(*) Corresponding author
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SUSTAINABLE MANUFACTURING THROUGH AUGMENTED REALITY (AR): THE ROLEOF AR TECHNOLOGIES IN INDUSTRIAL WORKFLOWS USING VISUAL ASSEMBLY INSTRUCTIONS

Aleksandar Trendov*
Ss. Cyril and Methodius University - Skopje, Macedonia
ORCID iD: https://orcid.org/0009-0000-2516-8369
E-mail:trendov@outlook.com

Katerina Mitkovska Trendova
Higher Colleges of Technology - Abu Dhabi, UAE
ORCID iD: https://orcid.org/0000-0003-3740-9865
E-mail: ktrendova@hct.ac.ae

ABSTRACT

Augmented Reality (AR) in visual assembly instructions is enhancing accuracy and efficiency in manufacturing, assembly tasks and contributes to sustainability in many ways, supported by different software. Sustainability benefits are amplified when AR is integrated into broader digital and eco-friendly initiatives within an organization, such as lean manufacturing or a circular supply chain and by integrating methodologies like poka-yoke, Six Sigma, Kanban, and TQM with AR technologies. This study examined sustainability benefits of implementing AR technologies in industrial workflows, particularly in visual assembly instructions. The primary aim was to determine how AR could improve manufacturing efficiency and reduce sustainability impacts through decreased waste, optimized training, and enhanced product quality. Related publications on AR's role in assembly, sustainability, and interface optimization in manufacturing were reviewed. Research methods also included testing AR-guided instructions on ergonomically designed hardware, such as 3D printed tablet-mounted device, to evaluate usability, assembly time, and error rates. For our prototype we developed visual instructions using Autodesk Maya and Substance Painter to create and animate 3D models, mapped and textured for realistic AR scenes in Adobe Aero. AR tools will advance sustainable industrial applications. Future developments in AR include enhanced real-time data integration and adaptive learning models, which support sustainable practices by dynamically adjusting or simulating assembly instructions based on individual performance and product life cycles.

Keywords: Augmented Reality; Visual Assembly Instructions; sustainable manufacturing; optimized training; ergonomically designed hardware; AR software solutions and tools.

INTRODUCTION

Augmented Reality (AR) has emerged as a transformative technology in manufacturing, bridging digital information with physical workflows to enhance precision, efficiency, and sustainability. By providing real-time, adaptive visual guidance, AR reduces cognitive load and assembly errors, optimizing manufacturing processes. This alignment with sustainable manufacturing goals is critical in addressing environmental challenges, as AR helps minimize material waste, improve energy efficiency, and streamline training processes (Azuma, 1997; Chu and Pan, 2024).

The integration of AR with established manufacturing methodologies such as lean production, Six Sigma, poka-yoke, and Total Quality Management (TQM) further amplifies its benefits. Lean principles, which emphasize waste reduction, are supported by AR's real-time workflow corrections, while poka-yoke and Six Sigma benefit from AR's ability to ensure error-proof processes through interactive feedback (Vogl, Brecher, and Kloeser, 2016; Marr, 2020). Additionally, AR plays a pivotal role in Industry 4.0 and the emerging Industry 5.0 frameworks, enabling human-centric, sustainable production systems by integrating with advanced technologies like IoT and digital twins (Pereira, Alves, and Arezes, 2023; Feng, Wang, and Xu, 2020).

This study explores the potential of AR in sustainable manufacturing by developing and testing AR-guided visual assembly instructions using Autodesk Maya, Substance Painter, and Adobe Aero. These tools were utilized to create photorealistic 3D models and immersive animations to guide assembly processes. The research evaluated usability, assembly time, and error rates using ergonomically designed hardware, such as 3D-printed tablet mounts (Dey et al., 2020). By integrating AR with adaptive learning systems and enhanced real-time data capabilities, this study demonstrates how AR can further align with sustainable manufacturing practices while fostering innovation and efficiency.

ANALYSIS OF AR CAPABILITIES IN VISUAL ASSEMBLY INSTRUCTIONS

Augmented Reality (AR) is becoming a vital tool in manufacturing and assembly, offering innovative ways to enhance accuracy and efficiency. By integrating digital overlays with physical components, AR helps workers perform complex tasks more intuitively and effectively. Key aspects of AR in visual assembly instructions include:

1. Guidance and Feedback: AR provides real-time, step-by-step guidance by overlaying virtual instructions onto physical components, which reduces cognitive load and improves task understanding. This capability enables workers to handle intricate processes with minimal training (Dassault Systèmes).
2. Error Reduction: AR systems leverage sensors and image recognition to detect and correct errors during assembly. These systems validate each step, ensuring precision and reducing the need for rework, which aligns with sustainable manufacturing practices (LightGuide).
3. Real-Time Data Integration: Modern AR applications incorporate live data from IoT-enabled devices, allowing workers to access metrics like torque levels or temperature during assembly. This integration helps maintain quality standards and minimize faults in real-time (NSFlow).
4. Adaptive Instructions: AR can tailor instructions to the user's skill level or assembly progress, which is particularly beneficial for less-experienced workers or when managing

complex assemblies. This adaptability enhances training and overall efficiency (Li et al., 2024).

5. Collaboration Features: AR facilitates remote collaboration by enabling real-time assistance from technicians or engineers, which accelerates troubleshooting and reduces production downtime (NSFlow).
6. Data Collection and Analysis: AR systems analyze user interactions, providing insights to refine processes and future instructions. This feedback loop helps identify frequent errors and improves workflow designs (IEEE Xplore, 2024).

The adoption of AR in visual assembly workflows demonstrates its potential to optimize operations, reduce waste, and improve product quality, while also advancing sustainability in manufacturing.

CONTRIBUTIONS TO SUSTAINABILITY

Implementing AR in visual assembly instructions can contribute to sustainability in several ways:

1. Reduced Material Waste: AR's precise guidance minimizes assembly errors, reducing the need for rework or replacement parts. This results in fewer discarded materials and lowers resource consumption.
2. Optimized Training: AR can replace or supplement traditional training, reducing the need for physical prototypes and practice parts. New workers can learn with virtual guidance, which lessens the demand for consumables used in conventional training processes.
3. Improved Product Quality and Durability: By enabling workers to assemble products with greater accuracy, AR helps create more reliable and durable products. Fewer defects in the final product can lead to less waste over time, as high-quality items are less likely to be returned or discarded prematurely.
4. Reduced Energy Use: AR's ability to streamline assembly and maintenance tasks means processes are completed faster, reducing overall energy consumption in manufacturing and assembly facilities.
5. Lowered Carbon Footprint from Remote Assistance: AR enables remote collaboration, reducing the need for travel by technical experts. This results in lower greenhouse gas emissions related to transportation.
6. Enhanced Circular Economy Practices: By improving product assembly and facilitating more efficient maintenance and repair, AR supports practices that extend product life cycles, potentially easing the strain on resources required for new manufacturing.

These sustainability benefits are often amplified when AR is integrated into broader digital and eco-friendly initiatives within an organization, such as lean manufacturing or a circular supply chain. Integrating methodologies like poka-yoke, lean manufacturing, Six Sigma, Kanban, and TQM with AR technologies can enhance industrial workflows using visual assembly instructions. For instance:

- Poka-yoke techniques can be embedded in AR systems to prevent errors during assembly, guiding users through each step.
- Lean principles can optimize AR workflows by identifying and eliminating wasteful steps in the assembly process.

- Six Sigma can use AR data analytics to monitor and improve quality by reducing defects in real-time.
- Kanban can be visually represented in AR to manage work-in-progress, ensuring a smooth flow of tasks.
- TQM can leverage AR for continuous feedback, enhancing collaboration and improving overall quality.

Together, these methodologies can create a more efficient, error-resistant assembly environment, ultimately supporting sustainable manufacturing practices.

EXPLORING AR SOFTWARE SOLUTIONS FOR VISUAL ASSEMBLY INSTRUCTIONS SUPPORT

Several AR software solutions support visual assembly instructions with a focus on improving efficiency, accuracy, and sustainability:

- PTC Vuforia: Known for its industrial AR applications, Vuforia allows for the creation of guided work instructions overlaid on physical objects. It offers remote assistance and performance analytics, which help reduce errors, training costs, and waste.
- Scope AR WorkLink: WorkLink provides a platform for creating AR-based visual instructions and remote collaboration. It's user-friendly, allowing companies to create detailed assembly instructions that help reduce rework and resource waste while optimizing the assembly process.
- Microsoft Dynamics 365 Guides: Integrated with the Microsoft ecosystem, this tool provides interactive AR guides for tasks like assembly and maintenance. It enables hands-free work through Microsoft HoloLens, which enhances accuracy and reduces training time and errors, contributing to sustainable operations.
- Tacton Augmented Reality: Tacton focuses on manufacturing and offers customizable AR guides for assembly and maintenance, especially useful in complex manufacturing setups. It can integrate with existing systems to optimize resource use and reduce errors in assembly.
- Atheer: Atheer's platform is tailored for "frontline" industrial tasks, offering step-by-step AR-guided instructions and real-time remote collaboration. It can support sustainable operations by enhancing first-time quality and reducing travel needs for expert support.
- JigSpace: JigSpace specializes in creating 3D instructions for assembly and maintenance, useful for visualizing parts and tasks in detail. It allows companies to share visual instructions that minimize material usage and accelerate training with fewer physical resources.
- RE'FLEKT ONE: This platform enables enterprises to create AR manuals that overlay real-time instructions on equipment and components, improving accuracy and reducing material waste from assembly errors. It's especially popular in industries with complex assembly requirements, like automotive and aerospace.

These solutions vary in their specific features, integration capabilities, and usability but all focus on streamlining complex tasks, lowering error rates, and supporting sustainability goals through enhanced precision and resource optimization.
Autodesk Maya, Babylon.js, and Adobe Aero are powerful tools for creating AR content. A brief look at what each brings to the table in the context of AR-based visual assembly instructions:

- Autodesk Maya: Primarily a 3D modeling and animation software, Maya is excellent for creating detailed 3D assets used in AR applications. In the context of assembly instructions, it's used to build complex 3D models of machinery or products, which can then be imported into AR software for interactive, immersive instructions. Maya is particularly valuable for creating high-quality, photorealistic models that help workers visualize assembly parts accurately.
- Babylon.js: This open-source, web-based framework allows developers to build interactive 3D applications and AR experiences directly in the browser. Babylon.js is beneficial for visual assembly instructions because it allows companies to make AR content easily accessible via web browsers, which can be a more affordable and versatile solution. This framework is ideal for building lightweight AR experiences that don't require specialized hardware, broadening access to AR-based instructions.
- Adobe Aero: Aero focuses on making AR creation accessible without requiring deep programming knowledge. It's excellent for prototyping or building interactive AR experiences for assembly instructions quickly. Aero's intuitive interface allows for importing 3D models and setting up interactive triggers, making it a practical choice for teams needing to develop instructions that overlay animations or guidance onto real-world objects. Although it's not as feature-rich for industrial applications as some other platforms, Aero is highly useful for generating initial AR experiences or testing assembly instructions.

While these tools are powerful for creating the AR content itself, they typically require integration with an AR deployment platform, like Vuforia or Microsoft Guides, for distribution and user interaction in industrial settings. This combination, model creation with Maya, web-based interaction with Babylon.js, or rapid prototyping with Aero, can bring high-quality AR instructions to life that improve both worker efficiency and reduce environmental impact through accurate assembly.

IMPLEMENTATION CASE

AR technology has the potential to revolutionize traditional workflows in certain industries, providing users with new tools to achieve higher levels of productivity and efficiency. By integrating virtual content with the real world, AR can transform the way businesses operate, offering innovative solutions for training, visualization, maintenance, and much more.
In this specific case, AR is being used to create a visual assembly guide that will be used in the Smart Learning Factory at the Faculty of Mechanical Engineering in Skopje. The visual assembly guide was created in three AR software tools, observing the positive and negative aspects of each.

Creation of 3D Model and Animation

The first step in the process of creating a visual assembly guide is to create a photorealistic 3D model. The four phases of obtaining a photorealistic 3D model are: modeling, lighting, texturing, and rendering. There are different AR software tools that support different file formats, so during the 3D model creation phase, textures need to be adjusted depending on which file format is used. After the 3D model is created, a 3D animation is made. For 3D modelling and animating, Autodesk Maya software was used. Once the 3D animation is completed, it needs to be divided into different steps, i.e., different files.

Creating a visual guide for assembly in AR

The visual assembly guide was created using three AR software tools: Adobe Aero, Reality Composer, and WebAR, while observing their positive and negative aspects.

First, to use the animation in Adobe Aero, it was necessary to divide the steps into the .glb file format. Since Autodesk Maya does not support exporting to this file format natively, the Babylon plug-in needed to be installed. The duration of each step (from frame to frame) is then specified, and the steps are exported. All steps are subsequently transferred as separate files into Adobe Aero. The division of the animation into steps is done to allow each step to be activated by touching the tablet screen.

To trigger individual animations by screen touch, touch triggers (behavior triggers) are set up in Adobe Aero's Behavior Builder, Figure 1. This ensures that upon the completion of one animation, the next animation begins.

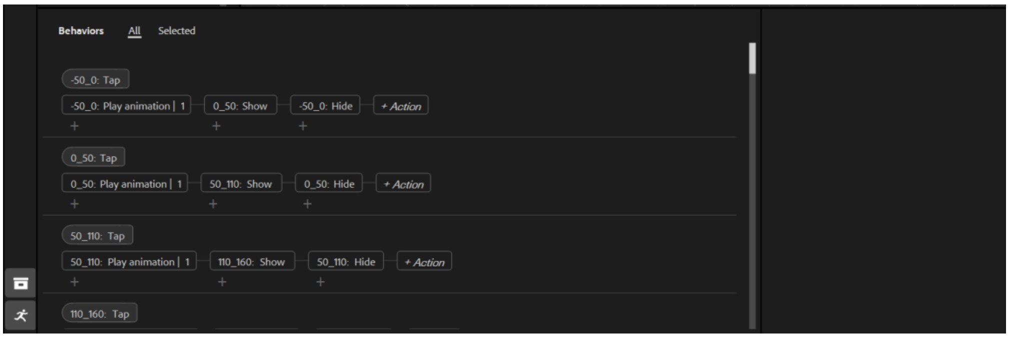

Figure1: Part of the triggers in the Behavior Builder

Then, using a mobile phone or tablet, the same .real file is loaded, and the entire assembly process of the part can be photographed or recorded with the camera by activating the steps through screen touches.The positive aspects of Adobe Aero (Figure 2) include its support for textures from Substance Painter, as the .glb file format supports .jpg and .png images.

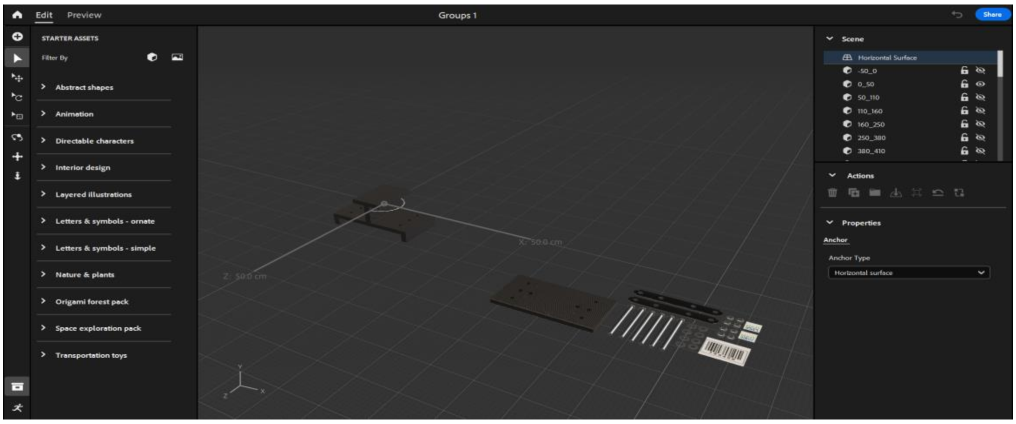

Figure2: Adobe Aero interface

Additionally, being an Adobe software, it has a wide user base and is compatible with other Adobe tools.However, regarding its negative aspects, since the application is relatively new, the file loading time is long and depends on the internet speed. Furthermore, the application often experiences sudden freezes, export issues, and similar problems. The main reason I would not recommend using this application is the limited availability of smart devices that can support it.

When it comes to Reality Composer, each step (from frame to frame) must also be divided, but the export process differs from Adobe Aero. Devices with iOS are compatible with a specific file format, .usd. For augmented reality, the .usdz extension is used, which needs to be added to the file name during export since Autodesk Maya does not have specific settings for exporting .usdz files.

Next, all the steps are transferred to an iPhone or iPad, and in Reality Composer, each step is uploaded into a separate scene. In the Behaviors section, triggers are set so that when a button is pressed, the button's animation plays first, followed by the animation of the part, and finally, the scene transitions to the next one, Figure 3.

Figure3: Reality Composer interface

The positive aspects of Reality Composer include the absence of sudden freezes and relatively fast scene loading. Additionally, there is a dedicated library with ready-made 3D models that can be used. The quality of the 3D models depends on the file size, specifically the number of scenes, Figure 4.

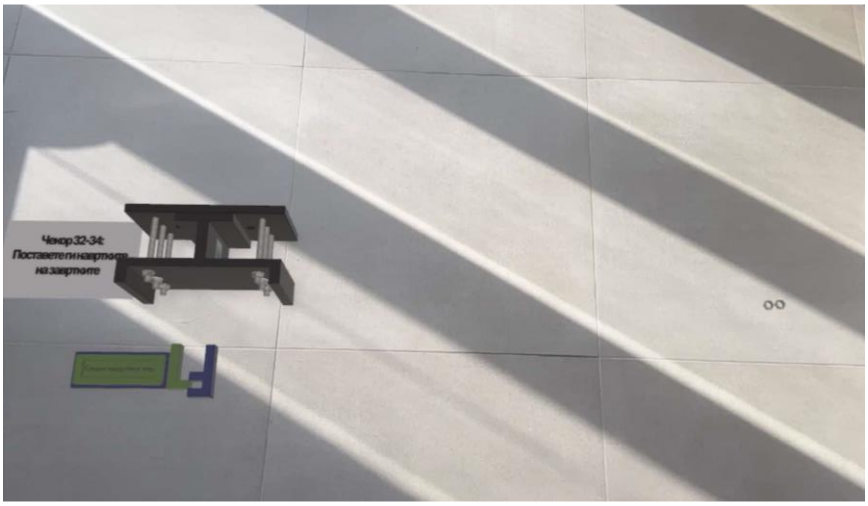

Figure 4: Visual assembly guide in augmented reality

The negative aspects of Reality Composer include the fact that scenes created in Reality Composer can only be used on Apple devices, and the number of scenes is limited to 30. However, with the advancement of devices used for augmented reality, these limitations could be eliminated.

The reason for not using both Adobe Aero and Reality Composer is that users cannot easily access the AR scene, meaning it cannot be launched directly through their camera. Because of this, the scene was also created in WebAR, a web platform that offers the ability to launch the AR scene through a QR Code or Image Target. Like Adobe Aero, WebAR uses .glb files. After setting up the scenes, a QR Code is generated, which, when scanned with a camera, leads to a webpage that requires permission to use the camera. Once granted, the entire scene is launched in augmented reality.

WebAR is compatible with both iOS and Android devices. It offers more capabilities than the other two platforms, and with this platform, augmented reality can be applied in a broader range of areas. In addition to QR Codes as triggers for launching the AR scene, other triggers such as images, geographic coordinates, and more can also be used.

Creating a Tablet Holder

In addition to creating the visual assembly guide in AR, it was necessary to design and create a tablet holder that will be used in the Smart Learning Factory at the Faculty of Mechanical Engineering in Skopje, Figures 5a and 5b.

Figure 5a and 5b: The work space

The holder was made using 3D printing, and the CAD model was designed in SolidWorks.
3D printing as a process offers the ability to reduce waste, use less energy in the manufacturing process, thus reducing costs, and using recyclable materials that are less harmful to the environment.

Before starting the design of the CAD model in SolidWorks, dimensions were taken from the workspace where the holder would be used to determine the necessary dimensions for the holder.Next, anthropometric data was taken from the internet to determine the desired height of the holder relative to the person using the tablet, Figures 6a and 6b.

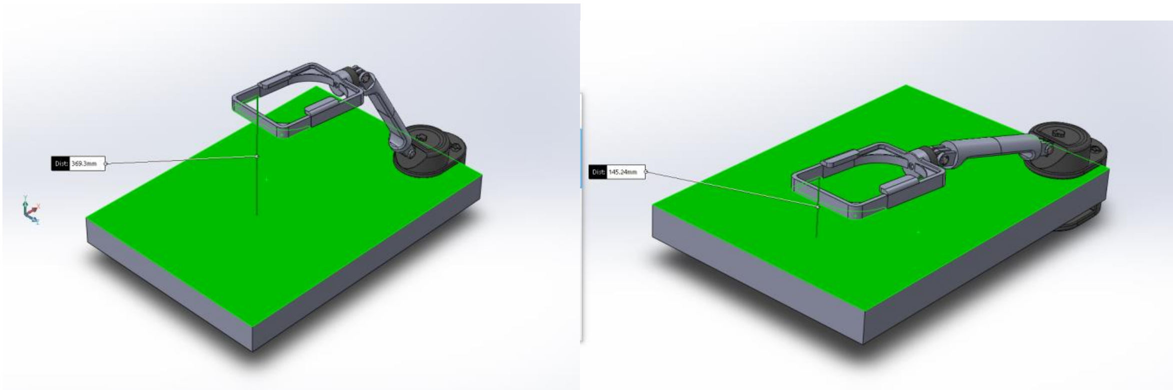

Figure 6a and 6b: Maximum required distance from the tablet to the table

To ensure that the holder can be placed in the desired position, it must rotate at several points, which was the main challenge in the design, as in Figure 7.

Figure 7: Points of rotation of the holder

Ergonomic guidelines for workstations with visual displays in a standing position were also considered, as in figure 8.

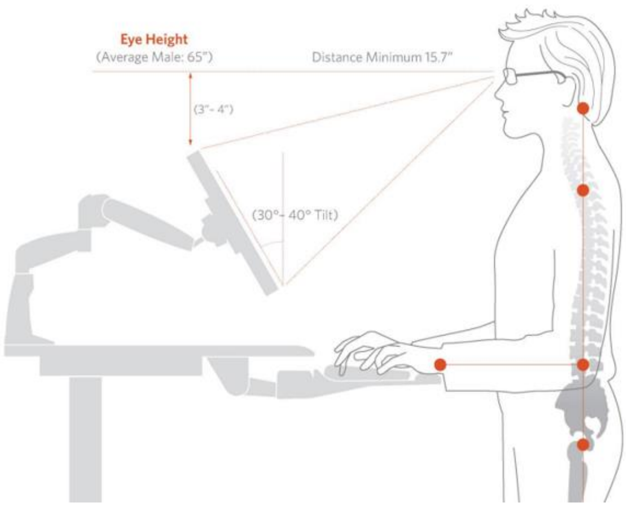

Figure 8: Ergonomic guidelines for workstations with visual displays in a standing position

Although it would be ideal to position the tablet at an angle of 30-40 degrees, this will not be possible in this case due to the need for the tablet's camera to record the assembly process.

After analyzing ergonomic guidelines, reviewed were existing designs of holders with similar applications.

During the design process, some of the guidelines for designing plastic products were also considered, which would be useful for producing plastic parts through 3D printing. The plastic parts were designed with uniform thickness, and where a change in thickness was necessary, a fillet transition was used to reduce the likelihood of part breakage, Figure 9.

Figure 9: Finished assembly

It is planned for the project to expand and improve in future, including all aspects of sustainability.

APPLICATIONS AND FUTURE PRACTICES

AR has a wide range of applications in many different industries. In medicine, AR is used to simulate complex surgical procedures, providing surgeons with realistic training conditions before working on real patients. AR enables industries like architecture, engineering, and product design to visualize and prototype projects. Architects can present 3D models of buildings displayed on construction sites, helping clients imagine the final structure in its real-world context. Engineers can explore virtual prototypes of machines, identify design flaws, and improve functionality before production. AR enables designers to rapidly iterate and refine ideas, speeding up product development. AR has revolutionized maintenance and repair processes in industries like automotive and aerospace. Engineers equipped with AR devices can access real-time information and step-by-step instructions directly on the equipment they are servicing. This eliminates the need for printed manuals and reduces downtime, as engineers can quickly identify and solve problems with greater accuracy. AR is increasingly used for safety training and simulations in hazardous environments. Industries like oil and gas, mining, and construction use AR to create virtual simulations of dangerous scenarios. Workers can practice safety protocols and emergency procedures in a controlled environment, minimizing real-world risks and improving overall safety standards. Future applications include more examples in different industries, manufacturing, as well as services.

CONCLUSION

This study highlights the transformative role of Augmented Reality (AR) in advancing sustainable manufacturing practices, particularly through visual assembly instructions. By integrating AR technologies into industrial workflows, significant improvements in efficiency, accuracy, and resource optimization were achieved. AR's ability to provide real-time guidance, minimize errors, and adapt to user skills supports not only enhanced productivity but also reduced material waste and energy consumption, aligning with sustainability goals.

The research demonstrated the effectiveness of AR tools like Autodesk Maya, Substance Painter, and Adobe Aero in creating immersive and photorealistic visual assembly guides. While platforms such as Adobe Aero and Reality Composer offer unique capabilities, limitations such as device compatibility and scene constraints highlight the potential advantages of WebAR, which provides greater accessibility and flexibility.

AR's alignment with methodologies such as poka-yoke, lean manufacturing, Six Sigma, and Total Quality Management further enhances its ability to create error-resistant and efficient workflows. Additionally, the development of a 3D-printed, ergonomically designed tablet holder underscores the importance of integrating AR with physical tools to optimize usability and comfort, which covers one more aspect of sustainability.

Future directions for AR in manufacturing include leveraging advanced technologies such as IoT and adaptive learning systems to further refine real-time data integration and personalized guidance. Expanding AR applications to new industries and adopting innovative AR hardware will ensure its continued impact on sustainability and operational excellence. This study provides a foundation for broader adoption and innovation in AR-driven manufacturing systems.

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