POLITECNICO DI TORINO
Repository ISTITUZIONALE

PRELIMINARY RESULTS FOR AN INSTRUCTION DESIGN PROCEDURE IN AERONAUTICAL MANUFACTURING

Original
PRELIMINARY RESULTS FOR AN INSTRUCTION DESIGN PROCEDURE IN AERONAUTICAL MANUFACTURING / Bartolomei, M., Barravecchia, F., Mastrogiacomo, L., Franceschini, F., Acerra, F., Gatta Davide, M., Cannizzaro, D.. - ELETTRONICO. - (2024). (34th Congress of the International Council of the Aeronautical Sciences, ICAS 2024 Firenze 9-12 Settembre 2024).

Availability:
This version is available at: 11583/2994869 since: 2024-11-28T14:20:41Z

Publisher:
International Council of the Aeronautical Sciences

Published
DOI:

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

09 November 2026

PRELIMINARY RESULTS FOR AN INSTRUCTION DESIGN PROCEDURE IN AERONAUTICAL MANUFACTURING

Mirco Bartolomei[1], Federico Barravecchia [1], Luca Mastrogiacomo[1], Fiorenzo Franceschini[1], Francesco Acerra[2], Davide Maria Gatta[2] & Davide Cannizzaro[3].

[1]Department of Management and Production Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy.
[2]Leonardo S.p.A., Viale dell'Aeronautica, 80038, Pomigliano d'Arco, Italy.
[3]Leonardo S.p.A., Corso Castelfidardo, 22, 10138, Torino, Italy.

Abstract

In the field of aeronautical manufacturing, compliance with strict quality standards is essential for ensuring the safety and reliability of aircrafts. Within this demanding environment, operators engaged in assembly tasks are bound to follow meticulous, standardized procedures. Under these conditions, providing clear and effective assembly instructions to the workforce becomes paramount for both meeting quality requirements and boosting production efficiency. With the aim of refining the existing protocols, this paper introduces a structured proposal to assembly instruction design. The contribution of this work is twofold. Primarily, by introducing a taxonomy of Assembly Features (AFs) it provides the designer with a valuable tool for identifying task-specific instruction content. Secondly, it offers a systematic framework for evaluating the most appropriate format for delivering task-specific instructions. The framework is based on two assessment dimensions: (i) the Representation Ability (RA), which gauges the format's capability in conveying the required AFs; and (ii) the Processing Efficiency (PE), which assesses the immediacy and clarity with which the format presents this information. Overall, this work introduces a structured, step-by-step approach to support designers, aiding them to strike a balance between the efficacy of information representation and the efficiency of its processing. To enhance its clarity and showcase its real-world utility, the approach is elucidated through applied examples focused on the assembly of a mechanical component.

Keywords: Quality Management, Aeronautical Manufacturing, Augmented Reality, Work Instructions, Assembly.

1. Introduction

The aeronautical manufacturing sector is distinguished by its specialized focus on low-volume production coupled with a high degree of product variability [1]. Unlike industries that prioritize mass production, aeronautical manufacturing often deals with components that are specifically designed for unique applications. This setting places a high value on the adaptability of human operators, who are frequently tasked with performing a diverse range of activities [2]. While this adaptability is advantageous, it is crucial to consider the human factors involved [3]– [5].

In such a scenario, assembly instructions assume a pivotal role. Defined as a structured set of guidelines that direct operators through the sequential actions essential for accurate and efficient assembly, these instructions are critical in maintaining procedural consistency [6]. However, the importance of following assembly instructions extends beyond enhancing workflow quality and efficiency [7]; it is also a contractual necessity. In aerospace manufacturing, work cycles are pre-determined in contractual terms, making any deviation from these not only detrimental to process integrity but also subject to contractual repercussions.

Despite their importance, a noticeable gap exists in both academic literature and industry practice regarding the systematic design of assembly instructions. In the aeronautical sector, the production of assembly instructions is subject to established standards. However, the initial stages of content definition and format selection often rely on the experience of the instruction designer, introducing an element of variability that could be managed more systematically.

Academic research in this domain is also limited, focusing mainly on evaluating the effectiveness of different augmented reality devices for delivering assembly instructions [8], [9]. Furthermore, although the efficacy of different instruction formats - such as text, video and 3D models- in presenting information has been explored [10]–[12], there is still a lack of a methodology for defining the content of assembly instructions and selecting the most appropriate format for their delivery [13].

To address this gap, the primary focus of this study is to develop a methodical and replicable approach to define the content and select the most effective format for delivering task-specific assembly instructions. At the core of this research is an in-depth analysis of how operators approach the assembly process from a cognitive point of view. Particular attention has been paid to understanding the types of information operators use to make effective decisions during assembly tasks. The findings from this analysis have been crucial in defining Assembly Features (AFs) as the building blocks of assembly instructions. Subsequently, a comprehensive taxonomy of AFs from the field of Design for Assembly (DFA) has been developed. This taxonomy captures all the elements that describe the assembly process and provides the basis for designers to easily select the subset of AFs that form the main content of the instructions. Subsequently, a thorough analysis of various instruction formats has been conducted to decipher both their limits and their potential. To capture these specific strengths and weaknesses, two key dimensions are adopted: *Representation Ability (RA)* and *Processing Efficiency (PE)*. RA is designed to assess the ability of the given instruction format to accurately represent AFs. On the other hand, PE assesses the immediacy, relative to task duration, with which these formats can convey the necessary information. By integrating these elements, this work aims to propose a structured method for optimizing the design and delivery of assembly instructions in the aeronautical manufacturing sector.

2. Instruction Content Taxonomy

The assembly process is often simplistically viewed as a chain of mechanical tasks. However, a more nuanced analysis reveals it to be a continuum of cognitive decisions made by the operator. Each stage - from component recognition to the final connection - relies on cognitive decisions. The operator leverages available data and personal experience to plan and implement these manual tasks, leading the system from its initial state to its desired target state.

In this context, assembly instructions serve as a pivotal guide that directs the operator's decisions. By providing essential cues for informed decision making at each stage, they ensure accurate and efficient assembly.

Assembly Features (AFs) are integral elements that delineate the specific characteristics of each component and its function in the assembly process [14]. These features guide how each component integrates into the overall structure, offering essential cues that instruct the operator on the required actions and their proper execution [15]. Given their role in guiding operator decisions during assembly, AFs can be viewed as the foundational elements of assembly instructions.

Considering this, assembly instructions can be redefined as a vector of AFs, fundamental for the assembly task at hand. In other words, assembly instructions must be conceived as a tailored set of AFs that fill in the gaps in the operator's existing knowledge and ensure that the assembly process is both accurate and efficient.

Extending this perspective on AFs, this study introduces a detailed taxonomy that acts as a repository for all potential 'building blocks' of assembly instructions (See Table *1*). Inspired by Van Holland et al. [16], this taxonomy provides designers with an organized framework for selecting key features that are critical to an operator's task understanding. Within this taxonomy, AFs are divided into two categories: *Handling Features*, required for component manipulation, and *Connecting Features*, required for proper component placement in the assembly.

Table 1 – Taxonomy of Assembly Features proposed by Van Holland et al. [16].

Category	*Assembly Feature*	Description
Handling	*Feeding*	*Feeding* refers to the predefined method by which components are introduced into the assembly area, such as through trays or feeders, along with their initial position and orientation.
	Fixturing	*Fixturing* is specific to base components and outlines how they should be secured in jigs or fixtures for the assembly process.
	Gripper	*Gripper* delineates the way the component is retrieved from its supply position, specifying how it should be accommodated in the tool being used.
	Grasping areas	*Grasping Areas a*re the permissible surfaces on the component that can come into contact with the tool used for its movement.
Connecting	*Involved form feature type*	*Involved form feature type* describes the geometric characteristics of the surfaces that come into contact at the initial stage of assembly.
	Final position	*Final Position* indicates the spatial orientation and location that the component will assume upon the completion of the assembly task.
	Insertion position	*Insertion Position* specifies the initial spatial orientation and location of the component as it is introduced into its mounting position on the sub-assembly.
	Insertion path	*Insertion Path* outlines the trajectory between the final and insertion positions, guiding the direction to be followed for successful component attachment.
	Tolerances	*Tolerances* are the allowable dimensional variations when connecting a component to a sub-assembly.
	Contact areas	*Contact Areas* refer to the surfaces on both the component and sub-assembly that will be in contact during the assembly;
	Internal freedom of motion	*Internal freedom of motion* pertains to the range of allowable movements for the component within the sub-assembly once it is secured.
	Geometric refinements	*Geometric Refinements* are specialized characteristics, such as rounding or chamfering, designed to facilitate the assembly process.

3. Assembly Instructions and Communication Modalities

The preceding discussions leads to a reconceptualization of assembly instructions as arrays of AFs essential for operators to carry out assembly tasks. However, the communication modalities for conveying these AFs are not uniform. This section aims to offer an overview of the various communication modes and to identify the AFs that each instruction format can represent.

3.1 Formats of Instructions

Instruction formats can be categorized based on two primary dimensions: the sensory channels they utilize to convey information and the types of media they incorporate. These formats span a range of sensory modalities, from visual and auditory to haptic. While senses like taste and smell have been employed in specialized contexts like hazard detection during production, they have not found widespread use as conventional channels for communicating assembly instructions and for this reason are outside the scope of this paper. Single instruction formats can be described as follows:

- *Written Text:* this format serves as a rich medium for delivering descriptive information about the assembly task. It employs a system of iconic signs, which are intrinsically linked to the subjects they are intended to represent [17], [18]. While written text is versatile enough to describe all previously defined AFs, it also presents some shortcomings. The semantic interpretation required for processing its symbols imposes significant cognitive demands, especially with complex instructions [19], [20]. This complexity can hinder the prompt retrieval of information from text-based instructions, impacting the efficiency of executing the assembly tasks.
- *Picture:* this format offers a snapshot-like, realistic depiction of the assembly system's current state. Pictures primary advantage lies in their immediacy; they do not require interpretative processing, thus enabling quicker decision-making [21]. However, their static nature inherently limits their ability to convey dynamic or evolving information, which could be crucial in certain assembly contexts [22].
- *Video:* videos take the capabilities of pictures a step further by dynamically illustrating the assembly system's evolution over time [22]. However, this dynamic representation comes at the cost of time-efficiency. Unlike pictures, which convey information instantly, videos require sequential viewing, thereby demanding more time from the operator for information extraction.
- *Static 3D Product Model:* within the field of augmented reality, static 3D models offer an immersive, three-dimensional representation of assembly components. These models share the representational capabilities of pictures but require less cognitive processing for people with low spatial ability due to their three-dimensional nature [23], [24].
- *Dynamic 3D Product Model:* these models extend the concept of static 3D models by incorporating animations that simulate a video-like effect. This enables a more dynamic representation of the assembly system's evolution, incorporating the strengths and weaknesses of videos.
- *Auxiliary Materials:* these include a range of visual aids, such as arrows, circles, and highlighted parts, designed to display a restricted set of AFs [25]. Although their simplicity provides excellent immediacy, it simultaneously limits their ability to communicate complex spatial or dynamic information.
- *Spoken Text:* audio format offers another avenue for describing the AFs required for an assembly task. However, it shares the same limitations as written text, particularly in terms of the time required for information processing. Challenges in articulating certain complex information verbally can make this format less efficient for certain tasks.
- *Audio Cues:* these are unique, specialized sounds designed to guide the user through specific steps of the assembly process. They can range from simple tones to complex sequences of sounds and can employ advanced techniques like 3D sound or spatialized audio for more nuanced guidance. The volume or pitch of the audio cue could dynamically change based on the operator's proximity to a particular assembly part, thereby providing an intuitive form of guidance. Additionally, confirmation cues can be employed to provide immediate feedback on a completed action. For example, a distinctive, positive tone could sound when a component is correctly assembled, offering an immediate and intuitive confirmation of success. While these information media are very simple and immediate, their ability to provide complex AFs

is very limited.

- *Vibrotactile Cues:* these cues offer haptic guidance through continuous feedback in the form of vibrations. The parameters of these vibrations, such as amplitude, frequency, and duration, can be varied to provide more specific guidance, such as the proximity to a component that needs to be gripped. Vibrotactile cues operate on the same principle of information transmission as audio cues, which means they inherit similar advantages and limitations.
- *Multimedia Instructions:* multimedia formats combine different instruction format into a unified guide, leveraging the strengths of each to offer a comprehensive instruction. However, their effectiveness hinges on the synergistic use of these formats. Mere duplication of information across formats can lead to cognitive overload, undermining instruction efficiency [26]. Therefore, careful design is needed to integrate diverse format, especially when the instructions are complex and information rich.

3.2 Framework for Mapping Instruction Formats with AFs

In the previous section, it was stressed that some instruction formats lack the information richness to represent certain AFs. The framework in Figure 1 formalizes this by associating each instruction format with the AFs it can represent. This tool provides a valuable support for designers, helping in the quick identification of the types of information that can be effectively delivered by each format. The development of the abovementioned framework is based on two fundamental principles. The first focuses the evaluation of each instruction format in its most independent and raw form. To illustrate, the ability of pictures to represent AFs are assessed without the integration with other formats such as text or additional visual aids. The second principle focuses on the completeness and explicitness of the information conveyed. A format is deemed effective only if it can represent an AF completely and explicitly. For example, a static picture would not adequately represent dynamic information, as it would require the operator infer the dynamic evolution of the system, contradicting the principle of explicitness.

			Single Media Formats								
			Written text	Picture	Video	Static 3D product model	Dynamic 3D product model	Auxiliary material	Spoken text	Audio cues	Vibrotactile cues
Assembly Features	Handling Features	*Feeding*	•	•	•	•	•	•	•	•	•
		Fixturing	•		•		•		•		
		Gripper	•		•		•		•		
		Grasping areas	•		•		•	•	•		
	Connecting Features	*Involved form feature type*	•	•	•	•	•	•	•	•	•
		Insertion position	•	•	•	•	•		•		
		Final position	•	•	•	•	•		•		
		Insertion path	•		•		•	•	•		
		Tolerances	•						•		
		Contact areas	•		•		•	•	•		
		Internal freedom of motion	•		•		•		•		
		Geometric refinements	•	•	•	•	•		•		

Figure 1 – Framework for Instruction Format and AFs mapping.

3.3 Metrics for Instruction Formats

The taxonomy of instruction formats presented in Section 3.1 highlighted the advantages and shortcomings of instruction formats. In particular, while some instruction formats provide a comprehensive depth of information, their intricacy may compromise immediate comprehension, thereby affecting the timeliness of task execution. On the other hand, formats that excel in immediacy often suffer from a deficiency in the capacity for complicated information. In general, for tasks that are straightforward and brief, immediate instructions are adequate. On the other hand, tasks that are complex and require extensive information to be fully comprehended might benefit from detailed and comprehensive instructions. Therefore, when crafting effective instructions, it is crucial to align the characteristics of the format with the specific characteristics of the task at hand. Two key metrics are introduced to evaluate the adequacy of single and multimedia instruction formats in representing a specific task: *Representation Ability (RA)* and *Processing Efficiency (PE)*.

Representation Ability of the i-th format for the j-th task ($RA_{i,j}$) is computed as follows:

$$RA_{i,j} = \frac{ReAF_{i,j}}{TR_j} \qquad (i = 1,\ldots, n);\ (j = 1, \ldots, N) \qquad (1).$$

Where:

- *n:* represents the cumulative count of both single and multimedia formats evaluated by the instruction designer.
- *N:* indicates the total number of tasks that constitute the assembly process at hand.
- *Represented Assembly Features ($ReAF_{i,j}$):* specifies the quantity of AFs that the i-th format

can convey, which have been identified as information requirements for the j-th task.

- *Total Requirements (TR_j):* refers to the count of AFs recognized as information requirements for the j-th task.

The $RA_{i,j}$ metric evaluates the ability of an instruction format to present the necessary AFs for a specific task. For example, if a task requires the presentation of 5 AFs for effective comprehension by the operator and a given instruction format can represent only 3 of these 5 AFs, Equation (1) would yield a $RA_{i,j}$ value of 0.6. This score indicates that the format falls short of fully meeting the information requirements of the task.

Processing Efficiency ($PE_{i,j}$) of the i-th format for the j-th task is computed as follows:

$$PE_{i,j} = \frac{PT_{i,j}}{TT_j} \qquad (i = 1, \ldots, n); (j = 1, \ldots, N) \qquad (2).$$

Where:

- *Processing Time ($PT_{i,j}$):* represents the duration needed for an operator to interpret the i-th instruction format, which is equipped with the information requirements for the j-th task. This metric is determined through an evaluation by the instruction designer, considering both the inherent characteristics of the instruction format and the specific Assembly Features (AFs) required by the task.
- *Task Time (TT_j):* is the time required to execute the j-th task.

The $PE_{i,j}$ metric quantifies the time required for full comprehension of an instruction relative to the task duration. For instance, if the estimated execution time for a j-th task is 10 seconds and the comprehension time for an i-th instruction format is 20 seconds, Equation (2) would yield a $PE_{i,j}$ value of 2. This implies that the time needed to understand the instruction is two times longer than the time required to complete the task.

4. Assembly Instruction Design Approach

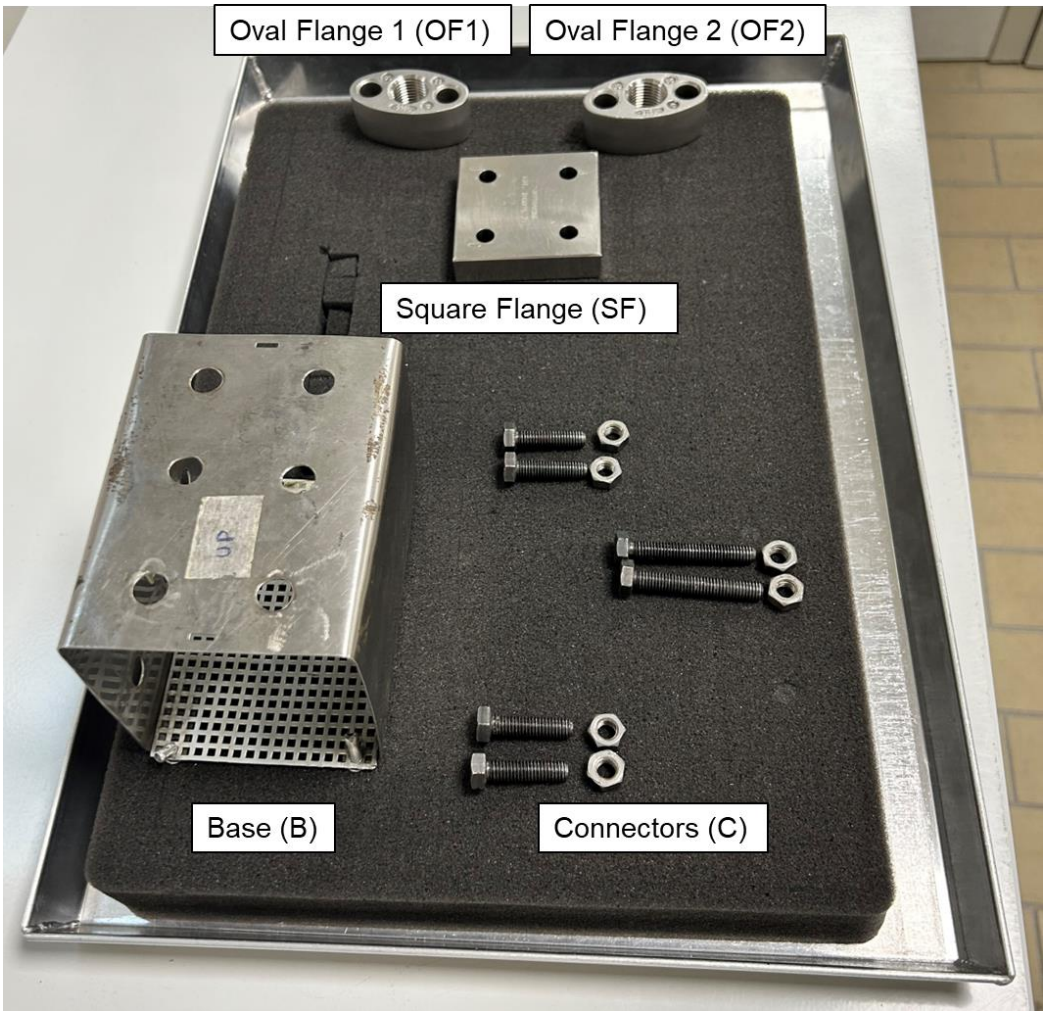
The following section details a structured approach to the design of assembly instructions. The method is organized to ensure the creation of efficient and timely assembly instructions that respond to the operator's information requirements and task characteristics. The approach is divided into several stages. Initially, guidelines are established to facilitate a systematic division of the assembly process into individual tasks. In the second stage, the content for the instructions is determined for each task. This is accomplished by analyzing the taxonomy AFs to identify those that represent essential information requirements for the operator, namely, crucial elements needed to accurately complete the task. This is followed by an exploration of the capabilities and limitations of different instruction formats to enable the rational selection of the optimal format to convey the task-specific information requirements. Overall, the final output of this methodology consists of a customized set of AFs, together with an optimally selected single- or multi-media format for delivering them.
To verify the practical utility of the methodology, a simple case study will be presented focusing on the assembly of a simple mechanical equipment (as shown in Figure 2a and Figure 2b, with components detailed in Table 2). The following sections will further explain the individual steps that characterize the proposed methodology.

Table 2 – List of mechanical equipment parts along with their corresponding identifiers.

Component	Identifiers
Base	B
Square Flange	SF
Oval Flange 1	OF1
Oval Flange 2	OF2
Connectors	C



(a)



(b)

Figure 2 – (a): Mechanical equipment in his assembled state; (b): Mechanical equipment in disassembled state, with main part identifiers.

4.1 Step 1: Decomposition of Assembly Process

In the first step, the assembly process is systematically segmented into distinct tasks. This step allows the identification of the specific manual operations that the operator is expected to perform within each task. These operations are essentially the core of what the instructions are intended to clarify, making this segmentation vital for establishing the scope and content of each assembly instruction. The logic behind this segmentation is crucial for two primary reasons:

- First, the operations included in each task segment must be congruent with the representational logic of the assembly features (AFs). These AFs are tailored to provide a comprehensive description of the assembly at component level. The assembly process is first divided based on a component-centric approach. For each main component, a separate task is assigned, covering all the operations required to assemble it. If connectors are involved, their use is integrated into the component assembly task, rather than being treated as a separate task.
- Secondly, each segment resulting from the subdivision of the assembly process should contain a balanced number of manual operations. An overly large set of operations would require detailed instructions, compromising their immediacy and user-friendliness. On the other hand, an overly granular segmentation would result in an excessive number of instructions, leading to inefficient interaction with them and a fragmented assembly process. To mitigate this, each task derived from the initial segmentation is further divided into two sub-tasks, following the decomposition framework proposed by Stork and Schubö [27]. The first, called 'commissioning' sub-task, includes all actions related to the handling of the component. The second, called the 'joining' subtask, includes the operations for positioning and securing the component on a sub-assembly.

Figure 3 provides a detailed example of the task segmentation for the assembly of the mechanical equipment. Each task corresponds to the assembly of a specific component of the equipment (See Figure 2).

Assembly Level	Task Level	Subtask Level	Description
Mechanical Equipment Assembly	**Base Fixturing**	*Base Commissioning*	The base needs to be anchored to the workbench using a clamping device.
	Square Flange Assembly	*Square Flange Commissioning*	The square flange should be located and picked up from the feeding tray.
		Square Flange Joining	The square flange should initially be aligned with the base and subsequently fastened using screws and nuts.
	Oval Flange 1 Assembly	*Oval Flange 1 Commissioning*	Oval Flange 1 should be located and picked up from the feeding tray.
		Oval Flange 1 Joining	Oval Flange 1 should initially be aligned over the square flange and then fastened using screws and nuts.
	Oval Flange 1 Assembly	*Oval Flange 2 Commissioning*	Oval Flange 2 should be located and picked up from the feeding tray.
		Oval Flange 2 Joining	Oval Flange 2 should initially be situated in the remaining open holes in the base and then anchored using nuts and screws.

Figure 3 - Example of mechanical equipment assembly process decomposition.

4.2 Step 2: Sub-Task Specific Information Requirements Identification

In the subsequent phase, the relevant set of AFs serving as information requirements for each subtask is chosen from the list outlined in Table *1*. To streamline this process, a support matrix is constructed. In this matrix, the columns correspond to the subtasks derived from the assembly process breakdown, while the rows feature the list of AFs as indicated in Table *1*. The process of pinpointing information requirements consists of several consecutive sub-steps. Initially, a thorough analysis is carried out to comprehend the decision-making activities necessary for performing the operations within each subtask. Subsequently, the subset of AFs that direct the identified decision-making processes are identified and reported in the matrix. This evaluation is tailored to the experience level of the operator, who will be the end user of these instructions. Figure 4 offers a comprehensive view of the information requirements for all subtasks involved in the assembly of the mechanical equipment.

Assembly Features (AF)		Mechanical Equipment Assembly							
		Base (C)	Square Flange (C)	Square Flange (J)	Oval Flange 1 (C)	Oval Flange 1 (J)	Oval Flange 2 (C)	Oval Flange 2 (J)
Handling AF	*Feeding*		•	•	•	•	•	•
	Fixturing	•						
	Gripper							
	Grasping areas							
Connecting AF	*Involved form feature type*			•		•		•
	Insertion position			•		•		•
	Final position			•				
	Insertion path			•				
	Tolerances							
	Contact areas							
	Internal freedom of motion							
	Geometrical refinements							

Figure 4 – Example of information requirements definition for the mechanical equipment assembly process. Legenda: C=Commissioning sub-task; J= Joining sub-task.

4.3 Step 3: Instruction Formats Assessment and Selection

The information requirements defined in the previous step are the prerequisite for an efficient selection of the appropriate instruction format for each subtask. Specifically, in the third step of the method, on the basis of the support matrix obtained in the previous step, an evaluation and selection of the best format to represent each subtask is performed. This consists of the two following consecutive sub-steps:

- *Instruction Format Mapping:* initially, a matrix is created for each subtask in which the rows include only the AFs identified as an information requirement in the previous step, while the columns contain the individual instruction formats. Then, using the framework in Figure 1 as a reference, the AFs that each instruction format can present are identified. The resulting matrix provides an overview of the suitability of each format to represent the subtask. Finally, to bridge the limits of the representational ability of the individual formats, they are combined in a complementary manner by the instruction designer, producing a set of multimedia formats. The operational flow, together with the resulting matrix for the square flange joining sub-task, is shown in Figure 5.

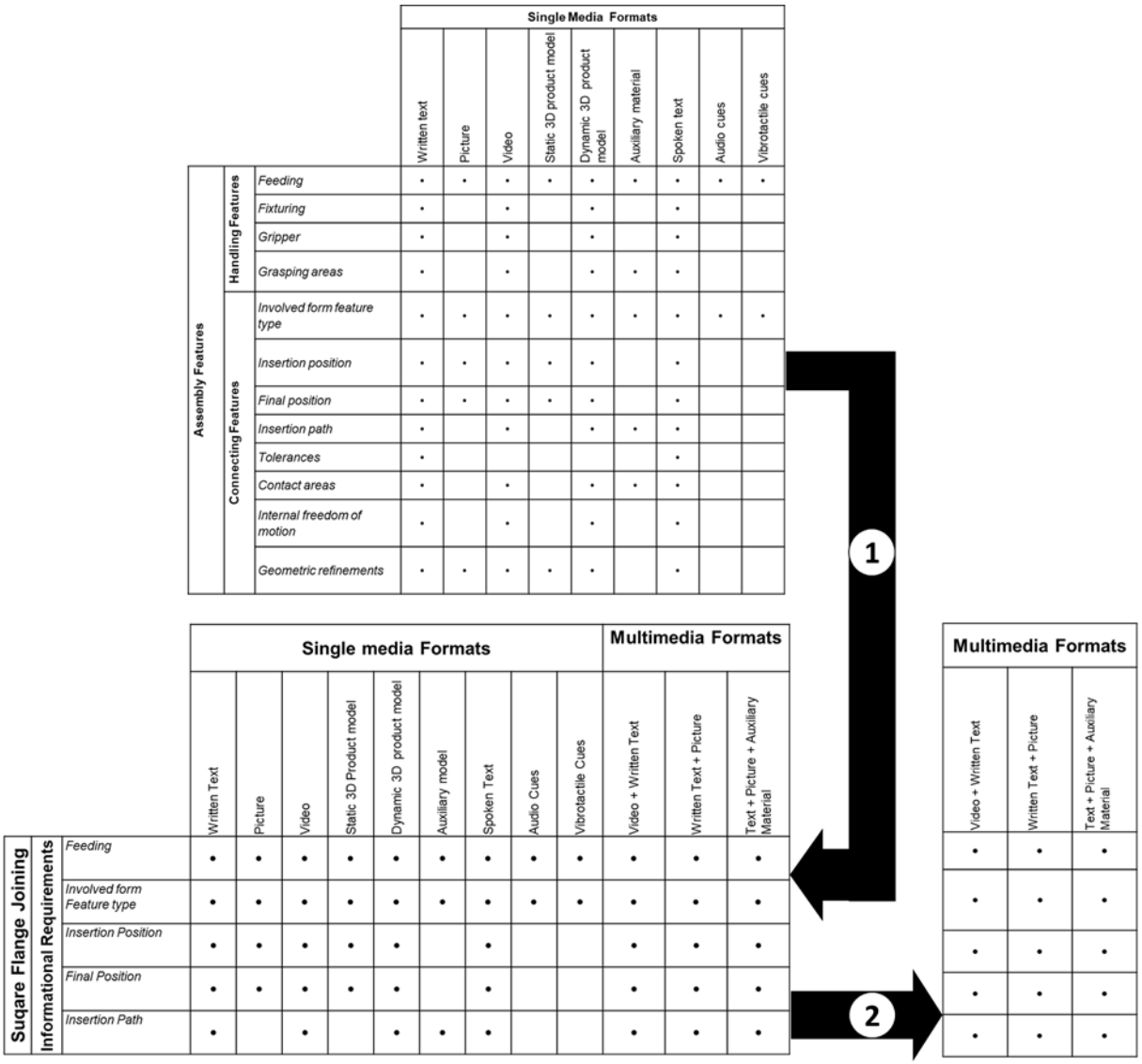


Figure 5 – Example of the instruction format mapping sub-step.

- *Instruction Format Assessment and Selection:* this sub-step involves the evaluation of each instruction format based on the two criteria described in Section 3.3. The $RA_{i,j}$ value is obtained by applying Equation (1). For each j-th format, the $ReAF_{i,j\,j}$ value is determined by totaling the elements in the corresponding rows. Conversely, the TR_j value is the overall number of AFs

considered as information requirements for the task in question. This assessment is conducted for all formats appearing in the matrix columns. Subsequently, the value $PE_{i,j}$ is derived by first assigning to each format a $PT_{i,j}$ value. This value is determined through the designer's subjective estimation, which may rely on historical data from similar tasks and instruction formats, or on an assessment of the specific information requirements and characteristics of the instruction format. Once the $PT_{i,j}$ value is established, it is divided by the time required to complete the analyzed subtask, as per Equation (2). The result of the formats evaluation for the square flange joining task is shown in Figure 6. The evaluations provide the basis for selecting the best instruction format for the analyzed sub-task. The selection takes place in two consequential sub-steps (See Figure 7). Firstly, the instruction designer excludes formats with a value of $RA_{i,j}$ of less than 1, as they are unable to fully present all the information required by the analyzed sub-task. Then, from the remaining subset of instruction formats, he/she selects the one with the lowest value of $PE_{i,j}$. In this way, the designer can strike a balance between the richness of the information presented, which guarantees the completeness of the instruction, and the efficiency of its processing.

	Single media Formats									Multimedia Formats		
	Written text	Picture	Video	Static 3D product model	Dynamic 3D product model	Auxiliary material	Spoken text	Audio cues	Vibrotactile cues	Video + Written text	Written text + Picture	Written text + Picture + Auxiliay material
$RA_{i,j}$	1	0.8	1	0.8	1	0.6	1	0.4	0.4	1	1	1
$PE_{i,j}$	2	0.5	1.5	0.5	1.5	0.25	2	0.25	0.25	2	0.75	1.25

Sugare Flange Joining		Single media Formats									Multimedia Formats		
		Written Text	Picture	Video	Static 3D Product model	Dynamic 3D product model	Auxiliary model	Spoken Text	Audio Cues	Vibrotactile Cues	Video + Written Text	Written Text + Picture	Text + Picture + Auxiliary Material
Informational Requirements	*Feeding*	•	•	•	•	•	•	•	•	•	•	•	•
	Involved form Feature type	•	•	•	•	•	•	•	•	•	•	•	•
	Insertion Position	•	•	•	•	•		•			•	•	•
	Final Position	•	•	•	•	•		•			•	•	•
	Insertion Path	•		•		•	•	•			•	•	•

3

Figure 6 – Example of instruction format assessment and selection.

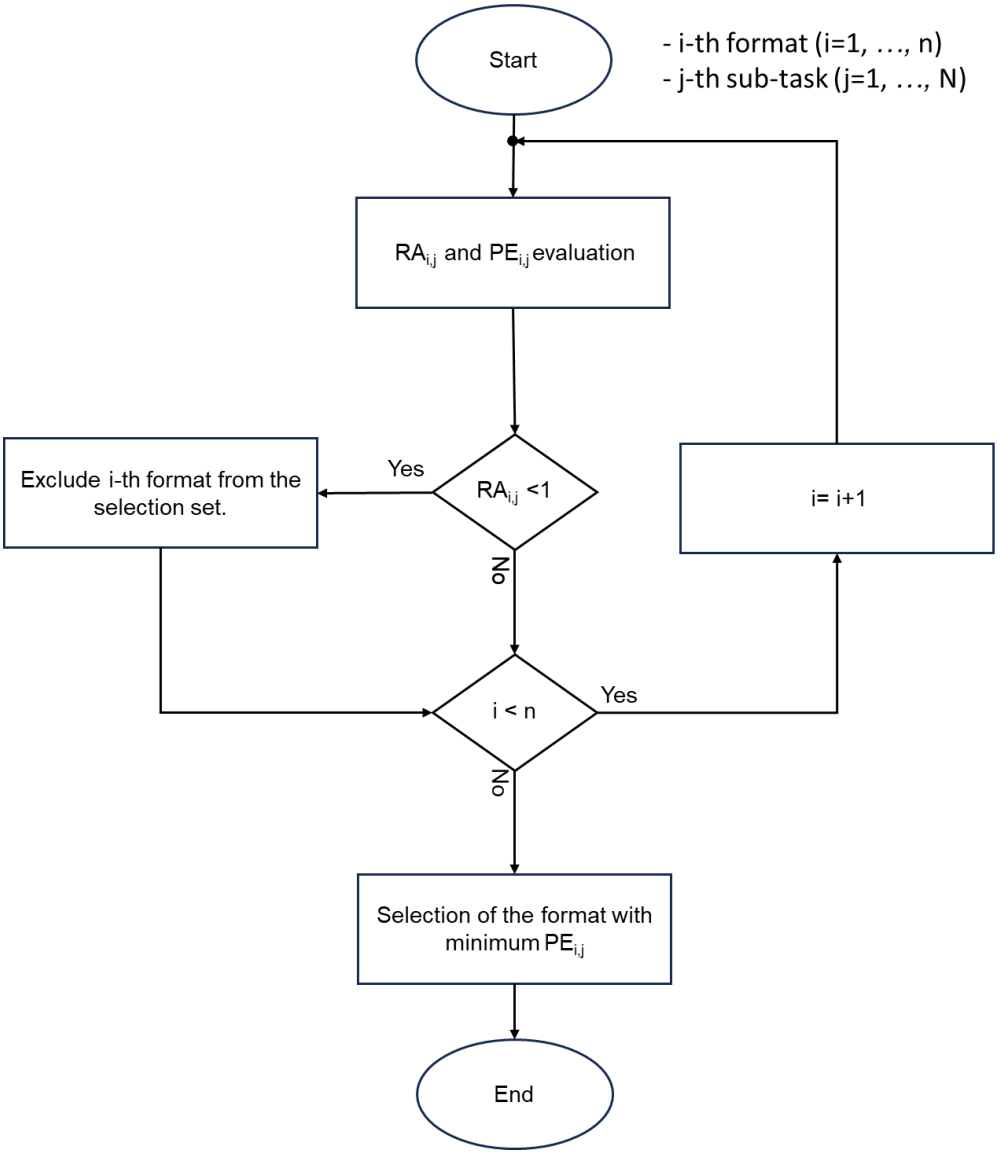


Figure 7 - Flowchart of the decision-making process for the selection of the optimal instruction format for the j-th sub-task.

5. Conclusions

With the aim of refining instruction design procedures in the aerospace manufacturing sector, this paper presents a structured approach for defining instruction content and selecting the most appropriate format for instruction delivery. The approach is anchored in a nuanced understanding of the cognitive processes that inform decision-making during assembly tasks. A detailed taxonomy has been developed to pinpoint all the specific types of information that operators require to perform an assembly task. In addition, the various formats available for the delivery of assembly instructions have been examined and categorized. Subsequently, to guide their appropriate selection, two critical variables have been introduced. The first, Representational Ability (RA), gauges the format's effectiveness in conveying the necessary information for a given subtask. The second, Processing Efficiency (PE), assesses how concisely the format can present this information. These variables collectively offer a step-by-step methodology that provides designers with structured guidance for creating assembly instructions. While the paper makes substantial contributions to simplifying and structuring the design of assembly instructions, it also highlights the need for further research. Specifically, additional studies are needed to further streamline the methodology. This should include the development of more objective scales for assessing PE, as well as the incorporation of factors such as the cognitive workload generated by following the instructions into the evaluation model. Finally, future studies will be directed to quantitatively validate the method to demonstrate its effectiveness in a real-word scenario.

Acknowledgments

This publication is part of the project PNRR-NGEU which has received funding from the MUR – DM 352/2022 and a collaboration between Politecnico di Torino and Leonardo S.p.A. This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them. The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third-party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

References

[1] Tahmina T, Garcia M, Geng Z, and Bidanda B. A Survey of Smart Manufacturing for High-Mix Low-Volume Production in Defense and Aerospace Industries. *Lecture Notes in Mechanical Engineering*, pp. 237 – 245, 2023.

[2] Barravecchia F, Bartolomei M, Mastrogiacomo L, and Franceschini F. Redefining Human–Robot Symbiosis: a bio-inspired approach to collaborative assembly. *International Journal of Advanced Manufacturing Technology*, vol. 128, no. 5–6, pp. 2043–2058, 2023.

[3] Verna E, Genta G, and Galetto M. A new approach for evaluating experienced assembly complexity based on Multi Expert-Multi Criteria Decision Making method. *Research in Engineering Design*, vol. 34 pp. 301–325, 2023.

[4] Franceschini F, Galetto M, and Maisano D. *Management by measurement: Designing key indicators and performance measurement systems*, 1st ed.: Springer Science & Business Media, 2007.

[5] Gervasi R, Barravecchia F, Mastrogiacomo L, and Franceschini F. Applications of affective computing in human-robot interaction: State-of-art and challenges for manufacturing. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 237, no. 6–7, pp. 815–832, 2022.

[6] Servan J, Mas F, Menéndez JL, and Ríos J. Assembly work instruction deployment using augmented reality. *Key Engineering Materials*, vol. 502 pp. 25–30, 2012.

[7] Serván J, Mas F, Menéndez JL, and Ríos J. Using augmented reality in AIRBUS A400M shop floor assembly work instructions. *AIP Conference Proceedings*, vol. 1431 pp. 633–640, 2012.

[8] Eversberg L, and Lambrecht J. Evaluating digital work instructions with augmented reality versus paper-based documents for manual, object-specific repair tasks in a case study with experienced workers. *International Journal of Advanced Manufacturing Technology*, vol. 127, no. 3–4, pp. 1859 – 1871, 2023.

[9] Funk M, Kosch T, and Schmidt A. Interactive worker assistance: Comparing the effects of in-situ projection, head-mounted displays, tablet, and paper instructions., in *UbiComp 2016 - Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, pp. 934 – 939, 2016.

[10] Ganier F. Processing text and pictures in procedural instructions. *Information Design Journal*, vol. 10, no. 2, pp. 146–153, 2001.

[11] Höffler TN, and Leutner D. Instructional animation versus static pictures: A meta-analysis. *Learning and Instruction*, vol. 17, no. 6, pp. 722–738, 2007.

[12] Loch F, Quint F, and Brishtel I. Comparing video and augmented reality assistance in manual assembly. *Proceedings - 12th International Conference on Intelligent Environments, IE 2016*, pp. 147–150, 2016.

[13] Laviola E, Gattullo M, Manghisi VM, Fiorentino M, and Uva AE. Minimal AR: visual asset optimization for the authoring of augmented reality work instructions in manufacturing. *International Journal of Advanced Manufacturing Technology*, vol. 119, no. 3–4, pp. 1769–1784, 2022.

[14] Zha XF, and Du H. A PDES/STEP-based model and system for concurrent integrated design and assembly planning. *CAD Computer Aided Design*, vol. 34, no. 14, pp. 1087–1110, 2002.

[15] Wang Z, *et al*. User-oriented AR assembly guideline: a new classification method of assembly instruction for user cognition. *International Journal of Advanced Manufacturing Technology*, vol. 112, no. 1–2, pp. 41–59, 2021.

[16] Van Holland W, and Bronsvoort WF. Assembly features in modeling and planning. *Robotics and Computer-Integrated Manufacturing*, vol. 16, no. 4, pp. 277–294, 2000.

[17] Schnotz W, and Bannert M. Construction and interference in learning from multiple representation. *Learning and Instruction*, vol. 13, no. 2, pp. 141–156, 2003.

[18] Scaife M, and Rogers Y. External cognition: How do graphical representations work?. *International Journal of Human Computer Studies*, vol. 45, no. 2, pp. 185–213, 1996.

[19] Van Genuchten E, Scheiter K, and Schüler A. Examining learning from text and pictures for different task types: Does the multimedia effect differ for conceptual, causal, and procedural tasks?. *Computers in Human Behavior*, vol. 28, no. 6, pp. 2209–2218, 2012.

[20] Ainsworth S, and Th Loizou A. The effects of self-explaining when learning with text or diagrams. *Cognitive Science*, vol. 27, no. 4, pp. 669–681, 2003.

[21] Larkin JH, and Simon HA. Why a Diagram is (Sometimes) Worth Ten Thousand Words. *Cognitive Science*, vol. 11, no. 1, pp. 65–100, 1987.

[22] Ng HK, Kalyuga S, and Sweller J. Reducing transience during animation: a cognitive load perspective. *Educational Psychology*, vol. 33, no. 7, pp. 755–772, 2013.

[23] Krüger JM, Palzer K, and Bodemer D. Learning with augmented reality: Impact of dimensionality and spatial abilities. *Computers and Education Open*, vol. 3 p. 100065, 2022.

[24] Huk T, . Who benefits from learning with 3D models? the case of spatial ability. *J. Comput. Assist. Learn.*, vol. 22 pp. 392–404, 2006.

[25] Gattullo M, Evangelista A, Uva AE, Fiorentino M, and Gabbard JL. What, How, and Why are Visual Assets Used in Industrial Augmented Reality? A Systematic Review and Classification in Maintenance, Assembly, and Training (From 1997 to 2019). *IEEE Transactions on Visualization and Computer Graphics*, vol. 28, no. 2, pp. 1443–1456, 2022.

[26] Trypke M, Stebner F, and Wirth J. Two types of redundancy in multimedia learning: a literature review. *Frontiers in Psychology*, vol. 14 p. 1148035, 2023.

[27] Stork S, and Schubö A. Human cognition in manual assembly: Theories and applications. *Advanced Engineering Informatics*, vol. 24, no. 3, pp. 320–328, 2010.