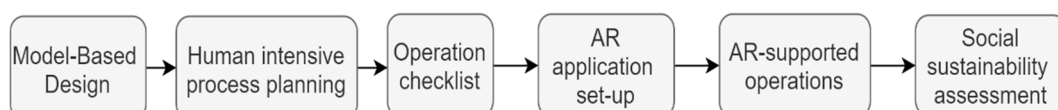
Figure 1. Procedure for effective implementation of augmented reality (AR) in industrial processes.

Step 1. At this initial stage, relevant manufacturing data are collected through the interaction between computer aided design (CAD), product lifecycle management (PLM), and enterprise resource planning (ERP) are software systems employed to generate geo-

metric models of products and menage the related technical documentation. Together, they convey through the standardized STEP AP 242 geometric format. Doing so, highly specific engineering data can be stored within geometrical data including points, curves, surfaces, solids, and a variety of annotations. Indeed, colors, materials, and non-geometrical properties are represented in the standard.

Step 2. Human intensive processes are planned (e.g., human intervention in a manufacturing procedure such as assembly, quality inspection carried out by humans) creating a human intensive process planning that is able to list the main human tasks and intercept main criticalities. This implies a special attention on implementing the structure of the digital application to be designed, from an accurate selection of proper information to unveil on screen to reduce the operator's mental workload compared to traditional and demanding paper documentation or 2D data interpretation.

Step 3. This step focuses on the definition of the detailed operation checklist to support operators performing selected tasks. At this stage, the checklist allows breaking down the task into a detailed list of single operations and convenient communication channels, such as visual and audio signals.

Step 4. Once the activities have been defined, a suitable AR application setup must be identified. For this purpose, the variety of AR devices, model target tracking algorithms, progresses of fruition engines, and content editing environments are analyzed and selected considering the specific application, the list of tasks to be accomplished, the environment, and the operating conditions. Once the hardware and software are arranged, robust AR wizards are created to support the intended users.

Step 5. This phase refers to the execution of AR-supported operations. The operator should easily keep track of task progression thanks to a proper user interface, while being instructed in each step to positioning, tools' provision, and technical documentation. This is achieved without deviating from an inclusive design vision, which allows for a comprehensive AR solution that can adapt to each end user requirements. Operators are expected to benefit from the capability of the AR technology to promptly recognize targeted elements by overlapping virtual and real 3D geometries. Device camera feedback proposes and supports operators in the tasks avoiding every possible misinterpretation.

Step 6. After task execution, the social sustainability assessment is carried out to estimate the AR application effectiveness and impact on social sustainability. For this purpose, a set of KPIs were defined accordingly with ISO 22-400 to transparently evaluate the overall social sustainability, as described in Table 1. Three classes were identified regarding the different aspects of social sustainability, respectively: impact on organizational aspects and performance implications, operator's knowledge and skills acquisition, and operator's mental workload. A set of metrics were also defined to measure the proposed KPIs. Table 1 shows how to use the proposed metrics to assess the different KPIs, such as:

- Task Completion Time;
- Time to Build Experience;
- Number of Errors;
- Time to Revise Technical Documentation;
- No. of Supported Devices;
- No. of Information on the Screen;
- No. of Employees Involved;
- No. of Accessible Application's Features;
- Time to Familiarize with the Application;
- Time to Find Desired Information;
- Subjective Workload Assessment by NASA-TLX (NASA Task Load Index).

Table 1. Key performance indicators (KPIs) and metrics for social sustainability evaluation.

Social Sustainability Classes	KPIs	Metrics										
		Task Completion Time	Time to Build Experience	Number of Errors	Time to Revise Technical Documentation	No. of Supported Devices	No. of Information on the Screen	No. of Employees Involved	No. of Accessible Application's Features	Time to Familiarize with the Application	Time to Find Desired Information	Subjective Workload Assessment by NASA-TLX
Organizational performance	Workflow efficiency	●	●	●							●	
	Training time	●	●		●		●		●	●	●	
	Errors	●	●	●								
	Flexibility				●	●	●		●		●	
Knowledge/ skills acquisition	Spatial representation of contextual information		●		●		●					
	Operator engagement in process monitoring							●	●		●	●
	Application accessibility regarding inclusive design	●		●	●		●	●	●	●	●	●
Mental workload	Ease to use	●		●		●	●		●	●	●	●
	Technical data accessibility	●		●	●		●		●		●	●
	Perceived workload			●	●		●		●	●	●	●

Metrics are then matched with the three pre-defined classes of evaluation for social sustainability (organizational performance, knowledge/skills acquisition, and mental workload), reworking the existing knowledge about social sustainability as presented by [40–42]. The proposed measures are able to qualify the social sustainability considering the management of business impacts (organizational performance metrics), the value creation for employees/workers (knowledge/skills acquisition metrics), and, finally, the impact on the employees/workers wellbeing and on the social community (mental workload metrics). In particular, the latter class is able to reflect both the workers' wellbeing in terms of mental fatigue and stress generation, and on the impact on society considering that stressed workers may bring their problems into their families and communities, creating an issue for the entire society. In this context, the NASA-TLX is a widely used, subjective, multidimensional assessment tool that rates perceived workload in order to assess a task or system effectiveness, developed by the Human Performance Group at NASA's Research Center. The measurement of such metrics can be carried out by combining objective and subjective techniques. On the one hand, external experts observe users during task execution in order to monitor the performance and to collect objective data; on the other hand, users are asked to fill in a post-activity questionnaires to collect subjective data. Some metrics about performance could be also automatically calculated as embedded within the AR application, e.g., exploiting task time data and user's on-time feedback.

Such an approach provides a structured way to redefine the workers' role and activities taking advantage from AR tools, focusing on the strong relation between humans and the surrounding working environment, and reasoning about a socially sustainable manufacturing workforce, making a further step with respect to Romero et al. [48].

4. Application to an Industrial Case: Quality Inspection Supported by MBD and AR

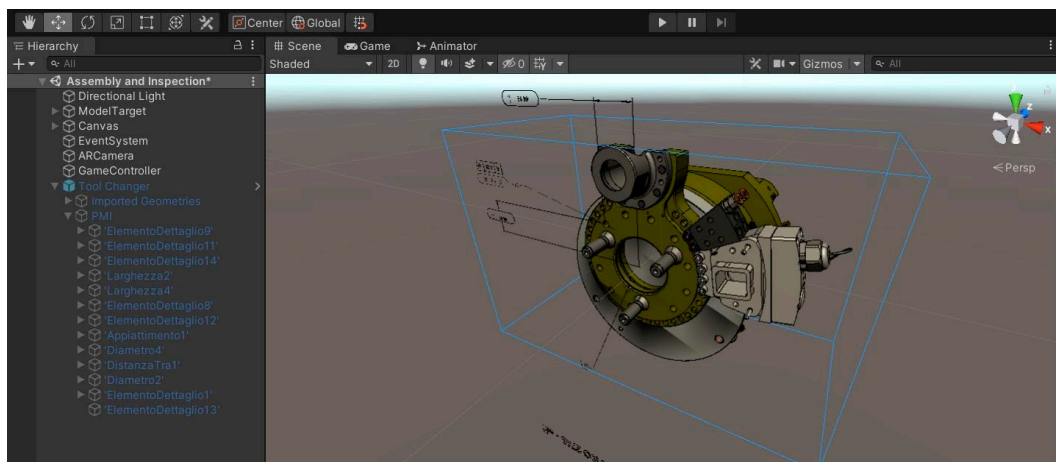### 4.1. AR Application Development

The proposed procedure was implemented for quality inspection and validated in an industrial case. The use case concerns the quality inspection process following the manufacturing and assembly phases of a mechanical device that must fulfill quality check requirements. In particular, a subassembly of a Stäubli tool changer for anthropomorphic robotic manipulators was chosen as a meaningful inspected product. This case was relevant in the current context of industry 4.0 where machines and people should be more strongly interoperable, as an example of human intensive task within an automated production line. The selected case study aimed at validating the proposed approach and demonstrating the benefits provided in manufacturing tolerances verification activities, ensuring that users can successfully complete the prescribed inspection plan by receiving the necessary information on-time. The application was deployed for a handheld device (i.e., an Android tablet) to limit the intrusiveness and related implementation costs. The 6-step general procedure has been implemented for the specific application, as shown in Figure 2.
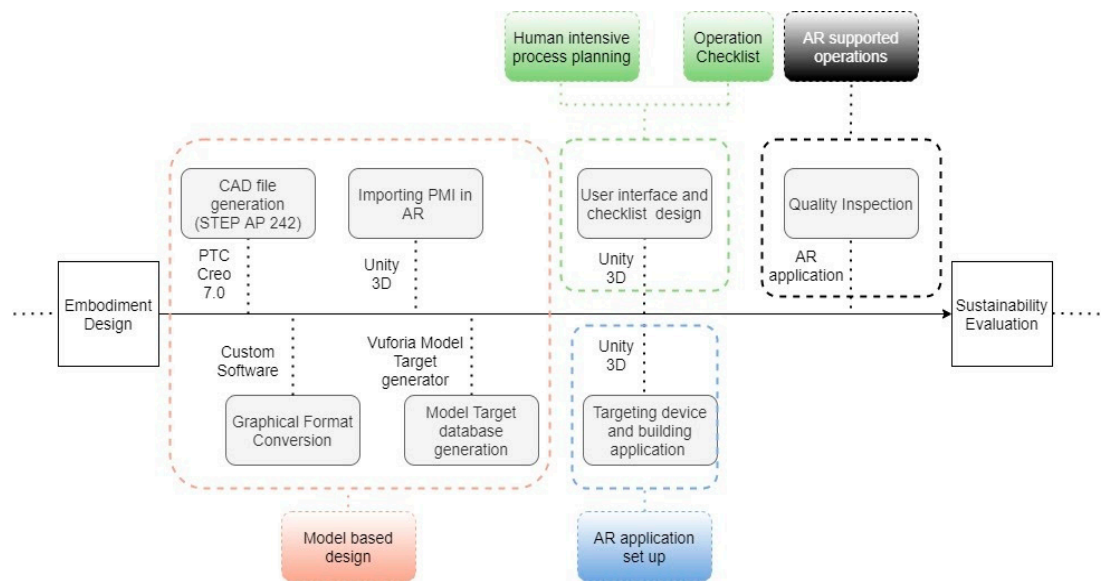
Figure 2. Scheme of the developed application for a quality inspection supported by AR.

The proposed system moves from an initial definition of enriched geometric models, including manufacturing specifications and the intended procedures for the verification process aiming at reflecting the original design intent. For the purpose, PMIs have been added to the 3D geometry of the tool changer using the dedicated functionalities of the PTC Creo 7.0 CAD software. Then, the STEP AP 242 format was chosen as a readable standard format to convey both geometric and inspection data. In particular, annotations such as geometric tolerances and surface finishing have been added to guarantee a correct functional behavior of the analyzed group (i.e., the tool changer slave assembly in its coupling with its counterpart, the master group mounted on the robotic arm). Desired information, in the form of PMI, was applied on a multibody geometry representation of the assembly (i.e., the geometry represented by multiple solid bodies in a single part file). Such an unusual choice was driven by the lack of implemented STEP AP 242 export functionalities for assembly models, as emerged from a benchmark on various commercial mechanical CAD software. In fact, current releases of CADs limit a correct export of PMI definitions in STEP AP 242 files only for part models, even if including more separate solid models. In STEP files, solid bodies are represented by storing both the analytical geometry and the topology of the solid definition according to the specific boundary representation (BRep) solid scheme. However, from this representation scheme, graphical data in the form of polylines and meshes need to be extracted, which are more usable in the context of AR applications. To this aim, we used a conversion to an intermediate XML (extensible markup language), which is a metalanguage that allowed us to define customized markup languages, especially in order to display documents on the Internet. We exchanged the provided file format in order to decouple the engineering information that is properly conveyed by STEP files from the pure graphical representation patterns, typical of AR applications. The adopted XML file schema was built to keep track of the product parts hierarchy, the geometry of the solid bodies through meshes of the contour faces, and annotations in the form of polylines or even meshes, as shown in Figure 3.

Figure 3. Structure of the XML (extensible markup language) file as exchange means between STEP 242 and AR application.

Data from the STEP files to the XML format are converted thanks to a software developed on purpose, based on standard triangulation algorithms applied to the face geometry and interpretation of the data structures used by STEP AP 242 files to represent annotations in terms of graphical and semantic content. The choice to develop an original translator was motivated by the fact that existing packages show shortcomings in terms of import of 3D annotations. More specifically, in the context of AR applications, only mesh data are usually extracted from standard file formats (such as fbx, .obj, etc.) while curve or polylines entities are not natively supported. Thus, flexibility and completeness of data can be guaranteed, as can independence from future enhancements in the managed entities. The converted geometry is imported in Unity 3D, which is a high-fidelity gaming engine used in the industrial context to develop virtual and augmented reality applications. Unity has been used as a platform to develop the AR application, define the user task list, and support the inspection operations. In order to build the 3D scene, an ad hoc plugin of Unity 3D was developed to read entities from the XML exchange file. According to Unity 3D standard procedures, the imported entities are organized in GameObjects and structured to separate solid geometries from PMIs—which are both children of the same parent GameObjects—for a flexible manipulation in the scene preparation phase, as represented in Figure 4.

The spatial recognition of the tool changer geometry and its tracking is guaranteed through the PTC Vuforia model target tracking algorithm (Vuforia is a commercial solution released by PTC to provide a comprehensive platform to develop AR application). The required Vuforia database, including the object's actual physical size and guide-views, was generated using the CAD STEP file within Vuforia model target generator software.

The model database and Vuforia software development kit (SDK) were afterwards imported into Unity and a single application was implemented to target "quality inspection" operations. As shown in Figure 5A, two side panels were provided to assist the operations, i.e., a checklist panel with PMI type indications to guide workers step-by-step and to track the task's progression and technical support, aiming at supplying technical sheets or activating the remote assistance through Vuforia Chalk (a PTC solution for remote assistance). Annotations were grouped according to the specific equipment required for their verification (e.g., coordinate-measuring machine (CMM)), caliper, and roughness tester. Each group corresponded to a single step of the operation checklist. The two buttons PMI and CAD allows the end user to activate/deactivate the visualization of the overlaid PMI annotations or CAD model, respectively. Lastly, further indications include the measuring equipment required for the specific task, textual notes, and total task completion time.

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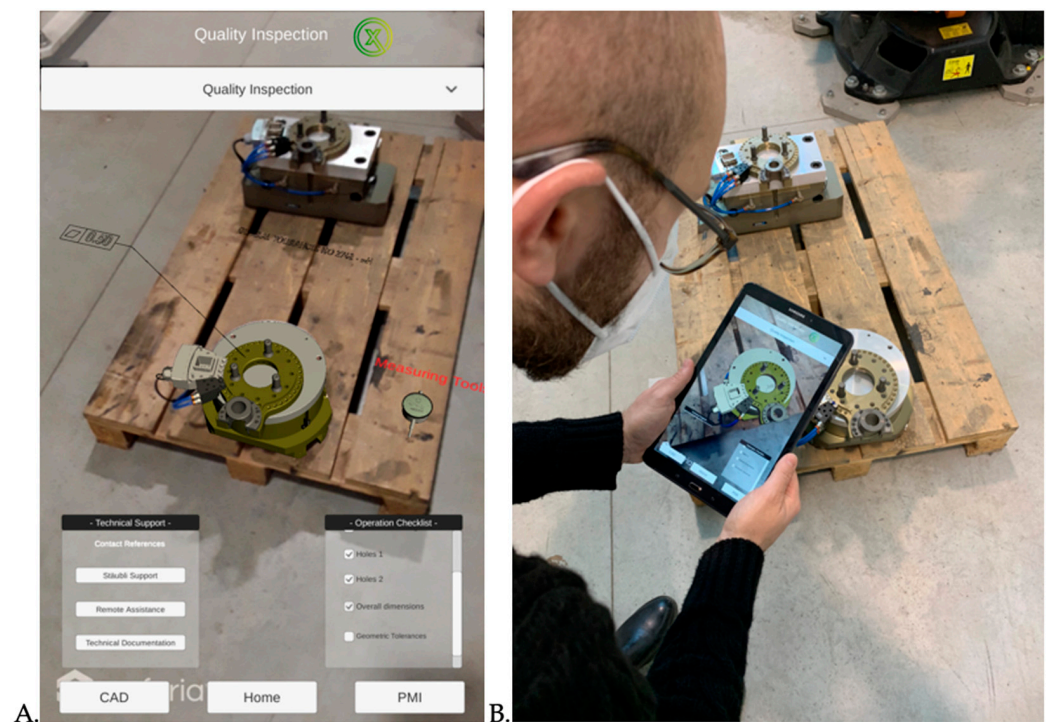
Figure 4. Unity 3D hierarchy during the development stage.

Figure 5. (**A**) Interface of the AR quality inspection application and an (**B**) example of users engaged in inspection operations with the handheld device.

The system was implemented and tested on an Android 8.1.0 device (i.e., Samsung Galaxy Tab A6). The application could be easily replicated for any other device supporting the Vuforia model target feature, such as an Android system with version 6.0 or superior or an iOS device. The application was devised for a handheld device. There are practical limits for the final user, particularly the fact that the operators will not have both hands free.

4.2. Testing with Users and Social Sustainability Assessment

Experimental testing involved 10 male users aged between 24 to 50. They all worked in different industrial fields without any prior knowledge of the specific task. All of them had previous experience with mobile devices and technical documentation interpretation, but they were not familiar with quality inspection operations. Before testing, any user was instructed on how to operate with the AR application. After 2 min of free navigation, the user started the AR-supported procedure. Execution times were recorded for each subject by directly using the application data. A UX expert observed the user and collected data about comments, number of errors committed, and requests of assistance. Ultimately, all users underwent a NASA-TLX questionnaire to evaluate the general mental effort required. A final area of the questionnaires was reserved for user suggestions or general considerations.

As emerged from the results, a general consensus was reached on the usefulness of the AR procedure in supporting highly specialized and human intensive operations, with a low level of physical discomfort. In addition, all users confirmed the ease of use of the proposed AR application and the clear understanding of task requirements, which made the skill's acquisition process much more effective, allowing for a greater sense of self confidence in individual technical knowledge. Some specific functions were found particularly useful. Activating and deactivating CAD/PMI visualization helped the user to reach a higher level of task awareness and to fully concretize each requirement. Several participants also appreciated the panel solution with the task progression, which recalls the traditional Excel inspection plans. In general, the clarity and efficacy of annotations were acknowledged to be of crucial relevance in understanding the original design intent and applying a correct measuring procedure.

Moreover, some interesting ideas for improvements were collected. Some users underlined the necessity of audio signal or haptic feedback to mark each step completion with regard to inclusive design. Moreover, a more flexible visualization of annotations on screen was considered of primary importance, allowing the user to selectively deactivate the single annotation element or to rescale it according to user necessity and point of view as in Figure 5B. According to operators, workers' well-being and physical comfort could greatly benefit from these expedients, which usually badly influence user experience and a task's performance.

During testing, users were observed by user experience experts and were asked to fill-in a post-activity questionnaire to deepen subjective impressions. A preliminary, qualitative KPI evaluation is shown in Table 2, considering the average values obtained on a 5-point Likert scale, where 1 means "very low" and 5 means "very high". As a result, the proposed AR application was positively rated as easy to use and effective, and also with a low perceived workload. Training times and errors were obtained objectively from a statistical analysis on the numerical results registered by experts while workflow efficiency and flexibility were derived respectively from the number of completed tasks compared to the mean time spent by the users to finish the task. As for KPI organizational and performance classes, the operator point of view was considered. In fact, a reduced training time and error rate could enhance worker satisfaction, eventually making their work experience more meaningful. Apart from a precise explanation of the task sequence, no further material was needed, since technical sheets and the required support was fully integrated within the device application if an active internet connection was supplied. The remote feedback from the engineering department implemented through Vuforia chalk with the remote assistance button helped the participants to feel more comfortable and socially integrated in the workflow process, reducing the time needed to detect product imperfections and to communicate information in a valuable way. This ultimately increased operator satisfaction. It also allows for the creation of highly specialized human technical capital without the need of several training sessions. This last point was considered of crucial importance in the overall effectiveness of the application proposed, since users

have the opportunity to concretely and directly test the knowledge acquired according to a "learn-by-doing" approach.

Table 2. Qualitative KPIs evaluation after user testing.

Social Sustainability Classes	KPIs	Evaluation (From 1 to 5) *
Organizational performance	Workflow efficiency	●●●●
	Training time	●●●●
	Errors	●●●
	Flexibility	●●●
Knowledge/ skills acquisition	Spatial Representation of Contextual Information	●●●●
	Operator engagement in process monitoring	●●
	Application accessibility regarding inclusive design	●●●
Mental workload	Ease to use	●●●●
	Technical data accessibility	●●●●●
	Perceived workload	●●

* qualitative evaluation as average values on 10 users.

The experimental testing also highlighted some critical points to be improved by further development from a technical viewpoint. In particular, the integration of tracking technologies with existing devices, which are not all compatible with Vuforia model target system, can cause some problems. In these cases, MBE should rely on other object tracking algorithms that alter the content implementation and force a methodical revision of the framework. An analytical comparison between several development toolkits available on the market (e.g., ARCore, ARKit) and its performance in terms of tracking stability, software sustainability, and features availability should be performed.

This preliminary evaluation was fundamental to validate the flexibility and suitability of the presented workflow to measure social sustainability. Flexibility was demonstrated by using open standards (STEP and XML formats) and exploiting PMI annotations, which are spreading in the industry and becoming standard in CAD system functionalities to convey manufacturing data and inspection procedures. Suitability to assess social sustainability was proven by user testing. Tests highlighted that data transferability is well executed and the AR application is easy to use and fast to learn. Moreover, user satisfaction is high and the perceived metal workload is very low. This means that the proposed AR tool is a good candidate to assist workers in their job with low intrusiveness and high usability. The obtained results were also useful to understand the user perspective and how to improve the current application.

5. Conclusions

This study aimed at proposing an innovative workflow to merge MBD with AR and to understand the impact of AR-supported applications on social sustainability. The final aim was to promote the introduction of AR practices in industry to promote social sustainability, in order to simultaneously improve user satisfaction and improve the human capital. In this direction, this work establishes a foundation for future academic research and industrial developments.

Thanks to the suggested procedure, by exploiting recently defined engineering communication protocols, AR interfaces can help workers improve performance, skills, and mental workload. The proposed AR-based application was shown to effectively support error reduction, lower training times, promote better quality of work, and have higher flexibility thanks to a wider knowledge about processes. With regard to human capital, it helped workers to deeply understand the processes where they are involved and to better manage their own skills, which promotes job satisfaction and motivation. Finally, with regard

mental workload, it was useful to reduce stress and mental fatigue, with a direct positive impact on the work-life balance and the global wellbeing. It can be considered as a starting point to progressively reshape industrial processes, focusing on people in factories and looking for their valorization. Moreover, the set of tools depicted in the specific application seeks to standardize the data flow between design practices and AR applications in order to guarantee seamless interfaces and maintain design intent. The use case demonstrated how the proposed procedure can be successfully applied to support human intensive activities, such as quality inspection, and its real impact on human perception of the work quality and workers' wellbeing. Experimental testing showed that all users were satisfied with AR application usage and successfully completed the predefined tasks, ultimately reinforcing their technical knowledge and with a lower workload. The AR application provided easy and multi-purpose feedback within the same application to facilitate users with a unique overview on the process and to collect the necessary information in a quick and reliable way regarding quality inspection operations.

The proposed application demonstrated how technical product data can be effectively shared within the company to improve the global process quality, to support multi-functional teams, and to promote remote assistance, as well as smart decentralized working. This study is particularly relevant in the current global scenario, where smart working and teleassistance have been pushed by recent factors, from cost reduction strategies followed by companies in the last 10 years, to the recent pandemic situation due to COVID-19.

Future works should create a central "brain" to keep track of product quality information and operators' satisfaction during task execution to better exploit the AR application. Moreover, they should introduce an automatic application to measure social impact and to finally provide a deeper analysis of the social sustainability aspects. This fact will also improve the attention paid by companies to this topic and the precision of user monitoring to finally benefit the global manufacturing system sustainability.

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