

Systematic Selection of Visual and Cognitive Assistive Equipment: The Case of Gas Turbine Assembly in Narrow Spaces

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Abstract

As companies continue to optimize their processes, many are adopting digital technologies. In sectors like automotive manufacturing and equipment maintenance, technicians must handle large volumes of task-related information. To support them, assistive systems based on augmented or mixed reality have been developed to deliver the right information at the right time. This study proposes a prototype approach to identify the most suitable technology for providing visual and cognitive support in specific work situations. Grounded in design research methodology, the approach draws on criteria identified through systematic literature reviews. It incorporates multicriterion analysis, the taxonomy of assistance systems, the Analytic Hierarchy Process (AHP), and a use-value study to compare several head-mounted display alternatives. Empirical validation was conducted through a case study in an industrial gas turbine assembly. The method stands out by integrating industrial constraints, such as narrow spaces and operator mobility, into the decision-making process. Both technical (processor, autonomy, connectivity) and ergonomic (field of view, weight, interactions) criteria were considered. In the case studied, Magic Leap 2 emerged as the most appropriate device. The findings underscore the value of a structured approach for selecting assistive technologies in complex environments and highlight the importance of combining expert evaluation with context-specific constraints. However, the study also emphasizes the need for further testing with end users to fully assess the usability and acceptance of the chosen solution.

Keywords

Industry 5.0, Assistance Systems, Head-Mounted Displays, Augmented Reality, Multicriterion Analysis, Cognitive Ergonomics, Selection

1. Introduction

With industrial expansion, intensifying competition in the manufacturing sector, and technological advances, product and service quality specifications are becoming ever more demanding. To meet these challenges, companies must not only optimize their production processes but also improve operators' working conditions to ensure greater efficiency [1], a drop in the occurrence of errors, and a reduction of occupational risks [2].

In this dynamic, the fifth industrial revolution, or Industry 5.0, marks a major evolution by integrating an anthropocentric approach, in which humans are positioned at the core of technological development. Unlike Industry 4.0, which focused primarily on automation and artificial intelligence, Industry 5.0 promotes harmonious collaboration between humans and machines [3]. It thus encourages the development of a wide range of assistive technologies designed to improve working conditions and optimize productivity. This equipment provides support to operators and can be grouped into three broad categories, according to the type of assistance provided: sensory, physical, or cognitive [4].

Sensory assistive equipment enhances operators' perception by improving their ability to detect visual, sound, or tactile signals that might otherwise go unnoticed. Physical assistive devices target muscular effort reduction by facilitating the handling of heavy loads or reducing fatigue associated with repetitive gestures. Finally, cognitive assistive equipment supports decision-making and complex task execution by providing real-time information or guiding operators through interactive instructions.

Nevertheless, as the range of assistive equipment continues to expand, selecting the most appropriate solution has become a critical challenge for companies seeking to optimize their production processes. Moreover, the adoption of such technologies is strongly influenced by factors such as user acceptance, perceived usability, and context-specific constraints [5]. An improper selection may result in ineffective support or even introduce new ergonomic or organizational challenges. A reliable selection approach must therefore identify the equipment best suited to each work situation, taking into account the specific constraints of the workstation, the operators' needs, and the targeted performance objectives.

This issue is particularly pressing in sectors such as the aerospace and automotive industries, where technicians frequently face complex assemblies performed in narrow spaces. Spatial constraints constitute significant bottlenecks for integrating many types of assistive equipment, which must therefore be chosen with great care. For instance, exoskeletons often used to reduce muscle fatigue may be difficult to operate in narrow spaces. Likewise, some cognitive assistance devices, such as head-up or head-mounted displays, may prove ineffective when space

does not allow for ergonomic use.

The present work aims to develop a prototype of a systematic approach for evaluating and selecting the most suitable assistive equipment for complex assemblies in narrow spaces. This approach provides companies with a structured process to guide their choice, taking into account technical, ergonomic, and organizational constraints. Identifying the most relevant devices enables significant improvements in operators' productivity while ensuring their safety and well-being at work [2].

2. Literature Review

Although the use of cognitive, sensory and physical support equipment is booming in the manufacturing sector, the state of the art is characterized by a notable dearth of methodologies dedicated to their selection. From the scientific literature, it can be seen that although numerous studies have focused on various aspects of assistive equipment [6], very few have looked specifically at setting up or proposing approaches for optimally choosing such equipment. Generally, existing research has focused more on equipment classification [7] [8], implementation and evaluation in real-life contexts [9] [10].

To the best of our knowledge, only two research teams have proposed methodologies to be used in choosing assistive equipment. The team of Mark, Rauch, et Matt [6] proposes an approach taking into consideration parameters related to the worker, the task and the workplace, in a bid to offer choice support adapted to assembly workstations and tasks in general. For their part, Syberfeldt, Danielsson, et Gustavsson [11] propose specific guidelines for choosing a particular type of assistive equipment, and they focus more on specific assembly cases.

2.1. Methodology Proposed by Mark, Rauch and Matt (2022)

The methodology proposed by Mark and his team incorporates guidelines covering both the selection and implementation of worker assistance systems. It is based on a high-level data catalog, which is a structured database providing a methodical listing of all assistive equipment available on the market.

The selection process itself consists of four steps:

2.1.1. Analysis of the Workplace and Work Environment

This step allows to identify the constraints and limitations to which the assistive equipment will have to adapt. It allows a comparison of the characteristics of the different pieces of equipment in the catalog with the basic characteristics of the work environment. It thus becomes possible, early in the process, to eliminate equipment that is not suitable for the given environment, or to remedy a limitation unique to the environment.

2.1.2. Task and Work Analysis

This step identifies relevant parameters related to the task and to workers' needs. To this end, Mark, Rauch, et Matt [6] propose a list of 23 parameters grouped into

five categories, namely, relevant human senses (e.g., sight), physical ability, cognitive ability, personal qualities, and skills. The task is assessed based on these 23 parameters, which allows to establish a:

- Vector \vec{A} , which encodes task requirements (1 = necessary, 0.5 = partially necessary, 0 = not necessary);
- Vector \vec{B} , which encodes the worker's support needs (0 = no help required, 5 = maximum help required).

2.1.3. Matching the Analysis of the Specific Task to the Worker

During this step, the worker's needs are matched to the task requirements by performing a component-by-component product of vectors \vec{A} and \vec{B} . The result is a vector $\vec{C} = \vec{A} * \vec{B}$, which identifies the parameters requiring assistance.

2.1.4. Correspondence with Assistive Equipment Catalog

Each piece of equipment in the catalog (25 pieces) is rated according to the 23 parameters, on a scale ranging from 0 (no assistance) to 10 (maximum assistance). This generates a matrix M with 25 rows (equipment) and 23 columns (parameters). Matching is realized by performing the product $\vec{S} = M * \vec{C}$, where each row of \vec{S} corresponds to a piece of equipment and indicates its suitability ranking. Equipment is ranked in descending order of relevance. Taking into consideration additional parameters, the top-ranking options are then examined in greater detail. Examples of these parameters include acquisition and implementation costs, technological maturity, organizational impact, etc.

The methodology proposed by Mark, Rauch, et Matt [6] stands out for its innovation and versatility, since it can be used in many different contexts and for different types of assistive equipment. It is not limited to cognitive assistive equipment, but also includes sensory and physical assistive equipment, and even allows to combine two or three of the categories to address a specific problem. The approach focuses on a detailed analysis of the task, the worker and the work environment. Furthermore, it takes into consideration the needs and constraints of all participants in a work system, while providing an exhaustive evaluation of available equipment thanks to its high-level data catalog.

It should nevertheless be noted that this methodology is primarily designed for a general manufacturing context. For complex assemblies realized in narrow workspaces, it cannot, by itself, precisely identify equipment that can provide optimum worker support.

Indeed, multiple studies have shown that the most suitable assistive equipment in such contexts are wearable devices. Although implementing Mark, Rauch, et Matt's methodology [6] may lead to this conclusion, further studies are still needed to determine which wearable devices provide the best ergonomic and technological performance.

2.2. Methodology Proposed by Syberfeldt *et al.* (2017)

Syberfeldt *et al.* [11] propose a structured and simple selection process designed

to help manufacturing companies efficiently identify the best augmented reality glasses from the many options available on the market. This process is based on a 12-stage sieve and takes as input a complete list of available glasses, after which it provides a single optimal option as output.

The initial list is built by listing all the augmented reality glasses available on the market. Each stage of the sieve corresponds to one of 12 comparison criteria: mass, visual field, battery life, optics, open programming interface, audio, control, processor, storage, processing memory and connectivity. Syberfeldt and his team also established an acceptability threshold for critical criteria such as battery life, mass and head-mounted display visual field.

The selection process at each stage follows a precise algorithm:

- **Elimination:** Exclude all glasses that do not meet the acceptability threshold for the criterion in question. For example, if the threshold for mass is set at 100 grams, all glasses weighing more than 100 grams are eliminated.
- **Ranking:** Rank the remaining glasses according to their performance with respect to the criterion, in descending order of relevance. For the weight criterion, glasses are ranked from lightest to heaviest.
- **Transition:** Move on to the next criterion (lower level) to continue the evaluation.

At each stage, glasses that do not meet the defined thresholds are eliminated, until, at the final stage, one is selected as the best among the initial 12.

However, this approach has several limitations. The first is related to the layout of the stages, which can lead to:

- Early elimination of a promising smart glasses. For example, if the mass criterion is placed in the first stage, a technologically high-performance goggle that meets all the other criteria can be excluded if its weight exceeds the set threshold;
- Late elimination or ultimate selection of an obsolete smart glasses. If an essential criterion such as connectivity is evaluated last, it may turn out that only smart glasses that cannot connect to the equipment or databases (via Wi-Fi or Bluetooth) will reach the stage. This could lead to a complete lack of selection, or to an unusable smart glasses being chosen.

The second limitation of this approach is linked to a strict use of acceptability thresholds. By proceeding as such, the algorithm results in the direct elimination of smart glasses without taking into consideration the influence that some criteria may have on others.

Though complementary, these two studies highlight a crucial need: develop an assistive equipment selection approach that combines technical rigour with a consideration of human and contextual factors, while remaining pragmatic and operational for companies.

The present article adopts this approach by proposing a systematic selection process for visual and cognitive assistive equipment, adapted to the diverse needs of operators and the constraints of modern industrial environments. Based on a

critical review of existing methodologies and an in-depth analysis of emerging needs, this approach aims to provide decision-makers with a practical framework for selecting the most suitable assistive equipment, while enhancing operational performance, safety, health and worker comfort.

3. Methodology

In our present work, we chose the Design research methodology to propose our approach. Blessing and Chakrabarti [12] define it as “an approach and a set of methods and guidelines to be used as a framework for conducting design research”. This approach is suitable for use in studies that aim to develop a new artifact or make room for innovations on how to use one or several existing artifacts. It effectively renders the design process more effective and efficient, ensuring that better-performing artifacts are developed.

This article was drafted in accordance with the methodological approach illustrated in **Figure 1** below, which defines the main objective of our study, as well as the problem to be solved. This objective is achieved through the implementation of four actions, each corresponding to a specific objective:

- **Action 1: Comparative literature review**

This methodology begins with an analysis of current approaches used to choose assistive equipment. The aim is to examine methods that are already in place to identify their strengths and limitations, and to better pinpoint any shortcomings.

- **Action 2: Review of the literature and identification of arguments**

The literature review had two primary objectives: first, to identify relevant criteria for evaluating and comparing assistive equipment, including ergonomic, functional, economic, and technological aspects; second, to collect theoretical and empirical evidence to guide the weighting of these criteria and to support the prioritization framework developed through expert elicitation with the research team members.

- **Action 3: Artifact construction**

Based on the results obtained in the preceding stages, a new systematic selection approach is proposed, which aims to provide a structured framework allowing companies and decision-makers to choose the most suitable equipment in keeping with operators' constraints and specific needs.

- **Action 4: Assessment of the proposed approach**

Finally, the approach developed underwent an empirical validation aimed at assessing its relevance and applicability in a real-life context. The validation was done through a case study, which allowed to review the performance of the proposed process and identify possible improvements. According to Gagnon [13], a case study allows an in-depth analysis of phenomena and processes in concrete situations, which ensures a solid internal validity. It also allows to clarify and nuance the theory developed, by highlighting any limitations.

Throughout this paper, the term HMD or Head-Mounted Display will be used as a generic designation for devices such as goggles, smart glasses, augmented re-

ality (AR) glasses, as well as augmented reality and mixed reality (MR) headsets.

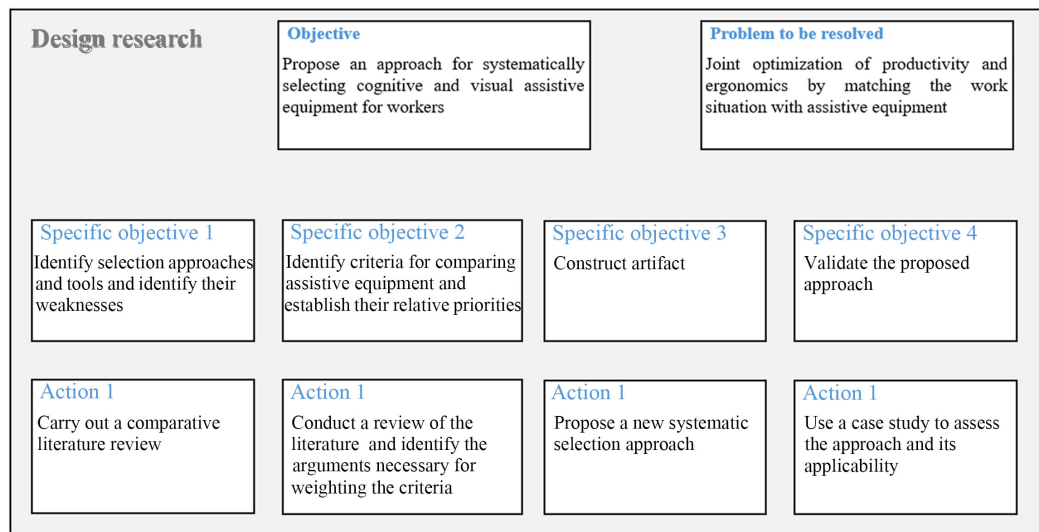


Figure 1. Methodological approach.

4. Tiering of Criteria Groups and Their Sub-Criteria

We feel that a weighted approach is more appropriate to overcome the limitations of the selection procedures described in Section 2. The Analytic Hierarchy Process (AHP) allows to tier criteria, thereby facilitating a more organized and rigorous analysis of influential factors. It is also particularly useful when having to consider several qualitative and quantitative dimensions simultaneously [14].

Another major advantage of the AHP method derives from its ability to weight each criterion by significance. It incorporates a pairwise comparison mechanism, allowing experts to express their preferences in a progressive and detailed fashion. Furthermore, this method includes a verification of the consistency of judgments, thus avoiding bias and ensuring decision-making that is reliable and rational. In our case study, this allows a more balanced comparison and avoids premature or arbitrary eliminations. Finally, the availability of dedicated software simplifies its application and strengthens its reliability.

Implementing AHP usually involves setting up a committee of experts or a group of people to conduct binary comparisons between the different criteria, to determine relative weights. This approach ensures an objective assessment and incorporation of participants' range of perspectives [14].

In our study, however, involving human participants was not feasible; this limitation required adopting alternative strategies to ensure that our results remained relevant and reliable.

As we were unable to establish a panel of experts, we relied instead on an in-depth review of the literature. Scientific works and similar studies helped us identify solid arguments and relevant data to guide binary comparisons, which were done by the research team. These elements allowed us to proceed with an assessment of the criteria, while observing the methodological rigour of the AHP.

An in-depth review of the literature allowed identifying the comparison criteria that was most used in the context of head-mounted displays. These criteria were then grouped and tiered, as illustrated in **Figure 2**. This tiering constitutes the basis for subsequent analyses. The identified criteria derive mainly from the work of Syberfeldt, Danielsson et Gustavsson [11], which explores the technical and ergonomic dimensions of head-mounted displays, as well as of Fraga-Lamas *et al.* [15].

The next step was to carry out pairwise comparisons between the elements of each hierarchical level, evaluating them against an element of the next higher level. This approach allows to construct comparison matrices by converting qualitative judgments into numerical values, in accordance with the Saaty [16] scale. Particular attention was paid to observance of the principle of reciprocity, ensuring that judgments were consistent.

Converting the judgments into numerical values generated the comparison matrices needed to calculate the relative weights of each criterion in relation to their higher hierarchical level. These weights provide a clear picture of the relative importance of the criteria and undergird the decision-making process.

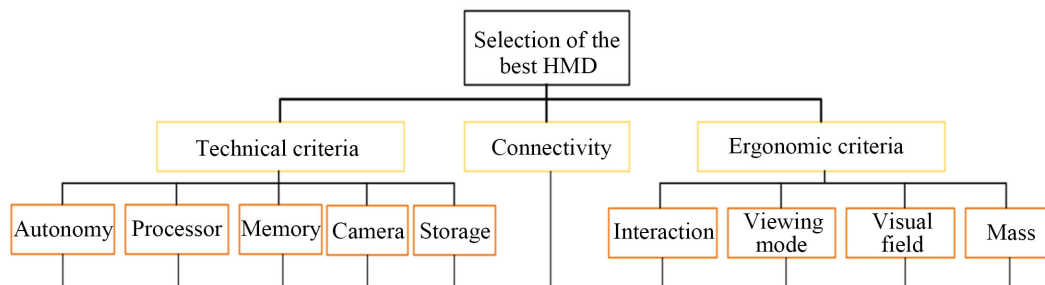


Figure 2. Comparison criteria used with the AHP method.

4.1. Set-Up of the Comparison Matrix for the First Criteria Level

4.1.1. Comparison of Ergonomic and Connectivity Criteria

Ergonomic criteria, including sub-criteria such as mass, interaction and the visual field, have a direct impact on worker comfort and performance. For example, an excessive weight or a poor load distribution of headsets can lead to increased muscle fatigue and neck pain, as has been demonstrated in work dealing with head-mounted devices [17] [18]. In addition, a fluid interaction and a wide visual field are essential for reducing visual distractions and improving efficiency in industrial environments [18] [19]. As a result, we consider ergonomic criteria to be far more important (8) than connectivity.

On the other hand, although connectivity does not contribute directly to physical comfort, it plays a crucial role in the integration of devices into connected industrial systems. It conditions the ability of HMD to provide real-time information, which is essential in modern production environments [19]. This justifies not neglecting this criterion, although its impact remains limited as compared to ergonomic criteria. We therefore assign a relative weight of 1/8 to connectivity with respect to ergonomics.

4.1.2. Comparison of Ergonomic and Technical Criteria

Technical criteria are mainly limited to the material performance of alternatives, such as durability, sensors, and computing capacity [19]. Although these criteria impact device reliability and longevity, their influence on users is indirect. Conversely, ergonomic criteria directly affect health and operator satisfaction, making them markedly more important. We therefore consider ergonomic criteria to be more important (5) than technical criteria.

4.1.3. Comparison of Connectivity and Technical Criteria

While having only a limited impact on the performance of alternatives, the connectivity criterion continues to be essential for their integration into a connected system and for their ease of use. However, because of their direct impact on the functionality and performance of alternatives, technical criteria are considered more important (3) than connectivity.

Table 1 below presents a comparison matrix for the first-level criteria in a bid to select the most suitable head-mounted display for the work situation under study.

Table 1. Comparison matrix for 1st-level criteria.

Criteria	Ergonomic criteria	Connectivity	Technical criteria
Ergonomic criteria	1.00	8.00	5.00
Connectivity	0.13	1.00	0.33
Technical criteria	0.20	3.00	1.00

Calculations carried out in Excel using the XLSTAT software gave the relative weights of each group of criteria: we obtained 73.70%, 7.68% and 18.63%, respectively, for the ergonomic, connectivity and technical criteria groups.

4.2. Establishment of the Comparison Matrix for Second-Level Criteria: Ergonomic Criteria

A poor visual field has a significant impact both on working posture [17] and on the frequency and intensity of head and neck movements [18]. These limitations increase muscle fatigue and can reduce operator efficiency, particularly in demanding industrial environments. Furthermore, a low display resolution will directly impact the functional efficiency of HMD, in addition to degrading the user experience [18].

Nichols [18] suggests that slightly heavier HMD are often preferable if they offer superior features in terms of the visual field and the display resolution. This underscores the importance of these two sub-criteria in the design and effective use of augmented reality devices.

4.2.1. Visual Field

A visual field of around 20° may be acceptable for applications such as sports or tourism. However, for industrial use, such a visual field is clearly not enough, making HMD practically unusable [11]. A wider visual field improves spatial per-

ception and reduces the need for repetitive head movements to adjust the perspective. As a result, we ranked this sub-criterion at a much higher tier (7) than mass.

4.2.2. Display Mode

The viewing mode also significantly impacts the efficiency of HMD. An inappropriate visualization mode, such as video-based solutions with high latencies, can disrupt the synchronization between visual information and operator actions, which can have a negative impact on task accuracy. Conversely, optical or retinal projection-based visualization systems are better suited to industrial environments and provide immediate visual feedback and better integration of virtual and real information [11]. Owing to the foregoing, this sub-criterion is deemed more important (5) than mass.

4.2.3. Mass

Although mass is a determining factor for long-term comfort, its impact is relatively less critical when offset by a good ergonomic design and superior performance in the other sub-criteria. We therefore ranked mass at a lower tier than visual field and viewing mode.

Table 2 below shows the comparison matrix for the four ergonomic sub-criteria with respect to the first-level hierarchical criterion, ergonomic criteria. Developed using the Saaty scale [16], this matrix ranks the sub-criteria according to their respective impacts on user comfort and efficiency in an industrial context.

Table 2. Ergonomic sub-criteria comparison matrix.

Sub-criteria	Visual field	Mass	Viewing mode	Interaction
Visual field	1.00	7.00	3.00	8.00
Mass	0.14	1.00	0.20	3.00
Viewing mode	0.33	5.00	1.00	7.00
Interaction	0.13	0.33	0.14	1.00

Using XLSTAT in Excel, we calculated the relative weight of each ergonomic sub-criterion based on the data presented in the table. We thus got: 41.66% for the visual field, 6.78% for mass, 21.77% for viewing mode and 3.47% for interaction.

4.3. Establishment of the Comparison Matrix for the Second-Level Criteria: Technical Criteria

Technical sub-criteria such as processor, RAM, battery life, camera and storage play a crucial role in the operation and performance of augmented reality HMD. However, their relative importance varies according to their direct impact on user experience and industrial task requirements.

4.3.1. Processor and RAM: Pillars for Performance

The processor and RAM are the driving forces behind HMD, defining their ability to handle complex processes in real time. Together, they impact essential functions such as:

- **Object geometry recognition:** Fast, accurate processing is essential for integrating virtual elements into the real world.
- **Overlay and visual rendering:** Display fluidity depends on processor computing power and RAM processing speed.
- **User interaction:** Gesture recognition and voice commands require instant responsiveness for an optimal user experience.
- **Virtual interface response time:** High latency can disrupt the user experience, reducing productivity and increasing discomfort.

Inadequacies in these two areas affect not only HMD performance, but also users' physical comfort. According to Nichols [18], slowness in the display or in controls can impair postural stability and cause fatigue [20]. Therefore, the processor is considered almost as important (2) as RAM, with both working in synergy to ensure optimal performance.

4.3.2. Autonomy: An Operational Priority

Autonomy is the third most important criterion. A long-lasting battery ensures continuous use of the HMD without frequent interruptions to recharge or replace the battery. This is particularly critical in industrial environments, where unplanned downtime can impact productivity. Autonomy is therefore deemed less important than processor and RAM (5) but remains a key priority.

4.3.3. Camera: A Secondary Functional Tool

The camera plays an important role in specific applications such as:

- **Remote assistance:** Enables remote collaboration by sharing the user's view in real time.
- **Documentation:** Facilitates recording and tracking of tasks performed [11].

However, its impact is limited to scenarios where these functions are necessary. As a result, the camera is considered slightly less important (1/3) than autonomy.

4.3.4. Storage: Minimal Importance

Storage is the lowest priority sub-criterion in this hierarchy. Thanks to network connectivity, HMD can access corporate databases in real time, limiting the need for local storage. The priority given to storage is therefore much lower than that of the other sub-criteria (8 with respect to the processor).

Table 3 below compares the five technical sub-criteria (processor, RAM, autonomy, camera and storage) against the first-level hierarchical criterion, *i.e.*, technical criteria.

Table 3. Technical sub-criteria criteria comparison matrix.

Sub-criteria	Autonomy	Processor	Memory	Camera	Storage
Autonomy	1.00	0.20	0.33	3.00	7.00
Processor	5.00	1.00	2.00	7.00	8.00
Memory	3.00	0.50	1.00	6.00	7.00
Camera	0.33	0.14	0.17	1.00	5.00
Storage	0.14	0.13	0.14	0.20	1.00

XLSTAT was used in Excel to calculate the relative weight of each of these sub-criteria. We thus got: 2.69% for autonomy, 8.49% for the processor, 5.38% for memory, 1.45% for the camera, and 0.62% for storage.

5. Proposed Selection Process

The proposed approach (see **Figure 3**) comprises four main steps for selecting and assessing assistive equipment. It focuses particularly on augmented reality (AR) and mixed reality (MR) head-mounted displays.

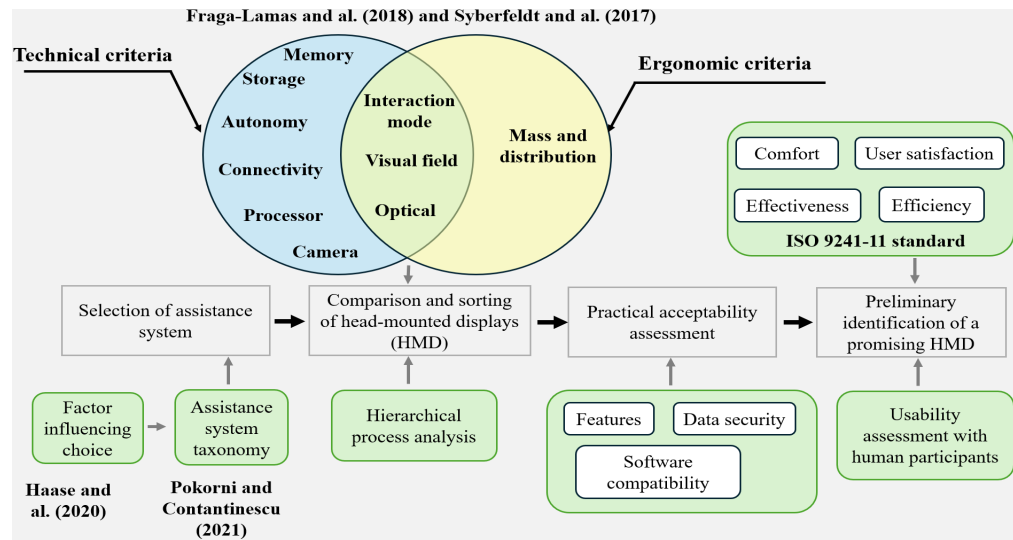


Figure 3. Systematic selection process.

5.1. Step 1: Selection of the Type of Assistance or Assistive Technology

Objective: Identify the technologies or types of equipment best suited to the context, taking into consideration the factors influencing their integration.

These factors, which were identified by Haase, Radde, Keller, Berndt, and Dick [21], are summarized in a table of parameters designed to inform the assistive equipment choice. These factors notably include:

- The work system: Organizational constraints, work environment and workstation, nature of tasks, specific needs and constraints linked to tasks requiring assistance;
- Individual employee characteristics: specific requirements and end-user needs.

According to Petzoldt *et al.* [2], incorporating workers' needs into equipment design improves its acceptability and effectiveness. The taxonomy of assistance systems described by Pokorni and Constantinescu [22] is used for a preliminary sorting of the technical characteristics required for the equipment to be able to optimally provide the assistance sought.

Deliverable: A shortlist of equipment potentially suited to operational requirements.

5.2. Step 2: Implementation of Analytic Hierarchy Process (AHP)

After a specific type of equipment is identified, a multicriterion analysis is carried out to compare different alternatives. Given that we are handling both qualitative and quantitative data, the AHP method was chosen for decision support. By simultaneously considering numerous criteria, the AHP will allow to easily obtain the weight of each of the alternatives and thus determine which is to be preferred [14].

The criteria used for the AHP are drawn from the scientific literature, including the works of Fraga-Lamas *et al.* [15] and of Syberfeldt, Danielsson and Gustavsson [11]. This method provides a rigorous framework to inform the decision-making process.

Deliverable: A priority alternative identified based on the relative weights calculated.

5.3. Step 3: Value-in-Use Assessment

Objective: Check how practically compatible the selected equipment is with the company's context.

This step assesses the practical acceptability of the alternatives selected in the previous step, taking into consideration the following:

- Equipment features: Ability to meet operational needs;
- Software compatibility: Integration with existing company software and infrastructures;
- Data security: Protection of sensitive information during use.

Deliverable: A report detailing the practical strengths and weaknesses of the selected equipment.

5.4. Step 4: Preliminary Identification of a Promising HMD

Objective: Test equipment under real-life conditions to validate its usefulness and effectiveness.

In this final step, human participants are brought in to test the equipment under real-life conditions. The assessment covers:

- Effectiveness: Ability to achieve objectives;
- Efficiency: Resources needed to achieve results;
- End-user satisfaction: Overall perception of the user experience;
- Ease of use: Simple interaction with equipment.

This assessment is carried out in accordance with the recommendations of ISO 9241-11 [23], which provides a framework for assessing the usability of equipment in terms of comfort, efficiency and satisfaction.

Deliverable: A final assessment to confirm or adjust the choice of equipment.

6. Case study

6.1. Presentation of Case Study

The industrial partner we worked with operates several workstations dedicated to gas turbine disassembly, inspection, maintenance and assembly operations. These

operations require specially adapted tools and methods to ensure worker efficiency, health and safety.

Figure 4 illustrates the work system currently used for the assembly and disassembly of gas turbines.

Tasks are carried out by a team of two technicians working closely and who communicate regularly to ensure effective synchronization. One of the technicians plays the main role in carrying out the tasks, while the other provides the necessary support by performing various complementary actions, such as operating workstation elements using joysticks, providing work tools, and ensuring backup lighting using a torch.

Interactions between technicians, as well as with tools and equipment, are strongly influenced by the work environment. Notable factors include lighting intensity, noise, temperature and chemicals occurring in mechanical parts.

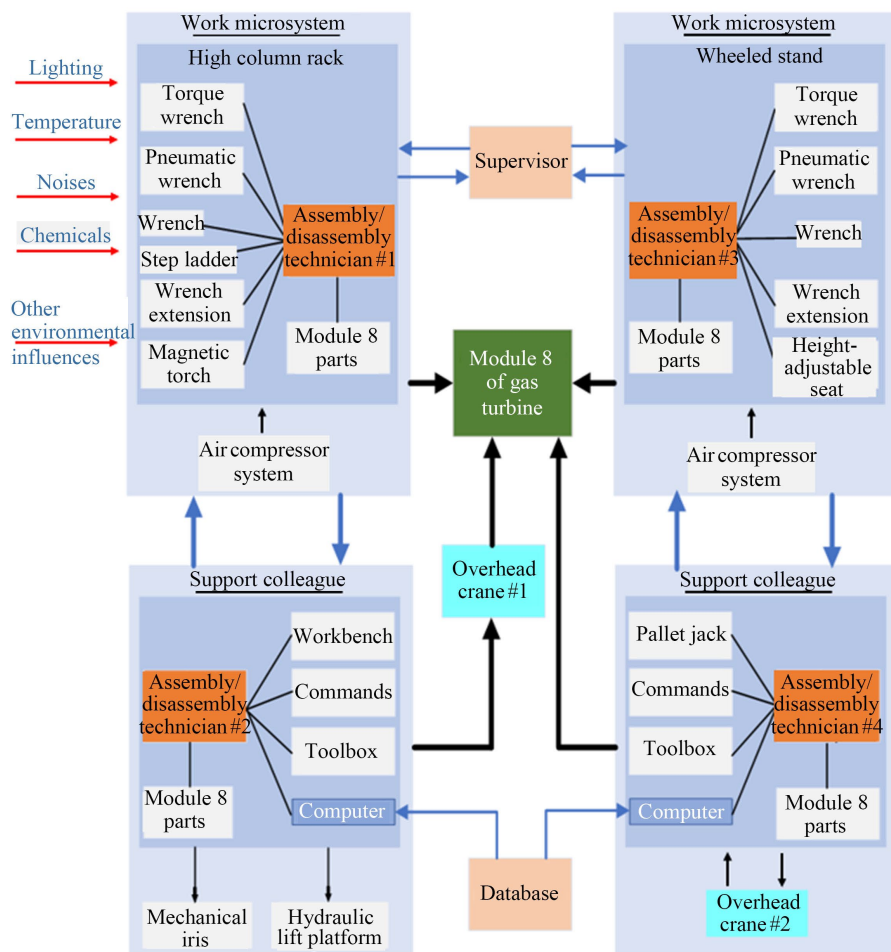


Figure 4. Working system.

In the present study, we are particularly interested in the assembly of one of the gas turbine modules (see **Figure 5**).

The workstation consists of:

- A wheeled stand on which the module elements are placed and assembled as

they proceed;

- A seat whose height can be adjusted within a limited range by the technician;
- An overhead crane (not shown in the figure) allowing technicians to lift and move the support, the module itself or its parts;
- A workbench on which technicians lay out tools and parts before assembling them to the turbine module;
- A computer the technician consults for task-related data and instructions, or to enter data once the task has been completed;
- A toolbox.

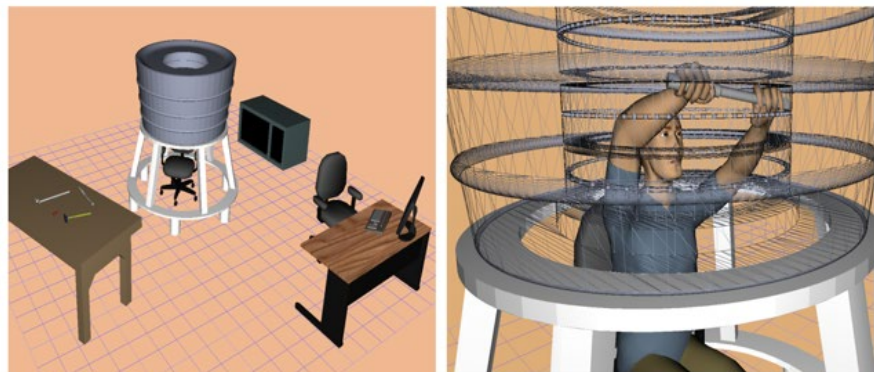


Figure 5. Gas turbine module assembly station.

Moreover, the configuration of the workstation makes it difficult for the technician already installed in the turbine module to access work instructions and data located on a remote computer. Nevertheless, the technician must regularly:

- Consult work instructions and keep abreast of any recent changes,
- Communicate with other technicians or with his manager,
- Document his activities and write reports,
- Request remote assistance if problems should surface.

This situation highlights the need for assistive equipment that meets these requirements, without requiring movement by the technician.

6.2. Application and First-Level Validation of the Approach

This section is dedicated to the first-level validation of the approach proposed in Section 5. The approach is applied to a real case study, centered on the assembly station of one of the gas turbine modules of an industrial partner, as described in the previous sections.

6.2.1. Step 1: Selection of the Type of Assistance or Assistive Technology

The first step in the process is to analyze the task, environment and workstation, based on the factors described by Haase *et al.* (2020). This analysis is crucial for the identification of the key points that will inform the preliminary choice of assistive technology or equipment. In the context of this case study, several significant observations were noted:

1) Mobility and flexibility of the assistance system:

- Turbine components are not assembled and disassembled at a fixed workstation;
- Operators alternate between tasks inside and outside the turbine modules, requiring frequent changes of position and working posture.

As a result, the assistance system cannot be fixed; rather, it must be mobile or portable to adapt to workers' frequent movements.

2) Hand occupation constraint:

- Assembly tasks require that both hands be constantly used and moved;
- Many of the assembly steps take place in narrow spaces, particularly inside the turbine module supports, where mobility is restricted.

These constraints underscore the importance of an assistance system that does not hinder operators' movements, while providing them with real-time information.

3) Geometry and workspace:

- The turbine's internal surfaces are characterized by revolution solids, which create a complex and tight work environment. Technological assistance must be able to adapt to these spatial peculiarities to ensure effective support;
- The space available to perform tasks is very limited, requiring a compact, ergonomic assistance solution.

Support equipment must therefore be compact, ergonomic and minimize excessive movement.

4) Difficulty accessing digital tools:

Because of to the workstation configuration, technicians cannot easily access the computer located outside the module. This computer is essential for:

- Consulting instructions and workflow updates;
- Communicating with colleagues or superiors;
- Requesting remote assistance as needed.

These constraints underscore the need for a solution that provides immediate, hands-free access to data and instructions, while eliminating the interruptions associated with movement.

Figure 6 below shows an extract from the taxonomy of assistance systems proposed by Pokorni et Constantinescu [22]. This classification provides an overview of the different categories of available assistive technologies and their characteristics.

Taking into consideration the specific constraints and requirements identified in the previous analysis, we conducted a preliminary selection by excluding solutions deemed inapplicable or unnecessary for our case study. These exclusions, represented by red boxes, allow to narrow down the range of choices and focus only on technologies suited to the needs of the gas turbine assembly station.

A preliminary sorting was carried out, based on the taxonomy of assistance systems, to identify the types of assistive equipment likely to meet the industrial partner's gas turbine assembly station's specific requirements. This sorting, presented

in **Table 4** below, allows to narrow down the field of alternatives by eliminating unsuitable options.

Feature	Configuration							
	Assistance	Information sensing			Perceptual assistance		Decision support	
Assistance function	See	Hear	Smell	Filter	Interpret	Cognitive	Activating	
Assistance system components	Screen	Tablet	Smart glasses	Smart watch	Projection system	Pick-by-Light	Audio guidance	Other
Mobility	Fixed			Mobile		Wearable		
Input	Auditive		Visual		Haptic		Kinetic	
	Micro-phone	Headset	Camera	Eyetracker	Button	Touch-screen	Wifi	Data glove, IPS
Output	Auditive				Visual			
	Speaker	Headphones	Display, signal light	Screen	Projector			
Interaction	Manual		Acoustical		Gesture		Motion data	
	Control elements		Voice input		Optical	Measurement	Tracking system	
					Gesture recognition			
Type of information output	Text			Visual		Acoustical		
	Text	Screen	Animation, Video	Marker	Light signal	Voice output	Warning tones	
Operation of assistance system	No physical impairment	Requires one hand for operation	Requires one foot for operation	Requires both hands for operation	Requires low ambient noise	Ob-structed vision	Physical movement limitation	
Freedom of use	Low		Medium			High		

Figure 6. Extract from the taxonomy of assistance systems adapted from Pokorni et Constantinescu (2021).

Table 4. Preliminary selection of assistive systems.

Technology types	Equipment or system type	Decision
Virtual reality	VR helmet	Exclude
	CAVE system	Exclude
	Power Wall	Exclude
Wearable augmented reality	Smartphone	Exclude
	Tablet	Exclude
	Computer	Exclude
	Head-mounted display	Retain
Spatial augmented reality	Instruction projection system	Exclude
	Pick by light system	Exclude

This analysis isolates the head-mounted display as the most appropriate type of equipment for this case study.

Integrating a head-mounted display into the assembly workstation offers multiple advantages for improving efficiency, communication, and the precision of the tasks performed by technicians.

5) Reduce unnecessary movements

Thanks to its features, the head-mounted display eliminates the need for the technician to leave his workstation to consult work-flow updates on a fixed computer. This optimizes working time and reduces unnecessary interruptions.

6) Real-time remote assistance

Equipped with an integrated camera and audio system, the head-mounted display enables the technician to benefit from real-time remote assistance. This support, described by Aranda-García *et al.* [24] and Klinker *et al.* [25], is particularly useful for quickly resolving problems encountered during task execution.

7) Simplified documentation

The integrated camera facilitates documentation of the work carried out and simplifies report writing [25]. This functionality is essential for detailed monitoring of operations and to ensure the traceability of actions.

8) Improved communication

Head-mounted displays represent a practical solution for communicating with other team members or line managers. This feature promotes smooth coordination and real-time monitoring of task progress, enhancing project collaboration.

9) Enhanced visibility in hard-to-reach areas

Connected via Bluetooth or Wi-Fi to a strategically positioned external camera, the head-mounted display overcomes the challenges of visually inaccessible areas, particularly during bolting operations. This connection provides effortless vision while reducing physical strain on the technician.

6.2.2. Step 2: Comparison of Head-Mounted Displays and Sorting with the AHP Method

There are a wide variety of head-mounted displays available on the market, each offering different features and functions to meet various cognitive assistance needs. One cannot simply conclude that a specific head-mounted display is the right equipment, as that would be an incomplete and imprecise statement. It is essential to go a step further and identify which head-mounted display is best suited to the specific needs and constraints of the task and workstation under analysis.

A pre-selection of HMD was carried out to limit the number of comparisons in the AHP and reduce the risk of errors (see **Figure 7**). This approach made it possible to focus on HMD most widely used in the manufacturing sector, with proven technologies and positive feedback.

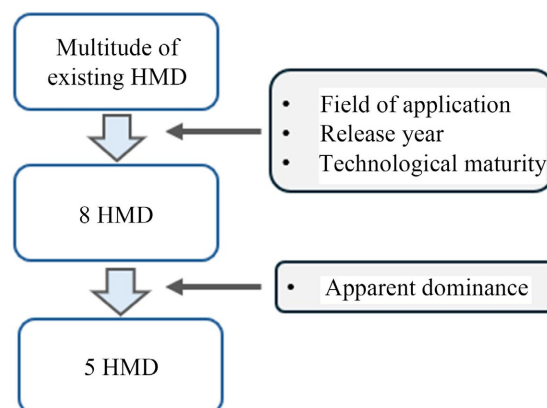


Figure 7. Head-mounted display pre-selection.

Newer head-mounted displays, whose reliability and effectiveness had not yet been validated, were excluded to ensure a selection based on equipment adapted to the industrial partner's operational needs.

Finally, a process of elimination by dominance was used to select the best-performing models when the same manufacturer offered several alternatives. This approach ensures the availability of a shortlist of reliable options suited to the assembly station.

The problem of selecting the best head-mounted display alternative is structured as illustrated in Figure 8 below.

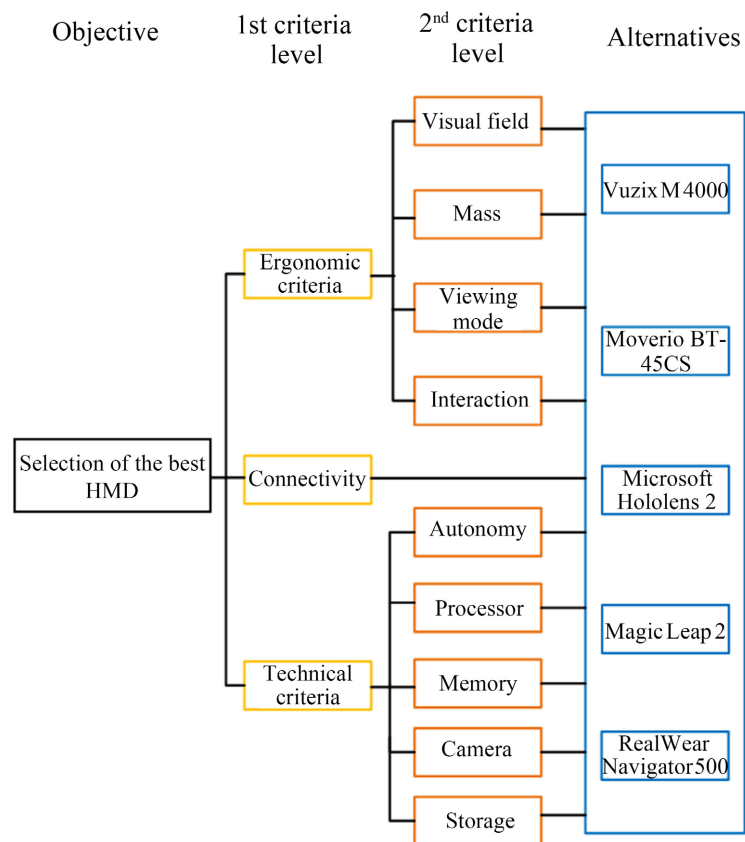


Figure 8. Prioritizing the choice of the best smart glasses.

1) Establishment of comparison matrices of alternatives against criteria

With the relative weights assigned to each group of criteria and sub-criteria (see Section 4), this step consists in making binary comparisons of the alternatives on each sub-criterion, using the Saaty [16] scale.

The numerical performance values of the head-mounted displays evaluated for each criterion were used as the basis for these comparisons. However, for non-quantifiable criteria such as viewing mode and interactions, a qualitative approach was adopted.

For the viewing mode, based on the literature review, a higher priority was given to binocular or visor-type glasses with a transparent optics mode. This was

followed by monocular glasses with transparent optics, while those using a transparent video mode were considered a lower priority. In terms of interaction mode, HMD offering greater diversity and flexibility of interaction were deemed superior.

The matrices obtained from the binary comparisons are shown in Appendix A.

Considering possible bias in judgments made during pairwise comparisons, it is essential to check the consistency of the matrices obtained. This step helps avoid assigning incorrect weights to the criteria, which could distort the study results.

Consistency is verified by calculating the consistency ratio (CR) and comparing it with the threshold value of 10%. Two possible scenarios may arise:

- $CR < 10\%$: the comparison matrix is consistent;
- $CR \geq 10\%$: the matrix is not consistent, and the pairwise comparisons need to be revised.

As all the calculated consistency ratios are below 10% (see Appendix B), the comparison matrices can be considered consistent and valid for analysis.

2) AHP results

Compiling all the calculations reveals a significant domination of the Magic Leap 2 (ML2) and Microsoft HoloLens 2 (MH2) HMD over all the other alternatives (see **Figure 9**).

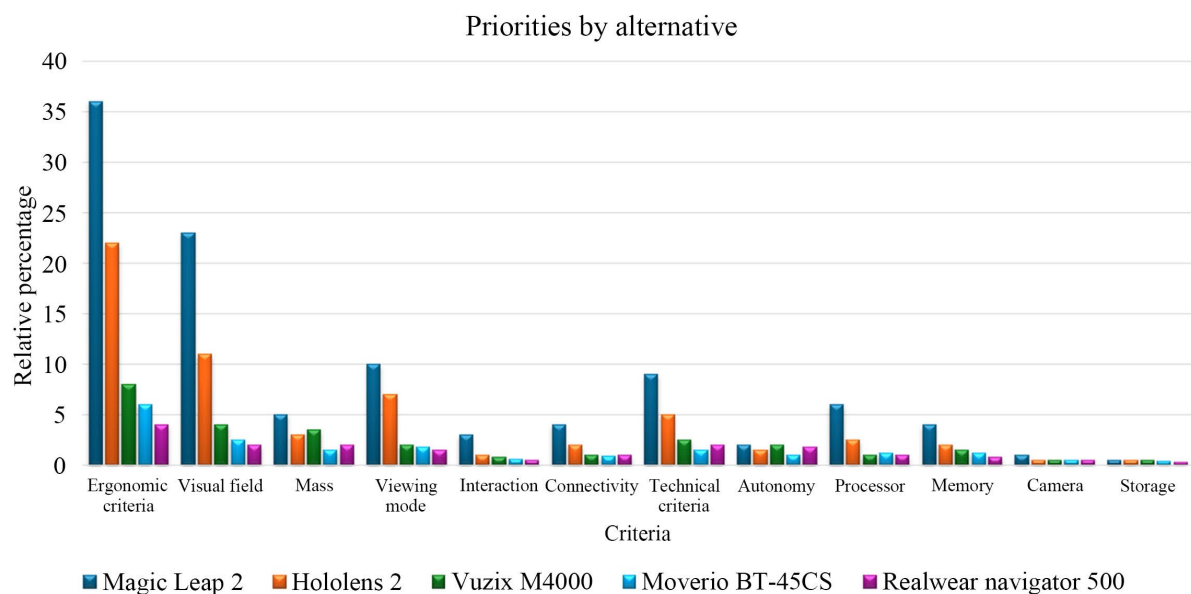


Figure 9. AHP results.

6.2.3. Steps 3 and 4: Assessment of Practical Acceptability and Usability

In literature, various methods are used to assess the acceptability of technological equipment. These methods share common features, notably the assessment criteria and the involvement of human participants in the process. However, in the context of our study, the direct involvement of users constitutes a limitation. To overcome this constraint, the assessment of practical acceptability and usability of the ML2 and MH2 is based on two main approaches: the use of basic knowledge

in ergonomics and the use of the results of similar studies carried out by other research teams.

The first assessment criteria pertains to user satisfaction. Studies carried out by Basoglu *et al.* [26] and Wang *et al.* [27] on HMD that are technologically inferior to the ML2 and MH2 (in terms of visual field, interaction mode, processing power, etc.) have shown that these devices, although less powerful, largely satisfy users' needs.

By extrapolation, the advanced features of the ML2 and MH2 offer sufficient guarantees to meet user expectations in the present case study.

For the other criteria, a separate assessment will be made for each of the two HMD.

1) Magic Leap 2

Comfort and Design:

The ML2 distinguishes itself through a compact, lightweight, and discreet design, resembling standard eyeglasses. In contrast to the more cumbersome visor-like MH2, the ML2 provides enhanced ergonomic comfort, addressing typical pressure points identified by Kim *et al.* [28], particularly around the nasal bridge and ears.

To optimize wearability, the ML2 includes an ergonomic adjustment kit: four interchangeable nose pads, two forehead pads, a flexible rear band for automated fit, and an optional top strap for added stability. This configuration ensures a balanced weight distribution, reducing fatigue even during extended use. Unlike other devices that suffer from asymmetrical weight distribution [29]-[31], the ML2 maintains comfort and equilibrium.

Additionally, ML2 features dynamic dimming technology, as described by Hoffman, Stepien et Xiong [32], which auto-adjusts display brightness based on ambient lighting and visual content. This improves visual clarity, reduces eye fatigue, and enhances usability in bright environments. However, a design limitation is the presence of bezel arms that may obstruct peripheral vision.

Ease of use and memorability:

The ML2 supports intuitive interaction through voice commands, gesture recognition, and a dedicated joystick. Voice input does not require strict syntax, and gesture-based control supports both near-field and far-field interaction modes. Real-time hand tracking and natural gestures enhance usability and memorability, even after prolonged periods of non-use.

Software compatibility:

Built on an open Android-based platform, ML2 supports custom application development via Android Studio and Unity. It is compatible with industry standards such as OpenGL, OpenXR, WebXR, and Vulkan, and integrates easily with enterprise systems through the Magic Leap Hub. Additionally, the Magic Leap App Store provides access to a variety of sector-specific applications.

2) Microsoft Hololens 2

Comfort and Design:

MH2 features a fold-down visor design with manual fit adjustment via a rear tightening ring. While it avoids direct pressure on sensitive areas like the nose and ears, its higher weight (556 g) may cause discomfort during prolonged use [17]-[19]. Its transparent visor allows easy transition out of AR mode and preserves peripheral vision, although outdoor use is limited due to poor screen visibility under bright light. Visual artefacts like reflections and rainbow effects can lead to eye fatigue.

Ease of use and memorability:

Like ML2, MH2 offers intuitive interaction via voice and gestures. It includes practical combinations such as eye-tracking with voice input. Environmental scanning is automatic and continuous, facilitating 3D mapping. MH2 supports multiple application windows simultaneously, whereas ML2 restricts to a single window, although the latter performs better with high-demand applications.

Software compatibility:

MH2 runs Windows Holographic, ensuring compatibility with most Windows 10 apps and tools such as Dynamics 365, Teams, and Remote Assist. While it enables custom development through Unity and Visual Studio, it is more closed than the ML2 in terms of integration. Its major strength lies in its autonomy, MH2 functions as a standalone unit, while ML2 relies on a cabled external processor.

7. Discussion

In the present article, we present a methodological approach aimed at facilitating the choice of assistive equipment for complex assembly tasks performed in a narrow space and at a mobile workstation. The main contribution of this research lies in the definition of a multicriterion selection process (integrating AHP in particular) based on prior analysis of the constraints linked to the work situation, allowing the weighting of criteria to be adjusted as effectively as possible.

For its part, the approach proposed by Mark *et al.* [6] aims to classify and select the types of assistive equipment best suited to a given workstation. However, it does not allow a precise selection of equipment within a given type. Instead, our approach provides guidelines for selecting a particular piece of equipment from the available alternatives. This additional step is essential, given the diversity of equipment available on the market for each type. For example, the approach of Mark *et al.* [6] might recommend a head-mounted display without specifying which one to choose. In comparison, our approach goes beyond this by proposing an in-depth multicriterion assessment to identify the most suitable head-mounted display for the situation under study, taking into consideration criteria related to ergonomics, technical performance and user acceptability.

As for the approach by Syberfeldt *et al.* [11], it also focuses on the choice of head-mounted displays. However, it has certain limitations, notably in the ordering of criteria and the use of acceptability thresholds that eliminate some promising equipment. Furthermore, this approach does not consider the reciprocal influence between selection criteria. Our approach, on the other hand, avoids a

“sieve” approach by considering all criteria simultaneously and assigning a relative weight to each one. It focuses especially on the physical, visual and cognitive ergonomics of workers, while taking into consideration the technical performance of equipment.

To illustrate and validate this approach, we conducted a case study in partnership with an industrial company, which allowed us to include concrete constraints (work environment, nature of tasks, mobility) and demonstrate the feasibility of our approach in real-life conditions. However, a single case study is not enough to ensure the applicability of this methodology to all industrial contexts. Consequently, its external validity remains limited. Carrying out several case studies could, however, help shed light on the generalizability of this approach [13].

Our systematic selection approach is based on a multicriterion comparison of head-mounted displays and is therefore limited to cases where a head-mounted display is identified as the appropriate type of assistive equipment. For other types, it would be necessary to redefine the comparison criteria employed, their priorities, and the criteria for assessing practical acceptability.

Due to the absence of human participant involvement, the assessment of the relative priorities of the criteria in the AHP was performed using secondary data and modeling. Similarly, the value-in-use study was conducted without direct input from end-users, which limits the validation of the results. Conducting a usability study with human participants remains essential to ensure that the equipment will be accepted and effectively used by its intended users.

Despite these limitations, our approach provides a sound basis for choosing assistive equipment in industrial contexts. It represents a major step forward in the systematic integration of ergonomic and technical performance criteria into the decision-making process.

8. Conclusion and Outlook

This study proposes a prototype of a structured and systematic approach to choosing assistive equipment adapted to the specific needs of industrial environments. Based on multicriterion criteria derived from Analytic Hierarchy Process (AHP), it allows to select equipment such as head-mounted displays, while taking into consideration ergonomics, technical performance and practical acceptability. The results obtained implemented in a case study of one of our industrial partner's gas turbine modules allowed us to identify Magic Leap 2 as the most suitable equipment for the given situation. This selection considers the specific nature of the tasks, environments and operators involved.

However, the external validity of this approach remains limited by its adaptation to a specific context. Future research should include practical tests involving end-users and extend the methodology to other types of equipment to strengthen its generalizability. It should also involve a committee of people or a group of experts in setting up the AHP, to improve the validity and reliability of the results.

In conclusion, this approach represents a major step forward for the integration

of assistive equipment into industrial systems, offering companies a reliable approach to improving productivity and operator well-being.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendixes

Appendix A: Pairwise Comparison

The tables below show the pairwise comparison of the five selected HMDs according to the different sub-criteria.

Table A1. Comparison matrix of alternatives with respect to visual field sub-criterion.

Alternatives	Magic Leap 2	Hololens 2	Vuzix M4000	Moverio BT-45CS	Realwear Navigator 500
A Magic Leap 2	1.00	5.00	8.00	7.00	9.00
Hololens 2	0.200	1.00	7.00	5.00	8.00
Vuzix M4000	0.13	0.14	1.00	0.33	3.00
Moverio BT-45CS	0.14	0.20	3.00	1.00	5.00
Realwear Navigator 500	0.11	0.13	0.33	0.20	1.00

Table A2. Comparison matrix of alternatives with respect to the mass sub-criterion.

Alternatives	Magic Leap 2	Hololens 2	Vuzix M4000	Moverio BT-45CS	Realwear Navigator 500
A Magic Leap 2	1.00	7.00	0.25	8.00	2.00
Hololens 2	0.14	1.00	0.11	0.50	0.13
Vuzix M4000	4.00	9.00	1.00	9.00	5.00
Moverio BT-45CS	0.13	2.00	0.11	1.00	0.13
Realwear Navigator 500	0.50	8.00	0.20	8.00	1.00

Table A3. Comparison matrix of alternatives with respect to the viewing mode sub-criterion.

Alternatives	Magic Leap 2	Hololens 2	Vuzix M4000	Moverio BT-45CS	Realwear Navigator 500
A Magic Leap 2	1.00	2.00	8.00	3.00	9.00
Hololens 2	0.50	1.00	7.00	0.50	9.00
Vuzix M4000	0.13	0.14	1.00	2.00	3.00
Moverio BT-45CS	0.14	0.17	4.00	1.00	3.00
Realwear Navigator 500	0.11	0.11	0.33	2.00	1.00

Table A4. Comparison matrix of alternatives with respect to the interactions sub-criterion.

Alternatives	Magic Leap 2	Hololens 2	Vuzix M4000	Moverio BT-45CS	Realwear Navigator 500
A Magic Leap 2	1.00	2.00	8.00	9.00	5.00
Hololens 2	0.50	1.00	7.00	9.00	5.00
Vuzix M4000	0.13	0.14	1.00	3.00	0.20
Moverio BT-45CS	0.11	0.11	0.33	1.00	0.14
Realwear Navigator 500	0.20	0.20	5.00	7.00	1.00

Table A5. Comparison matrix of alternatives with respect to the connectivity criterion.

Alternatives	Magic Leap 2	Hololens 2	Vuzix M4000	Moverio BT-45CS	Realwear Navigator 500
A Magic Leap 2	1.00	5.00	7.00	9.00	4.00
Hololens 2	0.20	1.00	3.00	7.00	0.50
Vuzix M4000	0.14	0.33	1.00	5.00	0.33
Moverio BT-45CS	0.11	0.14	0.20	1.00	0.17
Realwear Navigator 500	0.25	2.00	3.00	6.00	1.00

Table A6. Comparison matrix of alternatives with respect to the autonomy sub-criterion.

Alternatives	Magic Leap 2	Hololens 2	Vuzix M4000	Moverio BT-45CS	Realwear Navigator 500
A Magic Leap 2	1.00	3.00	0.11	2.00	0.17
Hololens 2	0.33	1.00	0.11	1.00	0.14
Vuzix M4000	9.00	9.00	1.00	9.00	5.00
Moverio BT-45CS	0.50	1.00	0.11	1.00	0.20
Realwear Navigator 500	6.00	7.00	0.20	5.00	1.00

Table A7. Comparison matrix of alternatives with respect to the processor sub-criterion.

Alternatives	Magic Leap 2	Hololens 2	Vuzix M4000	Moverio BT-45CS	Realwear Navigator 500
A Magic Leap 2	1.00	7.00	9.00	9.00	8.00
Hololens 2	0.14	1.00	3.00	3.00	4.00
Vuzix M4000	0.11	0.33	1.00	1.00	0.33
Moverio BT-45CS	0.11	0.33	1.00	1.00	1.00
Realwear Navigator 500	0.13	0.25	3.00	1.00	1.00

Table A8. Comparison matrix of alternatives with respect to the memory sub-criterion.

Alternatives	Magic Leap 2	Hololens 2	Vuzix M4000	Moverio BT-45CS	Realwear Navigator 500
A Magic Leap 2	1.00	9.00	7.00	8.00	8.00
Hololens 2	0.11	1.00	0.20	2.00	2.00
Vuzix M4000	0.14	5.00	1.00	6.00	6.00
Moverio BT-45CS	0.13	0.50	0.17	1.00	1.00
Realwear Navigator 500	0.13	0.50	0.17	1.00	1.00

Table A9. Comparison matrix of alternatives with respect to the camera sub-criterion.

Alternatives	Magic Leap 2	Hololens 2	Vuzix M4000	Moverio BT-45CS	Realwear Navigator 500
A Magic Leap 2	1.00	6.00	1.00	0.50	0.13
Hololens 2	0.17	1.00	0.17	0.17	0.11
Vuzix M4000	1.00	6.00	1.00	0.50	0.13
Moverio BT-45CS	2.00	6.00	2.00	1.00	0.14
Realwear Navigator 500	8.00	9.00	8.00	7.00	1.00

Table A10. Comparison matrix of alternatives with respect to the storage sub-criterion.

Alternatives	Magic Leap 2	Hololens 2	Vuzix M4000	Moverio BT-45CS	Realwear Navigator 500
A Magic Leap 2	1.00	7.00	7.00	0.14	7.00
Hololens 2	0.14	1.00	1.00	0.14	1.00
Vuzix M4000	0.14	1.00	1.00	0.11	1.00
Moverio BT-45CS	7.00	9.00	9.00	1.00	9.00
Realwear Navigator 500	0.14	1.00	1.00	0.11	1.00

Appendix B: Consistency Ratio of the Comparison Matrices

The consistency ratio (CR) was calculated for each pairwise comparison matrix to ensure the reliability of judgments made during the Analytic Hierarchy Process (AHP). According to Saaty [16], a CR lower than 10% indicates an acceptable level of consistency in the matrix. The following table summarizes the consistency ratios obtained for each matrix used in this study.

Table B1. Comparison matrix consistency ratio.

Comparison matrix	Consistency ratio (%)
Criteria for the 1st hierarchical level	3.83
Ergonomic sub-criteria	7.82
Technical sub-criteria	9.44
Alternatives to the visual field sub-criterion	9.51
Alternatives to the mass sub-criterion	9.85
Alternatives to the display mode sub-criterion	9.07
Alternatives to the interactions sub-criterion	9.81
Alternatives to the connectivity criterion	7.98
Alternatives to the autonomy sub-criterion	7.60
Alternatives to the processor sub-criterion	8.61
Alternatives to the memory sub-criterion	8.87
Alternatives to the camera sub-criterion	9.36
Alternatives to the storage sub-criterion	8.58

All consistency ratios fall below the 10% threshold, confirming the validity and coherence of the pairwise judgments used in the AHP process.