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A systematic review of Augmented Reality content-related techniques for knowledge transfer in maintenance applications

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Abstract: Augmented Reality (AR) has experienced an increasing trend in applied research in the last few years. This emerging trend is focused in content-related challenges: mainly creation (Authoring), adaptation (Context-Awareness) and improvement (Interaction-Analysis) of augmented content. Research in these techniques has enabled Academia to recognise Augmented Reality capability for knowledge transfer, either from AR systems to users or between users. But to the best of author's knowledge, there are no specific literature review in these areas, neither on their relations with AR knowledge transfer ability. Therefore, this paper aims to identify these relations through an analysis of state-of-the-art techniques in Authoring (A), Context-Awareness (CA) and Interaction-Analysis (IA) in the context of maintenance applications. In order to do so, a Systematic Literature Review (SLR) has been conducted on 74 application-relevant papers from 2012 to 2017. It comprised a thematic analysis to establish the relation between maintenance applications, research in A, CA and IA and AR knowledge transfer modes. Its results helped to classify AR maintenance-applications by technological readiness levels. They also revealed the potential of AR for users' knowledge capture, and future research required for full knowledge management capabilities. Furthermore, the SLR method proposed could be extended to correlate AR systems and applications by their knowledge management capabilities in any AR application context.

Keywords: Augmented Reality; Maintenance; Knowledge Transfer; Authoring; Context-Awareness; Interaction-Analysis; Knowledge Capture; Systematic Literature Review.

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1. Introduction

The Augmented Reality (AR) definition has evolved over the years alongside techniques and applications. Based on its extended capabilities, the authors propose to define AR as: *"a set of human-computer interaction techniques* [1] *that enriches user's real-world experience* [2,3] *by embedding contextualised information* [4] *into user's space in coexistence with real-world objects* [5]*"*. Moreover, Nonaka [6] defines knowledge as information in context. Knowledge transfer is also defined as *"the conveyance of knowledge from one place, person, system or ownership to another"* [7]. Therefore, if AR is able to transfer information and put it into context, then it should be able to transfer knowledge [1] to the users.

The idea of AR being a knowledge transfer technology is also confirmed by latest research in the area. Literature reviews in different application fields such as design and manufacturing [4], maintenance [8], surgery [9], or education [10] have identified research gaps regarding AR knowledge transfer abilities. Besides, these gaps were always related at least with one content-related technique: creation (Authoring), adaptation (Context-Awareness) or improvement (Interaction-Analysis) of augmented content. These methods are emerging AR research areas in their own:

- **Authoring (A):** the software techniques that aim to create augmented content and properly display it in the real world [11].
- **Context-Awareness (CA):** the software techniques that aim to use contextual information to characterise augmented content [12].
- **Interaction-Analysis (IA):** the software techniques that analyse the status of the interaction between user and augmented content to provide relevant feedback and/or improve the interaction [13,14].

To the best of authors' knowledge, no research has been found to review the state-of-the-art of these techniques. Moreover, there is no research focused on clarifying the relation between these techniques and AR knowledge transfer capabilities. Nevertheless, conduct that research can involve an immense amount of work if we consider to review these techniques from all AR applications. Therefore, it could be an intelligent strategy to narrow that research down to an application field where AR knowledge transfer capabilities can have a great impact.

Maintenance has a critical role improving organisations' competitiveness and contributing to their sustainable development [15,16]. The global-market size of high-value products maintenance-industries has been estimated in £490 billion by 2015 and £710 billion by 2025 [17]. High-value products are increasingly complex, technology intensive, expensive and critically reliable, requiring from continuous maintenance throughout their lifecycle [18]. This leads to two of the main challenges that drive maintenance research [15,18–20]:

1. Extend life of high-value products with optimum cost.
2. Improve efficiency and effectiveness of maintenance processes.

Due to high-value products' features, maintenance processes are knowledge intensive for maintainers [2,18,21,22]:

1. Number of equipment, subsystems and components implicates a large number of operations.
2. Complexity involves a large variety of different tasks from diagnosis to repair.
3. Long life causes varying levels of quality, standards and depth in documentation.

Therefore, the provision of the right information to the right user in the right quality and time is critical to increase efficiency of these maintenance processes [23,24]. As a visualisation technology, AR can provide support to maintainers with these knowledge-intensiveness challenges described above [25]. A, CA and IA techniques are identified as important AR areas to enhance maintenance efficiency and effectiveness [4,8]:

- **Authoring (A)** to provide proper maintenance processes visualisation and so enhance their efficiency.
- **Context-Awareness (CA)** to adapt visualisation to the maintainer and so enhance their effectiveness.
- **Interaction-Analysis (IA)** to capture maintainers feedback and analyse their performance in order to enhance visualisation and so improve its efficiency.

Therefore, A, CA and IA can help to enhance maintenance processes efficiency and effectiveness by providing an adaptive, increasing effective visualisation of maintenance processes to maintainers [18].

This paper aims to review the state-of-the-art of A, CA and IA research areas and establish a relation with AR knowledge transfer capabilities in the context of maintenance applications. In order to do so, a Systematic Literature Review (SLR), which includes a thematic analysis, is conducted to achieve the following research objectives:

- Identify the state-of-the-art of Authoring (A), Context-Awareness (CA) and Interaction-Analysis (IA) techniques in AR maintenance applications.
- Determine types and modes of knowledge transferred in AR maintenance applications.
- Determine A, CA and IA research relations with knowledge transfer.
- Identify A, CA and IA current challenges and potential future developments.
- Identify new potential AR applications in knowledge transfer.

The rest of the paper is organised in four sections. Section 2 describes the methodological approach for the SLR. Section 3 presents the results of the thematic analysis from the SLR. These results are used in Section 4 to provide an answer for the research questions. Then, Section 5 discusses the fulfilment of the research objectives. Finally, Section 6 reports paper's conclusions and proposes future research works.

2. Methodology

The research objectives identified in the previous section indicate the need to review existing literature. Besides, the specific research method to conduct this review was inspired by similar works in the field [8,26,27]. The comparison among these suggested to conduct a Systematic Literature Review (SLR). SLR is defined by Booth et. al [28] as a *"systematic, explicit, and reproducible method for identifying, evaluating, and synthesising the existing body of completed and recorded work made by researchers, scholars, and practitioners"*. In their book they also present the SALSA Framework [29], a methodology to determine research protocols for SLR's. The description of this methodology's steps is presented in Figure 1. It also includes the steps' outcomes and the research methods identified in this SLR to achieve them.

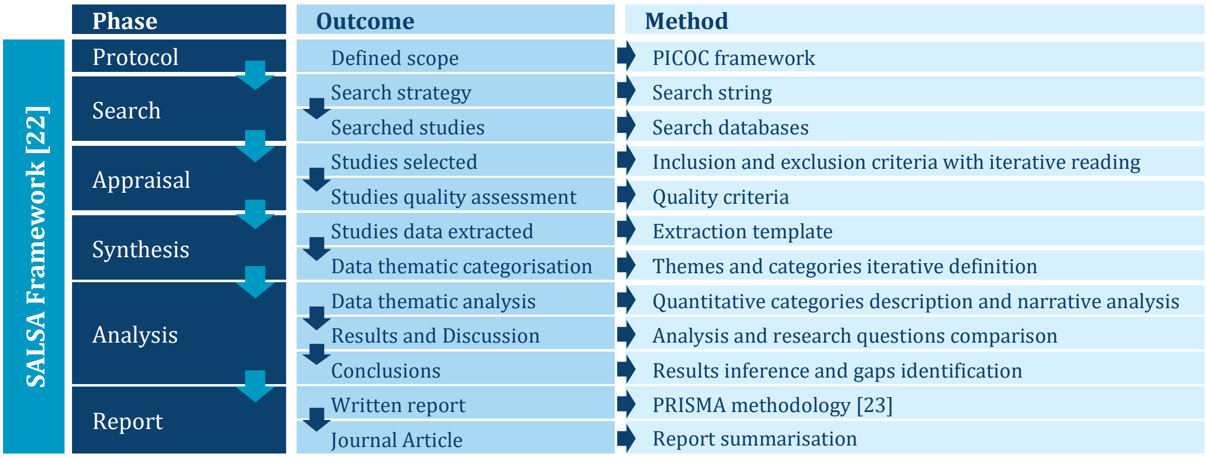


Figure 1. SLR methodology description: includes steps (dark), outcomes (medium) and the methods (light boxes) identified to achieve the outcomes.

Each step and the research methods to obtain their outcomes are explained in detailed in the following subsections.

2.1. Protocol – SLR methodology step 1

The need for a research protocol for SLR's is identified by Booth et. al [28] in the consideration of transparency, transferability and replicability, which are the characteristics that make a literature review systematic. The most critical stage in the protocol definition phase is determining the research scope. The scope helps to formulate answerable research questions and establish research boundaries to identify research methods for the SLR phases (Figure 1). In order to determine the scope of this research, the PICOC framework [28] has been used. PICOC (Population, Intervention, Comparison, Outcome and Context) is a formal structure to decompose research questions by their component concepts; thus, specifying the research scope of the research. Table 1 presents the application of the PICOC framework to this research objectives (Section 1), along with the definitions [28] for each concept.

Table 1. SLR research scope: obtained through the application of the PICOC framework to the SLR research objectives.

Concept	**Definition** [28]	**SLR application**
Population	The problem or situation the research is dealing with.	Augmented reality for maintenance applications research: training, monitoring, inspection, diagnosis, repair, assembly, reporting, maintenance.
Intervention	Existing techniques utilised to address the problem identified.	Methods, tools and techniques for augmented content creation, adaptation, analysis and re-use: Authoring, Context-Awareness and interaction analysis.
Comparison	Techniques to contrast the intervention against.	Contrast between intervention techniques.
Outcome(s)	The measure to assess the effect of the techniques in the population.	Maintenance key performance indicators: completion time and errors, etc. Augmented content effectiveness: data quality, overlay accuracy, etc. Learning effects: task normalisation, equipment use, shared experiences, etc.
Context	The particular settings or areas of the population.	Maintenance of medium-long life complex assets.

The research scope identified in Table 1 will be used to determine the approach to consequent SLR phases. Besides, it also helps to refine the objectives of this SLR. The refined objectives are presented in the form of research questions in the list below:

1. What is the state-of-the-art in A, CA and IA techniques for AR maintenance applications?
2. What are the research gaps in A, CA and IA for AR maintenance applications?

3. What are the relations between A, CA and IA techniques and knowledge transfer?
4. What knowledge types are transferable by AR?
5. What potential applications of AR knowledge transfer are in maintenance contexts?

These are the research questions that will be answered by this SLR through the conduction of the steps described in the following subsections.

2.2. Search – SLR methodology step 2

The search phase consisted of identifying sources of information that could be relevant for this research. In order to do so, it was required to first identify where to find those sources and then retrieve them. Those two were the steps in which this phase was separated into: search strategy and delivery.

The search strategy step aimed to identify search databases and define the search string that can obtain relevant documentation on this systematic review's scope. The search string definition was defined using the terminology identified for the population in this scope (PICOC framework - Table 1). This scope was also used to identify relevant databases within the research area. First, the authors created a list of search databases and engines considering those presented in similar works [8,27]. Then, those databases which did not allow to download references from the search results for further data processing were discarded. The resulted search databases/engines and search string are:

- Search databases: ACM, IEEE Xplore, ScienceDirect, Scopus, Web of Science.
- Search string: *("Augmented Reality") AND (Maintenance OR Assembly OR Repair OR Diagnosis OR Training OR Reporting OR Monitoring OR Inspection)*.

The search delivery step involved the application of the search string to the databases in order to retrieve related literature papers as search results. These results are classified by database in Table 2.

Table 2. SLR search: search delivery results classified by database.

Search String – To be used within advance search queries of the database (link)	**Database**	**Date**	**Papers**
"augmented reality" AND (maintenance OR assembly OR repair OR diagnosis OR training OR reporting OR monitoring OR inspection)	ACM	30/05/17	1712
(“augmented reality”) AND (maintenance OR assembly OR repair OR diagnosis OR training OR reporting OR monitoring OR inspection)	IEEE Xplore	31/05/17	1687
("augmented reality" AND (maintenance OR assembly OR repair OR diagnosis OR training OR reporting OR monitoring OR inspection))	ScienceDirect	13/06/17	3835
TITLE-ABS-KEY ("augmented reality" AND (maintenance OR assembly OR repair OR diagnosis OR training OR reporting OR monitoring OR inspection))	Scopus	03/06/17	2485
TS = ("augmented reality" AND (maintenance OR assembly OR repair OR diagnosis OR training OR reporting OR monitoring OR inspection))	WOS	12/06/17	2174
		Total	**11893**

Several observations according to the SLR search phase are made:

- The number of results was quite high, due to the length of the search string.
- As the searches in each database were independent, the results included duplicates.
- The results also included papers from different contexts that could be applicable.

Hence, strict inclusion and exclusion criteria was needed to narrow down the results in the study selection process.

2.3. Appraisal – SLR methodology step 3

The appraisal phase comprised the evaluation of search results in order to select those papers that are relevant according to this research scope and describe their validity. These two objectives were achieved in two different steps: study selection and quality assessment.

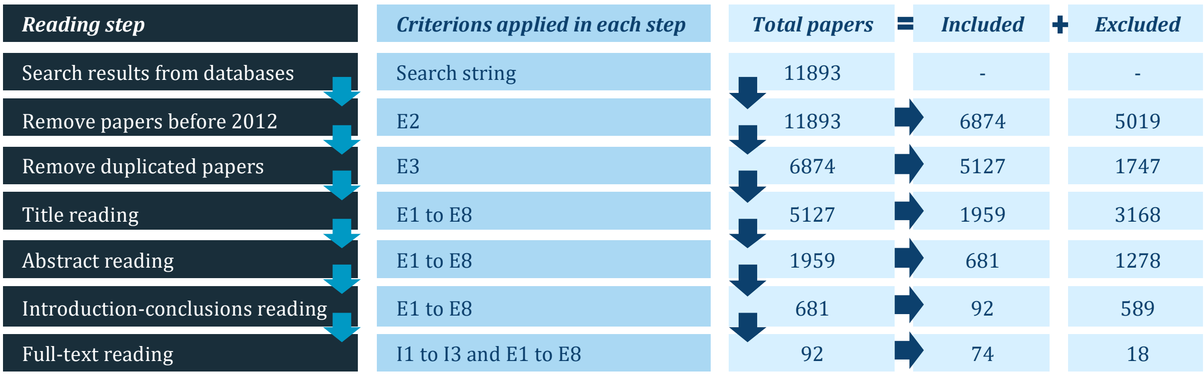
The study selection consisted of the screening of search results for selecting those papers that were relevant according to this review. In order to make this process as systematic and repeatable as possible, the authors used a set of predetermined inclusion and exclusion criteria. The authors defined these criteria to be relevant according to the review's scope (Table 1) and inspired by the structure of the selection criteria presented in similar reviews [8,10,27].

Table 3. SLR appraisal: study selection inclusion and exclusion criteria.

Type	ID	Statement
Inclusion	I1	Application-research studies that present evidences of Authoring
Inclusion	I2	Application-research studies that present evidences of Context-Awareness
Inclusion	I3	Application-research studies that present evidences of interaction analysis
Exclusion	E1	Papers not written in English
Exclusion	E2	Papers that were published before 2012
Exclusion	E3	Papers that are duplicated within the search documents
Exclusion	E4	Papers that do not meet any of the inclusion criteria
Exclusion	E5	Papers whose evidence is not applicable to maintenance of medium-long life complex assets
Exclusion	E6	Papers that are not primary research
Exclusion	E7	Papers that are not journal papers
Exclusion	E8	Papers that are not accessible

Table 3 presents the inclusion and exclusion criteria utilised. While some criterions are directly related to the interactions and context of this research scope (I1, I2, I3, E4, E5), others consider research-community focus in these matters (E2), and others focus on research quality and validity (E6, E7) and data accessibility (E1, E3, E8). Further discussions on the criteria definition can be found in Subsection 5.1.

These criteria were applied for screening a total 11893 papers. In order to increase screening efficiency, experts [28,30] suggest to apply the criteria iteratively at different reading phases. The screening process and the resultant included and excluded papers are presented in Figure 2. After removing old (E2) and duplicated (E3) papers, exclusion criteria (E1-E8) was applied for reviewing papers' title (5127), abstracts (1959), and introduction and conclusion sections (681). Then, inclusion and exclusion criteria were applied when fully reading the papers (92) to classify them by the evidence (I1, I2 or I3) shown. The process resulted on the selection of a sample of 74 relevant papers that complies with the selection criteria.



Reading step	*Criterions applied in each step*	*Total papers*	=	*Included*	+	*Excluded*
Search results from databases	Search string	11893		-		-
Remove papers before 2012	E2	11893		6874		5019
Remove duplicated papers	E3	6874		5127		1747
Title reading	E1 to E8	5127		1959		3168
Abstract reading	E1 to E8	1959		681		1278
Introduction-conclusions reading	E1 to E8	681		92		589
Full-text reading	I1 to I3 and E1 to E8	92		74		18

Figure 2. SLR appraisal: study selection results presented by reading steps according to the criteria applied on each step.

The quality assessment step comprised the evaluation of the internal (research methods) and external (results) validity [28] of selected-relevant papers. Frameworks for systematic reviews, such as SALSA [28] or PRISMA [30], include this step to *"localise how weaknesses or flaws of included studies may impact upon the review's findings"* [28]. In case any biases or contradictory ideas appear when analysing selected-relevant papers, quality assessment's results could be used to provide more transparent, repeatable findings. The assessment has been conducted following the validity criteria described by similar works [8,27] that is presented in Table 4. The total 74 selected-relevant papers were evaluated against each criterion with a score from 0 (no compliance), 0.5 (partial compliance) to 1 (full compliance).

Table 4. SLR appraisal: quality assessment criteria, scores and statistical results classified by validity aspect.

id	Criterion / Aspect	Score	Mean	Std. Dev.
	Internal validity	0-6	3.824	1.064
1	Appropriateness and clarity of research aim and objectives	0-1	0.858	0.254
2	Appropriateness and clarity of research design/methodology	0-1	0.547	0.320
3	Appropriateness and clarity of research process	0-1	0.642	0.334
4	Appropriateness and clarity of data support of analysis	0-1	0.628	0.359
5	Appropriateness and clarity of analysis methods	0-1	0.480	0.381
6	Appropriateness and clarity of conclusions	0-1	0.669	0.311
	External validity	0-6	3.709	0.930
a	Evidence for Authoring, Context-Awareness and interaction analysis	0-1	0.764	0.263
b	Appropriateness and clarity of system architecture	0-1	0.676	0.381
c	Appropriateness and clarity of knowledge involved	0-1	0.811	0.256
d	Case studies and applications not obsolete	0-1	0.824	0.323
e	Results applicable to maintenance of complex assets	0-1	0.635	0.388

Table 4 also presents the average statistical results (mean and standard deviation) for each quality criterion of all 74 papers assessed. It is important to note that the authors did not have the need to use these results further in the review. This was because no biases or contradictions were found in the analysis of the 74 selected-relevant papers. Still, the results are presented to provide the reader with a tool to assess the quality of this systematic review's findings. The application of validity criteria for quality assessment is a process subjected to biases itself. Therefore, while the average mean (Table 4) represents the quality of the papers assessed, the standard deviation for each criterion provides a numerical valuation on the potential authors' bias in the assessment process.

2.4. Synthesis – SLR methodology step 4

The synthesis phase consisted of the extraction and classification of relevant data from selected papers in order to map the evidence base for its analysis. Among others (e.g. logic models, Bayesian meta-synthesis), thematic synthesis was selected as research method for this phase as suggested by Booth et. al [28]. The reasons to make this choice were two. First, it is a mature method for synthesising qualitative data. And second, themes could be directly identified according to the research scope (Table 1). This method consisted of two steps: data extraction and thematic categorisation.

The data extraction step involved the identification and extraction of relevant data in the 74 selected papers. In order to do so, several themes were identified according to the research scope [28]. Table 6 presents their definitions. The first four themes (Asset, Operation, Task and Knowledge) provide a description of the maintenance operation and the AR application. The last three themes (A, CA and IA) detail the techniques used to provide knowledge transfer. The data related to each theme of each paper was extracted into an Excel sheet for data processing. An example of three papers is presented in Table 5.

Table 5. SLR synthesis: thematic data extraction example from three papers.

Theme	Paper 1	Paper 2	Paper 3
Asset	thermal power plant	machine tools	construction
Operation	periodical and repairing maintenance	condition-based, remote maintenance	progress monitoring and documentation
Task	occupational safety and work instructions	(1) technician report, (2) expert diagnosis, (3) expert repair Authoring, (4) technician repair, (5) technician completion report	inspection, survey and annotation of construction progress
Knowledge	procedural	procedural	procedural
Authoring	knowledge-based rules, manual-content	expert-based actions, automatic-content	knowledge-based algorithms, automatic-content
Context-Awareness	user-experience	machine-condition, diagnosis data	aerial images, georeferenced positions
Interaction-Analysis	none	expert questions, technician-procedures checklist	none

The thematic categorisation step included the classification and processing of the data extracted to prepare it for further analysis. In order to provide quantitative evidence about qualitative data, several categories for each theme are determined according to the data extracted. These categories comprise the different groups in which the ideas presented by the authors about the themes can be classified. A word-counting, iterative method (Figure 3) was proposed to identify categories based on the qualitative data extracted. The resulted categories are presented in Table 6 along with their themes.

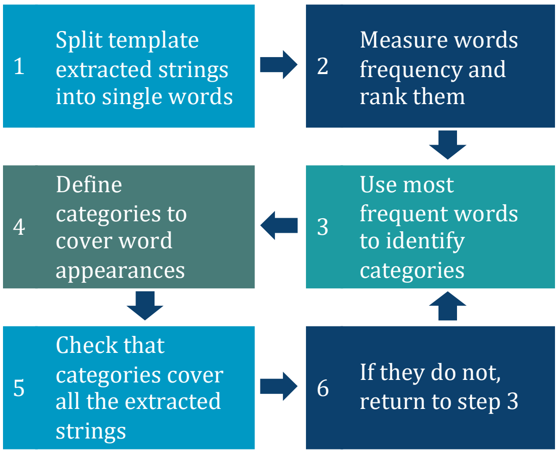


Figure 3. SLR synthesis: thematic categorisation method to obtain the categories for each theme based on qualitative data extracted from the papers.

Table 6. SLR synthesis: definition of themes used for data extraction and identified categories in data synthesis.

Theme	Definition	Category	Definition
Asset	The size of the augmented objects the AR application is targeting. The augmented object size is directly related with the type of assets considered within different industries (e.g. civil construction, manufacturing, etc.).	Small	The size of the object is similar to that of a device, product, equipment, etc.
		Medium	The size of the object is similar to that of a plant, construction, infrastructure, etc.
		Large	The size of the object is similar to that of an open space, environment, city, etc.
Operation	The maintenance processes the AR application described by the authors is supporting, e.g. diagnosis, repair, design, training.	Design	Any process related to the design of a maintenance operation.
		Assembly	Any process related to objects' assembly or disassembly within maintenance operations.
		Diagnosis	Any process related to the diagnosis of malfunctioning objects within maintenance operations.
		Repair	Any process related to objects' repair or replacement within maintenance operations.

		Training	Any process related to the training of a maintenance operation.
		Management	Any process related to the management of maintenance operations.
Task	The function that the augmented content described in the paper is conducting, e.g. monitoring, guidance, etc. The task directly relates the AR support given with the maintenance operation assisted.	Monitoring	Any AR function related to the observation and control of objects.
		Guidance	Any AR function related to the guidance of the user.
		Collaboration	Any AR function related to the collaboration among different users.
		Simulation	Any AR function related to the simulation of a real processes of objects.
Knowledge	The type of knowledge the AR application described in the paper is transferring and/or capturing (e.g. procedural, tacit, explicit).	Procedural	The knowledge related to the performance or conduction of a specific procedure.
		Declarative	The knowledge related to a specific fact or situation and the correlations between them.
Authoring	The set of software methods, tools and techniques to create augmented contents for the AR applications described in the papers.	Users	Consumers of Authoring tools, who can be either AR developers or subject-matter experts.
		Rules	The logic under which augmented content is created. These can be either specific-application algorithms or domain knowledge-structures (when the knowledge about a specific domain can be articulated, and so the information related directly identified).
		Automation	When the Authoring tools, can create the content automatically, semi-automatically (users-approved) or manually (users-made).
Context-Awareness	The set of software methods, tools and techniques to characterise the augmented content with relevant data regarding the task of the AR application described in the paper.	Contexts	The set of contexts the methods consider, it can be one or more of the followings: user, augmented object, activity, environment.
		Rules	The set of rules that determine how the context(s) are considered. These can be either specific-application algorithms or domain knowledge-structures.
Interaction analysis	The set of software methods, tools and techniques to analyse the interaction between the user and the augmented content, regarding the task status, in order to provide feedback for improving task's achievement.	Data	Interaction analysis tools can acquire data either automatically (sensors) or manually (users feedback).
		Automation	Whether the analysis made by these tools is automatic or manual (made by users).

The thematic categorisation method was proposed because most frequent words are more probable to be identified as categories [28], as they cover the meaning of similar approaches to a specific theme. Only relevant words (excluding those not related to the themes) from the most frequents were used to find specific definitions for the categories (steps 4, 5 and 6 in Figure 3). This process required of few iterations for obtaining consistent and coherent definitions for the categories.

2.5. Analysis – SLR methodology step 5

The analysis phase comprised the evaluation of synthesised data and the extraction of conclusions for providing enough findings to answer the SLR research questions (Subsection 2.1). It consists of three steps: (i) independent analysis of themes (thematic analysis), (ii) discussion of analysis results to answer research questions (results discussion) and (iii) extraction of conclusions (conclusions drawn).

The thematic analysis involved the assessment of quantitative results and qualitative data extracted during the synthesis phase. Its aim was to map how each theme was covered among the selected papers and find the correlations between themes. Each subsection in Section 3 presents the narrative analysis of the data extracted for each theme, along with the quantitative figures about the demographic description of categories between selected-relevant papers.

The results discussion step included the evaluation of the evidence-base given by the analyses in the previous step. It allowed to discuss and answer the research questions through the correlation between themes. In order to simplify the narrative of this paper, Section 4 briefly presents the answer to the research as results. Then, the discussion about those results is detailed in Section 5.

Finally, the conclusions drawn step incorporated inferring insights from the previous discussions. As a result, research conclusions and future works are presented in Section 6.

2.6. Report – SLR methodology step 6

The report phase involved the description and presentation of the methods and results on the research conducted. Two steps were determined for this phase: (i) description of the main elements in a SLR under a standard form (PRISMA report) and (ii) research summary for public presentation (Journal article).

The PRISMA report step comprised the presentation of the methods and results of this SLR as well as the description of any step in the process using a standardised method (PRISMA methodology [30]). This step resulted in the creation of a more detailed report that has been used to write this journal article.

The journal article step was the last step in the SLR. It consisted in the presentation of the research methods and results in a more comprehensive and succinct manner. So, that this research can be publicly available for scientific purposes.

3. Analysis

The thematic analysis consisted of the assessment of the research included in the 74 selected-relevant papers according to the themes, categories and data extracted in the synthesis phase. In order to provide the context on the papers' research, demographics results about them are presented. Figure 4 presents the 74 papers classified by publication year. Besides, Table 7 presents the top 10 publications with more selected-relevant papers.

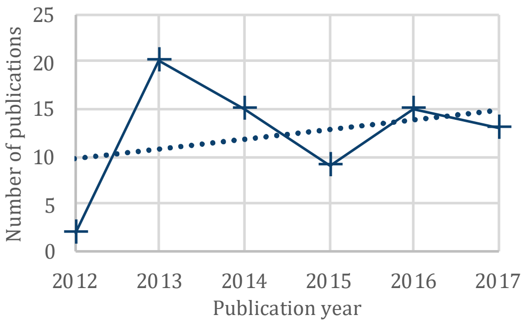


Figure 4. SLR analysis – Demographic description: classification of the 74 selected-relevant papers by publication year.

Considering the demographic data available, some comments about the selected papers can be made:

- Due to the dates of the search delivery (Table 2), 2017 cannot be considered as a complete year in relation to the number of papers published.
- Figure 4 shows an increasing linear (blue dots line) trend on the number of publications by year that can suggest an increasing interest on the research involved in this SLR. However, the number of papers

decrease between 2013 and 2015. Two reasons are suggested for this phenomenon. Either exist research cycles that do not allow authors to publish every year, or certain AR-maintenance applications considered within the SLR (Table 1) got mature, decreasing their number of publications.

- The maximum number of selected-relevant papers from one publication is five (Table 7). This represents a 7% of the total, which is not enough percentage to consider it as a reference publication in the research this SLR involved.

Table 7. SLR analysis – Demographic description: top 10 journals with most publications within the 74 selected-relevant papers.

Publication	Papers
Automation in Construction	5
CIRP Annals - Manufacturing Technology	5
Computers in Industry	5
Augmented Reality in Architecture, Engineering, and Construction	3
International Journal of Advanced Manufacturing Technology	3
International Journal on Interactive Design and Manufacturing	3
Robotics and Computer-Integrated Manufacturing	3
Assembly Automation	2
Personal Ubiquitous Computing	2
Proceedings of the IEEE	2
Others	41
Grand Total	**74**

Further categorisation and analysis is required to map the research in the selected-relevant papers. According to the research scope, the synthesis themes and categories will be used to drive the analysis and describe the research. So, this analysis can provide enough evidence base to answer the research questions. The following subsections provide an analysis (Subsection 2.5) of each theme and its categories (Table 6). First, selected-relevant papers are examined according to the 'assets' (Subsection 3.1) the AR applications provide support to. Second, they are analysed according to the maintenance 'operations' supported and how this support is provided (Subsection 3.2). Then, the focus is set on how the support 'tasks' relate with AR knowledge transfer capabilities (Subsection 3.3) and the 'knowledge' types involved (Subsection 3.4). Finally, the Authoring (Subsection 3.5), Context-Awareness (Subsection 3.6) and Interaction-Analysis (Subsection 3.7) techniques are independently analysed, classified and their relation with AR knowledge transfer capabilities assessed.

3.1. Asset

As defined in the thematic categorisation (Table 6), by 'asset' the authors consider the size of the objects targeted by the AR applications described in the selected relevant papers. These assets can be 'small' (e.g. equipment, devices, etc.), 'medium' (e.g. infrastructure, buildings, etc.) and 'large' (e.g. open spaces, cities, etc.). Figure 5 presents the percentages of the 74 selected-relevant papers that target the three different sizes of 'Assets'.

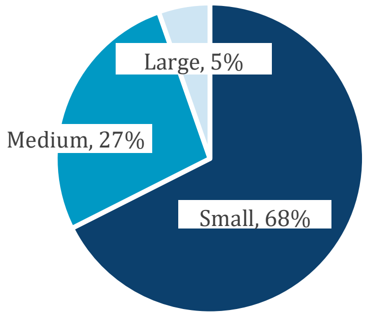


Figure 5. SLR analysis – 'Asset' analysis: classification of the 74 selected-relevant papers by type of 'Asset' targeted by their AR applications.

3.1.1. Findings summary

According to Figure 5, most of the selected-relevant papers (68%) have proposed AR-maintenance applications for 'small' assets (e.g. machine tools, motherboards, etc.). Only a few of these papers (5%) have focused in 'large' assets such as rivers or cities. The 'Asset' size affects to the kind of maintenance operations that are considered by the AR applications in the papers. That is the reason why the 74 selected-relevant are described in the following subsection by their 'Operations' according to the size of their 'Asset'.

3.2. Operation

By 'operation', the authors refer to the maintenance process the AR application is supporting (Table 6). Figure 6 presents the papers classified by maintenance 'operation': 'design', 'assembly', 'diagnosis', 'repair', 'training' and 'management'. Compared to other reviews with similar categorisations [8], some operations such as 'design' and 'management' have been added. This was due to the categorisation method that created the categories on its own (Subsection 2.4). Therefore, the similarities with other reviews help to corroborate the validity of the results of that categorisation methodology.

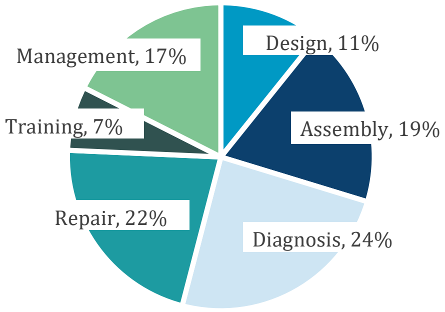


Figure 6. SLR analysis – 'Operation' analysis: classification of 74 selected-relevant papers by type of 'Operation' supported by their AR applications.

During the analysis it was noted that the AR applications were similar for each 'operation', but they vary from 'asset' to 'asset'. Therefore, it was worthy to analyse the 'operations' based on their 'asset'. Also, because not all 'operations' have AR applications for every 'asset'. Furthermore, not all 'operations' within each 'asset' have a similar amount of relevant papers for all the years included. This fact can offer valuable insights regarding the maturity of AR applications in specific 'operations' and 'assets'. Besides, it can also point to differences in the A, CA and IA techniques and their requirements by 'asset' and/or 'operation'.

Subsections 3.2.1, 3.2.2 and 3.2.3 describe the AR applications according to the maintenance 'operations' they support respectively for 'large', 'medium' and 'small' Assets.

3.2.1.Operations in 'Large' Assets

The selected-relevant papers classified by 'operation' within the 'large' asset category are presented in Figure 7. Only 4 papers were considered relevant under this category during the study selection process. These were the only papers that considered the AR research areas of Authoring, Context-Awareness and Interaction Analysis. Due to the AR technological challenges in outdoor applications, it appears that research in AR for 'Large' Assets is not mature enough [31] to consider yet the broad application of these techniques.

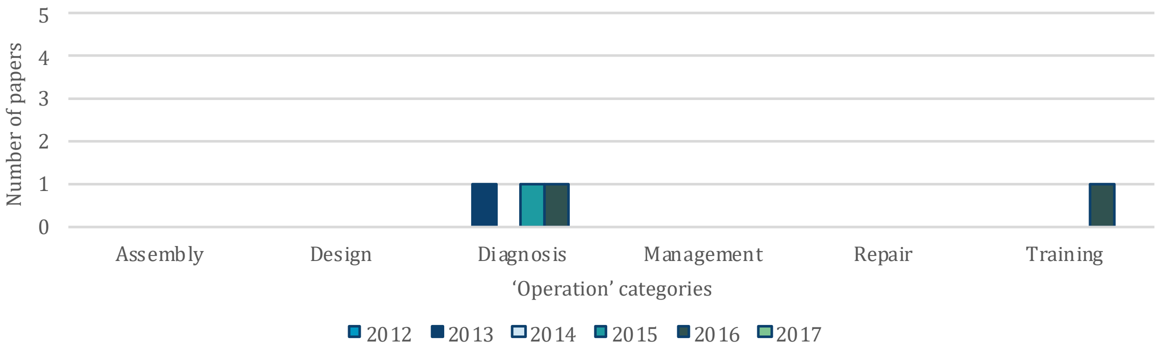


Figure 7. SLR analysis – 'Operation' analysis: classification of 4 selected-relevant papers by type of 'operation' in 'large' asset.

Sebillo et. al [32] described an AR training application for emergency responders that aimed to enhance their effectiveness with emergency technologies and procedures. Apart from an Authoring tool that was able to display location-context information regarding the user's tasks during the training, this application also had an Interaction-Analysis tool that enabled trainers to automatically collect data from trainees and adapt their training tasks on real-time.

On the other side, the three papers describing 'diagnosis' operations where focused on the monitoring of different environments. First, Veas et. al [31] presented an automatic Authoring tool to generate environmental sensor measures content on augmented environments to enhance data visualisation and interaction of domain experts. Pokric et. al [33] described an Authoring tool for creating pollution monitoring applications in smart cities for citizen participation. This tool allows experts to create content using serious gaming concepts based on the data acquired from the monitoring IoT (Internet of Things) devices. Then, Pierdicca et. al [34] presented an AR application for riverbanks maintenance. It included an Authoring tool based on a standard data layer that considered all the tasks to be done by the environmental inspectors. Therefore, considering the task selected by the inspector, different automatically-generated was displayed on-site over the riverbanks to enhance their efficiency.

3.2.2.Operations in 'Medium' Assets

The selected-relevant papers targeting 'medium' assets classified by 'operations' are presented in Figure 8. There is a total of 20 papers, mainly distributed in the earlier years considered within this review. Only one is from 2017 while 16 of them are from 2012, 2013 and 2014. Only two papers – one in 'assembly' (tele-operated cranes support) [35] and another in 'training' operations (escape guidance for radioactive accidents) [36] – are not from 'diagnosis' and 'management' operations.

In 'diagnosis' operations, all papers are focused on three topics. One is the monitoring of different defects, such as segment displacement in tunnels [37], underground manholes [38] or building damage reconnaissance [39]. Two is the monitoring of building power consumption data for energy performance [40–42]. And three is the monitoring of construction site progress [43]. All these AR applications present automatic Authoring tools based on physic models and BIM data. Besides, some present additional Interaction-Analysis techniques to support users in their evaluation and inspection tasks.

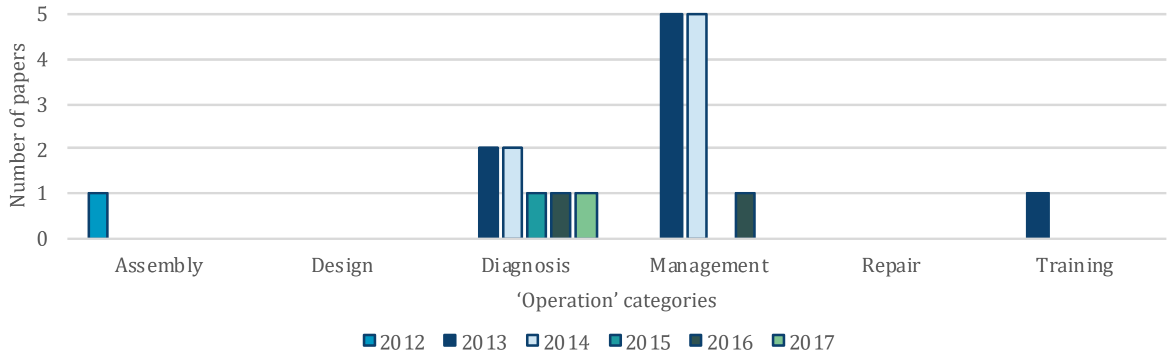


Figure 8. SLR analysis – 'Operation' analysis: classification of 20 selected-relevant papers by type of 'operation' in 'medium' asset.

In 'management' operations, the focus of papers is different. There are some case-specific applications about construction-site defect management [44,45], library management [46], or air-traffic management [47]. Nevertheless, most of them are focused on project management for the construction site. The Architecture, Engineering and Construction (AEC) industry is advanced in the representation of knowledge for project management [48]. And Building Information Modelling (BIM) is a mature technology in this area. Therefore, most of these AR applications are focused on Authoring tools for BIM data visualisation. Different approaches have been taken in different contexts. For example, the usage of GIS (Geographic Information System) data for underground infrastructure [49] or Photogrammetry in the facility management of oil refineries [50]. BIM data visualisation using AR can be considered a mature application. This is because there already exist different Authoring tools for automatically creating and augmenting BIM data [51–55]. Nevertheless, there is less reported evidence on Context-Awareness and Interaction-Analysis techniques. Only the case-specific applications above-mentioned considered them. Besides, the BIM data considered in the Authoring application papers do not mention neither contextual nor task- and user-status data that could trigger the development of these techniques.

3.2.3.Operations in 'Small' Assets

The 'small' assets category is the most relevant in number of selected-relevant papers (50). Figure 9 presents these papers classified by 'operation' categories. 'Small' asset is the only category with representation in all 'operation' categories. The papers within each 'operation' category are described below in ascending order of number of papers.

In the case of 'management' operations there are only 2 selected-relevant papers. Suarez-Warden and González Mendívil [56] proposed an AR-based method to transfer procedural knowledge in the aerospace service industry. Differently, Liu et. al [57] proposed an AR interface for cyber-physical machine tools, that enabled the user to control its machining process in real time. This paper presented evidence on all A, CA and IA research areas. An Authoring tool that automatically generates the simulation of the machining process, a Context-Aware technique to adapt the augmented simulation based on monitoring data, and an Interaction-Analysis approach to evaluate the feasibility of the process.

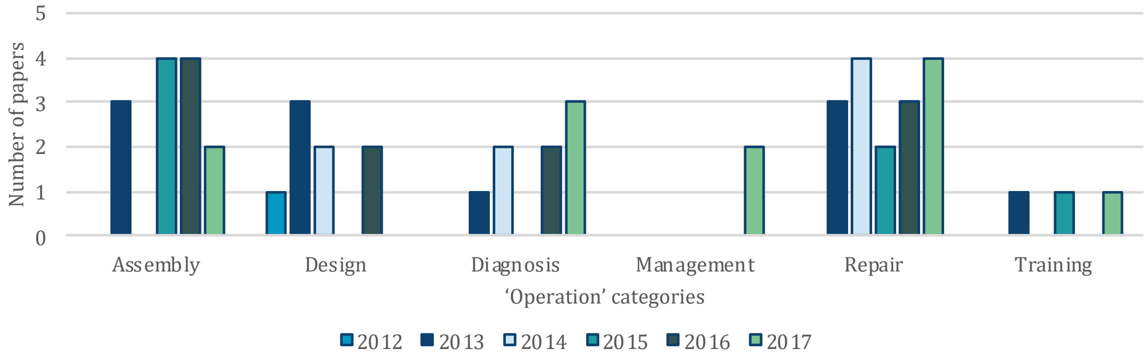


Figure 9. SLR analysis – 'Operation' analysis: classification of 50 selected-relevant papers by type of 'operation' in 'small' asset.

Similar to 'management' is the case of 'training' operations. The use of expert systems to support traditional AR training is proposed by Westerfield, Mitrovic and Billinghurst [58] to enhance the learning process rather than just training procedural skills. In contrast, Webel et. al [13] proposed the use of haptic feedback based on the outcomes from the training status to enhance the practice on the undergoing skills of procedural works. On a different application level, Okazaki and Takaseki [59] proposed an AR-based training simulator for maritime navigation. Due to the novelty of this field of application, only evidence in Authoring has been found. Meanwhile, the researches on training of procedural works also included research on Context-Awareness and Interaction-Analysis.

Within 'design' operations, one of the most relevant fields is the design, planning and simulation of assembly procedures. Different papers have shown different Authoring tools for automatically creating assembly procedures based on real and virtual components [60,61]. Based on visualising assembly procedures, user-virtual components-interaction capabilities have been included in following works, in order to enhance design and planning effectiveness. That is the case of Wang, Ong and Nee [62]; they proposed a bare-hand interface to contextualise the manipulation of virtual components. Moreover, they extended their own work with Interaction-Analysis methods to evaluate the status of assembly situations based on user interaction and provide more accurate assembly simulations [63,64]. Additionally, other design applications have been proposed in the context of 'small' assets. One was an Authoring tool for robot trajectory planning and simulation [65]. Another was a different Authoring tool for collaborative design through tele-presence systems [66]. The latest allowed users to create and interact with their own-created and other users-created content in the same virtual space. Also, a context-based approach was proposed [67] to access enterprise knowledge in design processes by means of AR. Nevertheless, there was not that much research and so, only independent Authoring and Context-Awareness techniques have been considered within selected relevant papers in 'design' operations in 'small' assets.

Figure 9 shows an increasing interest in 'diagnosis' operations due to the increase on published papers over the last years in this area. Nevertheless, the specificity of inspection and monitoring processes in most of the cases has narrowed the research. Authors have been able to investigate together either Authoring and Context-Awareness or Authoring and Interaction-Analysis to provide further insights within AR applications about the actual processes. Some examples are: post-impact inspection of thin structures [68], crack growth monitoring in bonded single-lap joints [69], 'Situated Analytics' for health product evaluation [70], strain and stress visualisation for mechanical systems [71], finite element analysis visualisation and interaction [72] and real-time monitoring by comparison of 3D printing processes [73]. Conversely, inspection applications on less specific domains have only considered Authoring tools for automatic content creation. That is the case of AR applications for support of maintainers inspection procedural tasks [74] or visualisation support of acceptance sampling procedures [75].

'Assembly' is one of the most famous fields of AR application. Thirteen (13) relevant papers have been identified and they mostly cover visualisation support of assembly procedures. The fame of assembly as AR application has led to an extensive representation of assembly knowledge. Moreover, it has also revealed the latest advancements in Context-Awareness and Interaction-Analysis techniques. The AR applications studied are able to achieve knowledge capture and discovery of procedural assembly expertise. Initially, research was focused on the automatic content generation of assembly procedures based on existing virtual data for human users [76,77] or for programming robots without programming skills [78,79]. Then, Context-Awareness methods have been introduced to provide more effective support based on user's experience and assembly status [80–82]. Based on determining assembly status, Interaction-Analysis methods have been used to capture assembly expertise, evaluate it and transfer it to robots [83–85] or other human users [86–88]. Nevertheless, the introduction of different areas of research (CA and IA) has been progressive and based on the advancements of the previous (Authoring). Contextualisation could not be provided until there was automatic augmented content. Then, based on the insights in task status and user experience given by Context-Awareness methods, interaction analysis techniques for assembly evaluation and optimisation could be introduced.

'Repair' is another of the most famous and oldest fields of AR application. It comprises repair and replacement procedures in corrective or preventive maintenance. These have the need to enhance their efficiency by better visualising existing procedural documentation. Based on the sixteen relevant papers selected within this operation, the same pattern as in 'small' assets 'assembly' or 'large' assets 'management' operations was identified. First, Authoring tools are developed for different applications such as machine tools [89], aircrafts [90], consumer products [91], hazardous environments [92], or industrial-like environments [93–95]. Then, Authoring automation and Context-Awareness techniques are developed once the areas of application are better investigated. That is the case of several systems such as CARMMI [96] (integrating existing information from different sources) or ACARS [97], COARS [12] and ACAAR [11]. In the latest three, the same authors first developed a context-aware method, and then included Authoring capabilities, first for programming experts and then for non-programmers. Also

ARAUM [98] considered methods to adapt content and interactions to users' expertise. Context-Awareness techniques have also been used to enhance safety in such difficult environments [99,100]. Following the same, pattern, Interaction-Analysis techniques are introduced after to track the performance of users and status of repairing processes. That was the case of Nakai and Suzuki [101] for faster procedures in chemical plants. Also from Mourtzis, Vlachou and Zogopoulos [102], who are the latest authors to present a new approach for machine tools servitisation. This was based on remote AR-supported maintenance that enable knowledge transfer from remote experts to on-site technicians.

3.2.4. Findings summary

From the narrative analysis that supports the numerical results presented in the previous Subsections (3.2.1, 3.2.2 and 3.2.3), several findings can be summarised:

- There appears to be a correlation between knowledge representations in an 'operation' domain and the relevancy of Authoring, Context-Awareness and Interaction-Analysis research in those 'operations'.
- There appears to be certain 'operations' within certain 'industries' where more generic knowledge-domain representations have been studied (e.g. equipment repair or construction management). Instead, there are others in which these representations are more limited.
- Those 'operations' with more limited knowledge-domain representations do not present as much evidence in Authoring, Context-Awareness and Interaction-Analysis as those with more generic ones.
- Generality of knowledge-domain representations can be seen as an indicator of knowledge transfer effectiveness. The easier to represent knowledge, the easier to transfer it effectively.
- Therefore, it seems reasonable to identify a correlation between knowledge transfer and Authoring, Context-Awareness and Interaction-Analysis techniques.

3.3. Task

'Task' has been defined (Table 6) as the support function that augmented content provides to AR users. While 'operations' refer to the labours associated to the 'asset' (e.g. repair, assemble, design, etc.), 'tasks' relate to the AR information delivery that support those. Therefore, 'tasks' can be considered as the methods AR enables to transfer knowledge ("information in context" [6]). Four non-mutually exclusive categories have been declared for 'tasks' (Table 6): 'monitoring', 'guidance', 'simulation' and 'collaborative'. Good explanations from each category can be found in [43,66,71,99] respectively. Besides, it seemed interesting to analyse the relation between 'operations' and 'tasks' (Figure 10) and 'tasks' and A, CA and IA techniques (Figure 12) to further understand AR knowledge transfer capabilities.

If 'task' is considered as the support offered by AR applications to maintenance 'operations', then it can be said that the type of support varies from one 'operation' to another. Based on the results presented in Figure 10, all 'operations' have a component of 'guidance' tasks. Meanwhile, 'collaborative' has a minimum effect in any 'operation'. Therefore, it seems that 'monitoring' and 'simulation' are the tasks that differentiate between 'operations'. At this point in the analysis, the authors noted that the more mature AR applications for those 'operations', the more combination in 'tasks' (e.g. 'guidance' and 'monitoring', 'monitoring' and 'simulation', etc.) they provided. Figure 11 is used to discuss whether this affirmation can be considered correct. As it can be seen, the AR applications published in later years have more 'tasks' combined (e.g. 'simulation' and 'guidance') than those for previous years. From a 0% of combinative support in 2012 and 20% in 2013 to a 40% in 2017, it seems there is an increasing trend in research for AR maintenance applications that offered more than one kind of support or 'tasks'.

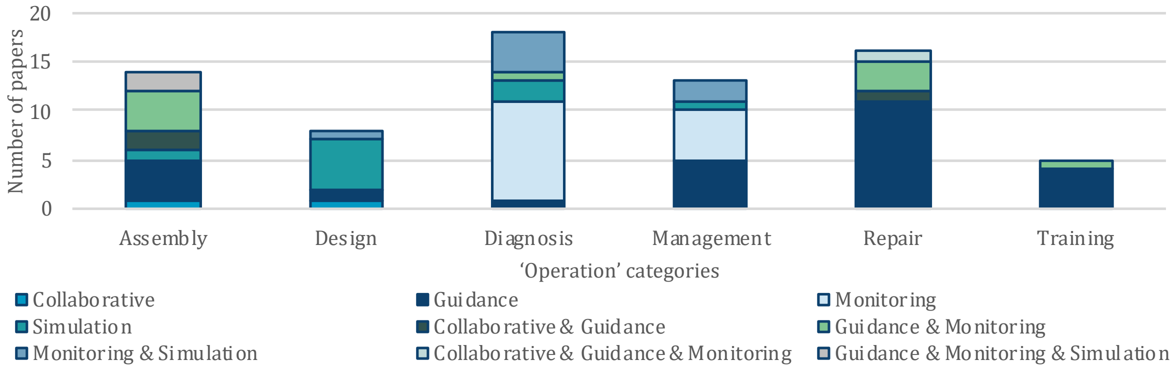


Figure 10. SLR analysis – 'Task' analysis: classification of 74 selected-relevant papers by type of 'operation' and type of 'task'.

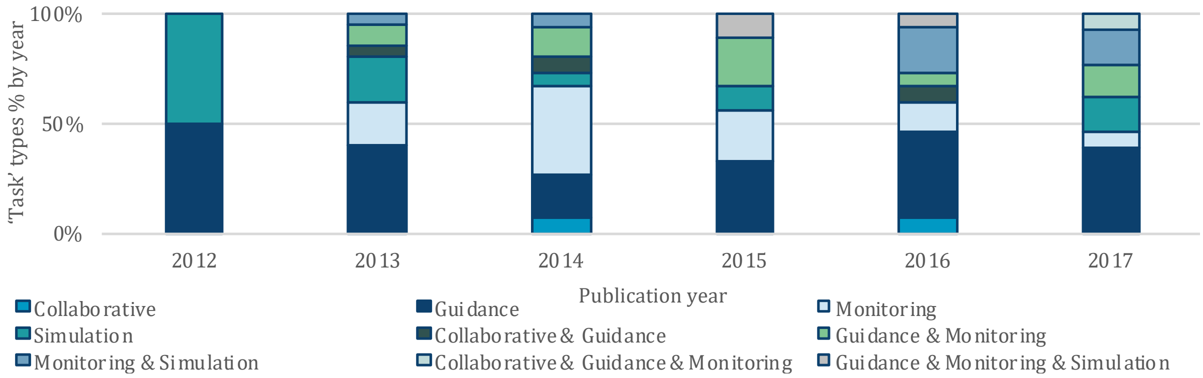


Figure 11. SLR analysis – 'Task' analysis: classification of 74 selected-relevant papers by year and type of 'task'.

The previous paragraph supports the idea that for every 'operation', the more mature AR applications, the more 'tasks' they can offer to support users in their maintenance processes. Considering the relations between 'tasks' and knowledge transfer, it can be said that the more 'tasks' an AR application provides, the more knowledge it can transfer. Due to the objectives of this SLR, it seemed important to analyse whether more knowledge transferred is accompanied with more A, CA and IA techniques. For this matter Figure 12 is presented. It shows that the papers with more combined 'tasks' present more evidence of Authoring, Context-Awareness and Interaction-Analysis techniques. Therefore, it seems reasonable to establish a positive correlation between A, CA and IA techniques and knowledge transfer. Nevertheless, how each technique relates to knowledge transfer has not been identified yet. This will be discussed in each technique Subsection (3.5, 3.6 and 3.7).

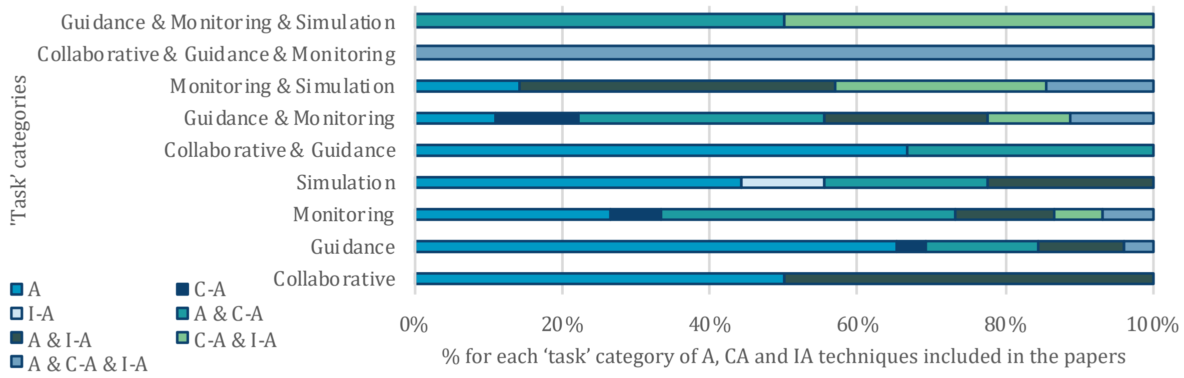


Figure 12. SLR analysis – 'Task' analysis: classification of 74 selected-relevant papers by type of 'task' and A, CA and IA techniques included.

3.3.1. Findings summary

From the analysis presented in this subsection, several findings can be summarised:

- The more mature AR applications are, the more 'tasks' they provide.
- The more 'tasks' AR applications provide, the more knowledge these applications can transfer.
- The more 'tasks' AR applications provide, the more evidence shown of A, CA and IA techniques.
- Therefore, it appears to be a positive correlation between A, CA and IA techniques and AR knowledge transfer capabilities enabled.
- The inference above is only an appreciation. So, further analysis is required to identify how each technique relates to AR knowledge transfer capabilities.

3.4. Knowledge

Nonaka [6] defines knowledge as information in context. Moreover, he also defines as 'explicit' the knowledge that can be easily transferred to others as information [6]. In other words, knowledge that can be easily represented or codified by data with a specified format [103]. Because AR transfers knowledge by putting information in an explicit context, it is limited to transfer explicit knowledge. Table 6 identifies the categories of explicit knowledge: (i) procedural (sequences of steps, actions) and (ii) declarative (relationships among variables, facts) [103]. Regarding this SLR objectives, it seemed important to analyse the relation between knowledge types and AR knowledge transfer capabilities.

Figure 13 presents the 'knowledge' types transferred by AR applications considering the maintenance 'operations' they support. Compared to others, 'diagnosis' and 'management' operations transfer more 'declarative' than 'procedural' knowledge. A similar relation between 'operations' and 'tasks' was found in Subsection 3.2. So, it would be interesting to see the relations between 'task' and 'knowledge' types.

Figure 14 presents the comparative between 'task' and 'knowledge' types. The results show that 'simulation' and 'monitoring' tasks provide more support in the form of 'declarative' rather than 'procedural' knowledge. Different examples can be found in [37,43,71,73]. These papers emphasise the idea of using AR to provide the necessary knowledge for users to make certain decisions on their maintenance 'operations'. Nevertheless, less evidence has been found on how AR can be used to provide instructions ('procedural' knowledge) for making those decisions in order to increase maintenance efficiency.

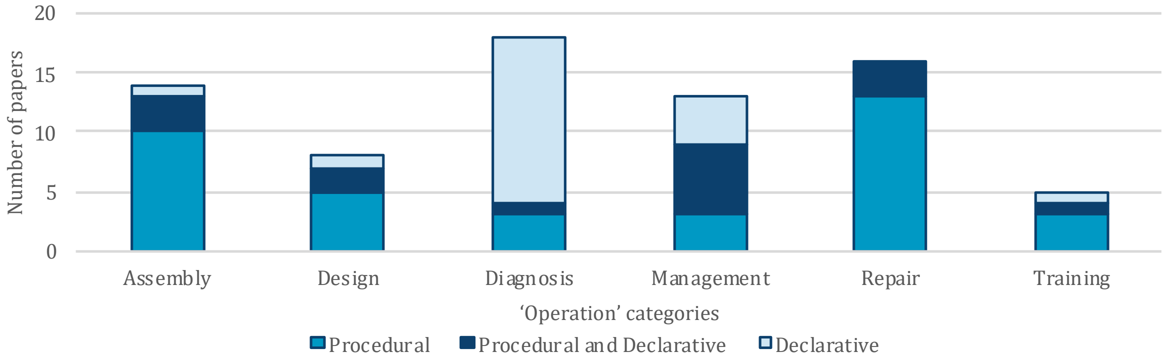


Figure 13. SLR analysis – 'Knowledge' analysis: classification of 74 selected-relevant papers by type of 'operation' and type of 'knowledge'.

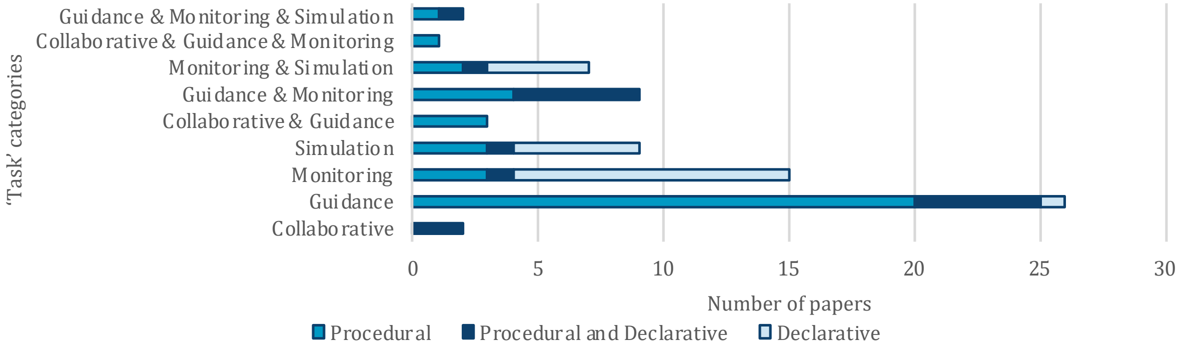


Figure 14. SLR analysis – 'Knowledge' analysis: classification of 74 selected-relevant papers by type of 'task' and type of 'knowledge'.

Another correlation to analyse is between 'knowledge' types and evidence on A, CA and IA techniques. That is presented in Figure 15. Apart from papers where only IA techniques are presented, the rest present similar numbers on the 'knowledge' types to which of A, CA and IA techniques are applied. Therefore, it seems reasonable to say that A, CA and IA techniques do not affect the 'knowledge' types being transferred.

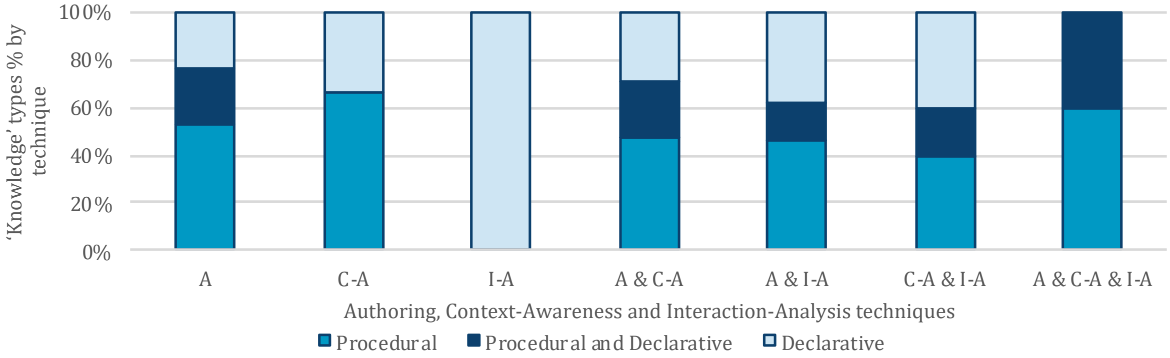


Figure 15. SLR analysis – 'Knowledge' analysis: classification of 74 selected-relevant papers by A, CA and IA techniques and type of 'knowledge'.

3.4.1. Findings summary

From the analysis presented in this subsection, several findings can be summarised:

- There appears to be lack of 'procedural' knowledge for 'diagnosis' and 'management' operations.
- There appears to be a correlation between 'tasks' and 'knowledge' types provided. 'Declarative' knowledge is more common in 'simulation' and 'monitoring' tasks.
- There is no reason to believe certain 'tasks' (e.g. guidance) cannot be applied to certain 'operations' ('diagnosis'). It seems that lack of 'tasks' to support certain 'operations' is due to the inability to explicit they 'knowledge' type being provided.
- Therefore, further research is required to specify explicit 'procedural' knowledge in 'diagnosis' and 'management' operations.
- There appears to be no correlation between 'knowledge' types and the use Authoring, Context-Awareness and Interaction-Analysis techniques.
- Therefore, it seems reasonable to believe that A, CA and IA techniques affect the way knowledge is being transferred but not its type.

The following subsections discuss existing A, CA and IA techniques and how these affect to AR knowledge transfer capabilities.

3.5.Authoring

'Authoring' techniques are the set of software methods, tools and techniques to create augmented content for AR applications [80]. Figure 16 presents the existing categorised types and their distribution among those selected-relevant papers (66) that present evidence of 'Authoring' techniques.

The categories identified (Table 6) for 'Authoring' techniques can be classified according to: (i) potential users, (ii) automation, and (iii) content-creation rules. Techniques that are automatic (ii) do not require from users (i) and vice versa. But, all can be classified according to their content-creation rules (iii). Therefore, six types are identified within the selected-relevant papers (Figure 16), two automatic, two for software developers (AR expertise), and two for application experts (maintenance expertise). Each pair is further categorised according to content creation rules. These rules can be programmed ad-hoc for each application (algorithmic) or taken from a structured knowledge-domain (knowledge-based). These types are presented in the following paragraphs, starting from the top and reading clockwise on Figure 16.

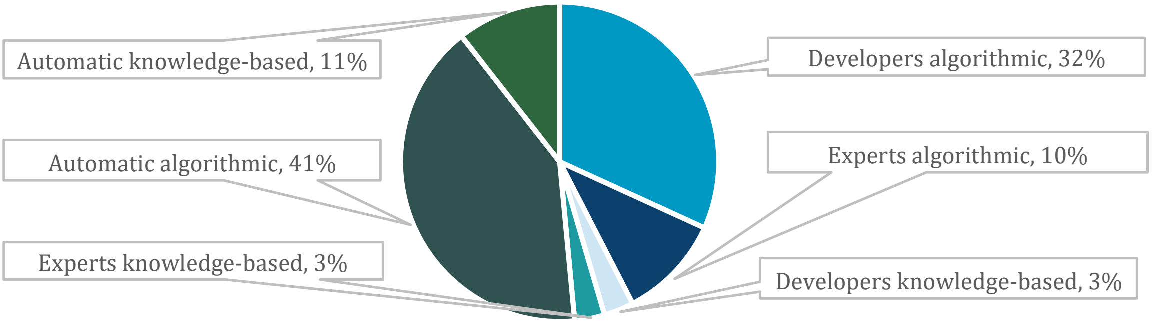


Figure 16. SLR analysis – 'Authoring' analysis: classification of 66 selected-relevant papers by type of 'Authoring' techniques.

'Developers algorithmic' techniques are those that manually create and display the content. This means that AR programmers (developers) "hard-code" the content and its interactions ad-hoc for the application being considered. A clear example is presented in [99]. Tatić and Tešić present a step-by-step logic which displays content based on markers recognition. They also described the storage and the format given to the content created. 'Developers algorithmic' is the simplest form of Authoring and is often used in applications which focus is solving more fundamental AR challenges [89]. That is why these "manual" techniques are still being used in research of new fields of application. The authors have noted evidence in papers presenting new AR applications in: safety monitoring [100], human-robot collaborative assembly [84], remote maintenance in radioactive environments [92] and procedural guidance in chemical plants [101]. Moreover, the papers presenting evidence of 'Developers algorithmic' techniques mention the need to research more effective Authoring methods. These should enhance AR industrial implementation and decrease development and support costs.

'Experts algorithmic' techniques are an advancement towards AR industrial implementation and the previous step to introducing knowledge-structures for creating augmented content. These techniques are based on pre-programmed algorithms that allow non-programmers (application experts) to create content and determine its overlay. Application experts use interfaces, desktop or AR, to access virtual data, format it and generate the content. A good example is presented by Wang et. al in [66] for collaborative design. In this case, application experts are given a desktop tool to import virtual data and allocate it as content in an augmented desktop where the design is taking place. Therefore, 'experts algorithmic' techniques are easier to implement because no AR experts are required to create content. Still, the algorithms for content generation are ad-hoc; and so, any changes to the rationale for content display have to be "hard-coded". That is why 'Experts algorithmic' share challenges (development cost, generality, etc.) and research focus (new AR applications [66,73,82,89]) with 'Developers algorithmic' techniques.

Compared to 'algorithmic' techniques, 'developers' and 'experts knowledge-base' techniques differ in the way their algorithms are programmed. Instead of being "hard-coded", 'knowledge-based' algorithms are based on knowledge-domain structures that represent the 'operations' and/or 'tasks' being supported by the AR application. These structures for knowledge-representations (often ontologies [11] or taxonomies [33]) provide a generic rationale that describe the knowledge and information associated to 'operations' and 'tasks'. So, there is no need to reprogram algorithms to augment new kinds of information. Although, they are the next logic step towards Authoring automation, fewer evidence has been found regarding these techniques compared to automatic ones. This is because once the knowledge representation for an 'operation' or 'task' is obtained, the automation of content creation is straightforward. Only those cases where the virtual data to be augmented needs from reformatting, these techniques have been considered. The authors would like to note two relevant examples. ARAMS [80] presents a bi-directional Authoring tool in which developers create content using a repair ontology and experts cross-validate the content created. The other example is called CARAGS [81]. It presents an ontology for creating assembly content based on existing data (e.g. CAD models, assembly paths, etc.). So, experts only have to decide about the order of the content rather than its format. Overall, 'developers' and 'experts knowledge-base' techniques are better than the previous two, as they reduce development costs while maintaining accuracy and validity of content created, and so the knowledge being transferred.

'Automatic algorithmic' are the most present Authoring techniques within the SLR relevant papers. These techniques are programmed to create augmented content automatically from existing data without the need of experts' or developers' input. A clear example to describe these techniques is presented in [98]. The Authoring software retrieves text and 3D models from an existing database and creates instructions and animations to overlay regarding the repair operations about the asset being tracked. These techniques are a step forward towards automatic content creation. But, they are still quite limited when considering adaptability of the AR applications to different scenarios (e.g. diagnosis instructions in repair operations) and acceptable data formats (often pre-determined by algorithms). Therefore, although these techniques reduce even further development costs, they don't perform better in terms of adaptability (data, scenarios) for industrial implementation. Relevant evidence of these techniques can be found in [31,41,42,63,70,102].

'Automatic knowledge-based' techniques are the ultimate approach to augmented content creation. These create content automatically based on existing data, as 'automatic algorithmic', but they also contextualise it according to knowledge-domain structures, as 'developers' and 'experts knowledge-base' techniques. Therefore, 'automatic knowledge-based' techniques hold the advantages (cost reduction, knowledge transfer accuracy) of those while reducing their disadvantages (validity and adaptability). Nevertheless, although these techniques overperform others, they are as difficult to achieve as the knowledge-domain representations they require to work. That is why only few 'operations' in certain 'industries' have achieved them. Relevant 'automatic knowledge-based' techniques have been found in 'equipment' 'assembly' [64], 'equipment' 'repair' [96] and 'environmental' 'inspection' [34].

3.5.1.Findings summary

Table 8 presents Authoring techniques classified by supported 'operations.'

Table 8. SLR analysis – 'Authoring' analysis: classification of 66 selected-relevant papers by type of 'Authoring' techniques and type of 'operations'.

	Assembly	Design	Diagnosis	Management	Repair	Training
Developers algorithmic	2	0	3	3	10	3
Experts algorithmic	2	1	1	1	1	1
Developers knowledge-based	2	0	0	0	0	0
Experts knowledge-based	0	0	1	0	1	0
Automatic algorithmic	2	5	10	7	2	1
Automatic knowledge-based	3	2	1	0	1	0
Total	**11**	**8**	**16**	**11**	**15**	**5**

The numbers in Table 8 help to support the findings discussed above, which are summarised below:

- There appears to be a correlation between the advancements in Authoring techniques and solutions for more fundamental AR challenges that is dependent on the 'operation' supported. Application fields where fundamental AR challenges have been solved have more advancements in Authoring techniques.
- AR knowledge transfer is affected by Authoring through its ability to create content. If the augmented content is correct, then the knowledge transfer obtained is valid.

- Development costs, industrial implementation, data and 'operation' adaptability, and knowledge transfer validity appear to be the research challenges in which Authoring techniques are focused on.
- 'Automatic' techniques perform better regarding development costs and industrial implementation.
- 'knowledge-based' techniques outperform in data and 'operation' adaptability as they represent better the maintenance 'operations' and data formats to be supported by AR applications.
- Research gaps in Authoring depend on the techniques their selves and the maintenance 'operations' where are being applied.
- There appears to be lack of research in Authoring automation for less-matured applications.
- Further research is required to automatise Authoring generically independently from the application.
- There appears to be lack of research in knowledge-domain structures for automatised Authoring.
- Further research is required in knowledge-domain representations for maintenance 'operations'.
- There appears to be lack of research in the effect of Authoring in knowledge transfer validity.
- Further research is required to improve Authoring adaptability to changing scenarios to increase AR knowledge transfer validity.

3.6. Context-Awareness

Context-Awareness techniques are defined as software methods, tools and techniques that use contextual information to characterise augmented content [98]. Where context is understood as *"any information that can be utilized to describe the situation of an entity. Where the entity can be a place, a person, or an object that is relevant to the interaction between a user and an application, such as time, location, activities, etc."* [12].

Contextualising augmented content in AR applications has the target of enhancing the user in his/her consecution of a 'task' [100]. Context-Awareness techniques achieve this by modifying already created content according to data obtained about the relevant context. This explanation includes the categories identified (Table 6) to classify Context-Awareness techniques: (i) contexts and (ii) rules. Rules refer to the logic/rational used to modify the content. These rules can be made ad-hoc for the AR application ('algorithmic') or based on knowledge-domain representations of the 'task' supported ('knowledge base'). Contexts refer to the relevant data according to which the content is being modified. These can be 'single', when rules consider only one piece of data, or 'multiple', when multivariable data is considered. Figure 17 presents the distribution of techniques categorised in the selected-relevant papers (29) that mention them.

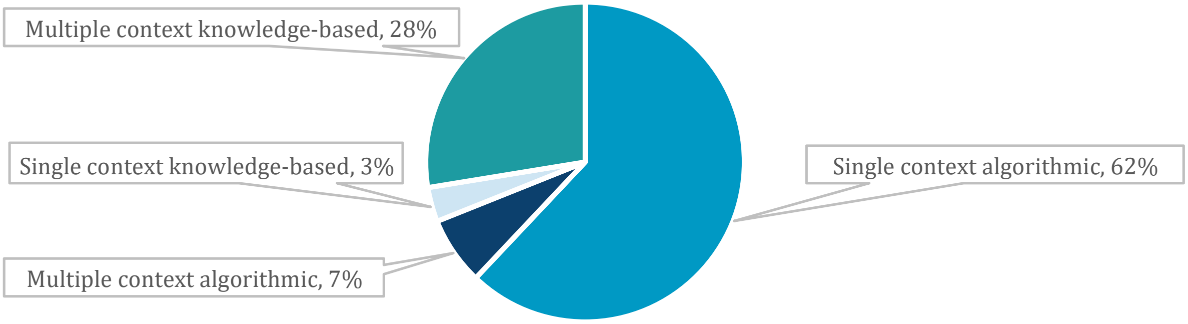


Figure 17. SLR analysis – 'Context-Awareness' analysis: classification of 29 selected-relevant papers by type of 'Context-Awareness' techniques.

Starting from the top and reading clockwise the first technique is ’Single context algorithmic’. It is worthy to note that 62% of selected-relevant papers that present evidence of Context-Awareness are related to this type. ’Single context algorithmic’ is the simplest method as it modifies augmented content according to one single variable through an algorithm “hard-coded” for the application. So, the adaptability of this technique to different situations is limited. A good example is presented in [73]. They present an algorithm that adapts the percentage of 3D model shown to the technician according to the percentage of 3D model printed. So, the technician can check for potential errors in the 3D printing process. These techniques help to modify the content accurately to the context. So, they are really good to increase the effectiveness of knowledge transfer. Relevant evidence can be found in [31,33,37,57,102].

A similar approach is taken by ‘Multiple context algorithmic’ techniques. A clear example can be found in [77]. In this case, the “hard-coded” algorithm considers the complexity of the visual interface and the difficulty of an ‘assembly’ operation to adapt the format of the content being shown. However, the content shown is not modified but instead, new content is created for each context scenario. Although, the benefits of these techniques are similar to the previous, they arise some drawbacks: increased development cost and difficulty to analyse the context. Content development costs are increased as more formats, and so contents, have to be created in order to keep up with contextualisation. Besides, the more complex the context is, the more difficult is to analyse it and identify the relevant variables.

The reason to use ‘knowledge-based’ techniques is to overcome the drawbacks mentioned above. They use knowledge-domain representations to identify context variables and determine the rules for modifying the content based on those. These techniques have direct advantages compared to the previous. First, there is no need to analyse relevant variables independently, as knowledge representations already consider them. Second, rules for adapting content can adapt to data formats; and so, content can be contextualised automatically. Therefore, there is no need to duplicate content and the associated costs can be reduced. The difference between ‘single context’ and ‘multiple context knowledge-based’ techniques is also related to the number of variables considered. Although, consideration of variables now depends on the ability to access or capture related data. A good example is presented in [97]. They present a Context Ontology for Maintenance Services (COMS) in which they consider variables (e.g. equipment model, expertise level, etc.) from different contexts (equipment, technician, etc.). They also use this ontology to add features to the content (e.g. text with associated 3D model), so it does not have to be duplicate it when contextualising it. More relevant evidence about these techniques can be found in [11,12,47,67,68,73,77,81,83,88].

3.6.1.Findings summary

Table 9 presents Context-Awareness techniques classified by ‘operation’ categories.

Table 9. SLR analysis – ‘Context-Awareness’ analysis: classification of 29 selected-relevant papers by type of ‘Context-Awareness’ techniques and type of ‘operations’.

	Assembly	**Design**	**Diagnosis**	**Management**	**Repair**	**Training**
Single context algorithmic	2	1	9	3	3	0
Multiple context algorithmic	0	0	0	0	1	1
Single context knowledge-based	0	0	0	1	0	0
Multiple context knowledge-based	4	1	0	0	3	0
Total	**6**	**2**	**9**	**4**	**7**	**1**

The numbers in Table 9 help to support the findings discussed above, which are summarised below:

- There appears to be a correlation between research in 'Context-Awareness' and advancements in 'Authoring' techniques. The more content is automatically created, the more content is contextualised.
- AR knowledge transfer is affected by Context-Awareness through its ability to adapt content. If the content is more accurate according to its context, then the knowledge transfer is more effective.
- Development costs, content accuracy and knowledge transfer effectiveness appear to be the research challenges in which Context-Awareness techniques are focused on.
- 'Algorithmic' techniques achieve a more accurate contextualisation at the expense of being limited and costly (replicated content).
- 'Knowledge base' techniques provide a wider contextualisation at the expense of being less accurate.
- Research gaps in Context-Awareness depend on accuracy, adaptability trade-off and the maintenance 'operations' in which is being applied.
- There appears to be lack of automatic contextualisation in 'algorithmic' techniques.
- Further research is required to automatise contextualisation and avoid content replication.
- There appears to be lack of data acquisition for context accuracy in 'knowledge base' techniques.
- Further research is required in automatic data acquisition to increase contextualisation accuracy.
- There appears to be lack of knowledge representations for context of certain maintenance 'operations'.
- Further research is required in knowledge-domain representations in 'diagnosis', 'management' and 'training' operations.

3.7. Interaction-Analysis

'Interaction-Analysis' techniques are defined as software tools, methods or techniques that analyse the status of the interaction between the user and the augmented content to provide relevant feedback and/or improve the interaction itself [13,14]. These techniques can be classified (Table 6) according to the level of automation regarding data acquisition (i) and analysis (ii). These categories identified the level of user input required to conduct the analysis of interactions. Figure 18 presents the distribution of categorised types among the selected-relevant papers (25) that present evidence of 'Interaction-Analysis' techniques.

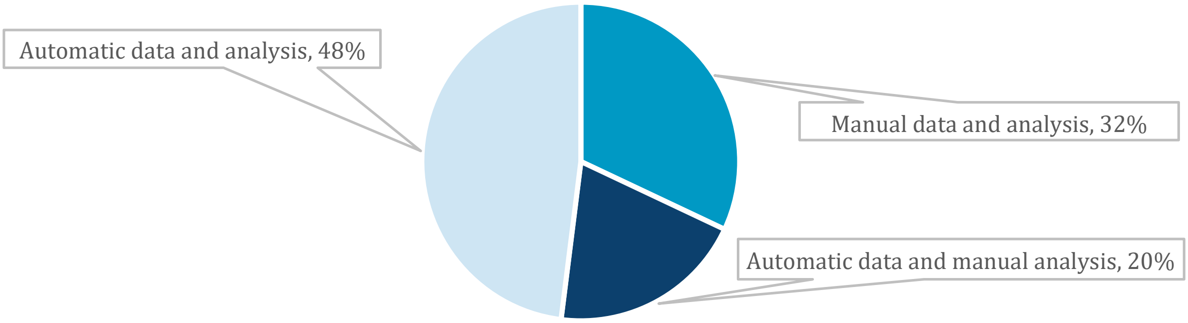


Figure 18. SLR analysis – 'Interaction-Analysis' analysis: classification of 25 selected-relevant papers by type of 'Interaction-Analysis' techniques.

'Manual data and analysis' are the second most extended 'Interaction-Analysis' techniques within the selected-relevant papers. These techniques provide manually acquired data (user feedback) for content creators to analyse it and modify contents and/or interactions. A good example is presented in [102]. They utilise users feedback about an asset for maintenance experts (content creators) to provide efficient augmented instructions about its repair in a product-service environment. These techniques help to increase knowledge transfer efficiency through a more accurate content at the expense of real-time content creation. They are mainly focused in human collaboration [13,97,102], human-robot collaboration 'management' operations [44,49,53] and procedural guidance [101]. Nevertheless, no real analysis is made by these techniques. They only gives support to users, who really made the analysis and/or the decisions.

'Automatic data and manual analysis' techniques are the least represented within selected-relevant papers. They automatically acquire data for users to achieve a more efficient analysis. Compared to 'manual data and analysis' techniques, the structure of data captured speed up the analysis increasing the efficiency of knowledge transfer. A clear example is described in [32]. Their AR system allows trainers to make decisions on next training steps based on real-time trainees' status. The same approach has been described in different contexts: assembly design [63], tunnelling construction inspection [37] and building energy performance evaluation [42]. Nevertheless, all these papers mention the need to provide automatic analysis in order to increase the efficiency of these techniques.

'Automatic data and analysis' techniques are the most represented (48%) within selected-relevant papers (Figure 18). These techniques acquire data and analyse it automatically, whose results are then use to modify content. Most techniques [14,40,41,45,47,57,70,87] still providing these results to experts for them to update augmented content. Instead, few latest papers have achieved to automatically connect these techniques with 'automatic' Authoring. So, they are able to create content or modify existing automatically according to the interaction between users and augmented content. Apart from increasing knowledge transfer efficiency and reducing developments costs, these mixed techniques [81,83,86,88] have achieved knowledge capture capabilities. A good example is presented in [83]. They track the interaction between users and 3D models to analyse their trajectories and infer movement tasks associated with the real objects the 3D models represent. These tasks are then transferred to humanoid robots (programmed) or other users (animations). Apart from merging Authoring and Interaction-Analysis, these papers also present evidence of Context-Awareness for automatic interaction-data acquisition. Therefore, it appears reasonable to believe that joining Authoring, Context-Awareness and Interaction-Analysis techniques it is possible to also enable knowledge capture capabilities in AR technologies.

3.7.1.Findings summary

Table 10 presents Interaction-Analysis techniques classified by 'operation' categories.

Table 10. SLR analysis – 'Interaction-Analysis' analysis: classification of 25 selected-relevant papers by type of 'Interaction-Analysis' techniques and type of 'operations'.

	Assembly	Design	Diagnosis	Management	Repair	Training
Manual data and analysis	1	0	0	3	3	1
Automatic data and manual analysis	1	1	2	0	0	1
Automatic data and analysis	4	1	3	3	0	1
Total	**6**	**2**	**5**	**6**	**3**	**3**

The numbers in Table 10 help to support the findings discussed above, which are summarised below:

- There appears to be a positive correlation between advancements in Interaction-Analysis and Context-Awareness and Authoring advancements classified by maintenance ‘operations’.
- AR knowledge transfer is affected by Interaction-Analysis through its ability to improve content. If content’s accuracy and correctness are increased, then knowledge transfer is more efficient.
- AR knowledge capture capabilities are obtained when Authoring, Context-Awareness and Interaction-Analysis techniques are enabled jointly.
- AR knowledge capture capabilities have only been achieve in ‘assembly’ operations.
- Knowledge transfer efficiency and development costs appear to be the research challenges in which Interaction-Analysis techniques are focused on.
- The more automation in data acquisition and analysis, the more efficient knowledge transfer becomes. Although, the ability to adapt content to different situations (content validity) decreases.
- Research gaps in Interaction-Analysis depend on their relation with maintenance ‘operations’ and Authoring and Context-Awareness research gaps.
- There appears to be lack of manual data acquisition research in ‘design’ and ‘diagnosis’ operations.
- Further research is required in how to capture user feedback in maintenance ‘design’ and ‘diagnosis’.
- There appears to be lack of automatic analysis research in ‘management’ and ‘repair’ operations.
- Further research is required to understand how AR interactions affect maintenance ‘management’ and ‘repair’ efficiency.
- There appears to be lack of research in AR knowledge capture capabilities in maintenance ‘operations’.
- Further joint research in Authoring, Context-Awareness and Interaction-Analysis is required in maintenance ‘operations’ but ‘assembly’.

4. Results

The thematic analysis provides enough evidence base to answer adequately the research questions. These answers, which are the results of the research conducted, are presented in the following subsections.

4.1. What is the state-of-the-art in A, CA and IA techniques for AR maintenance applications?

A detailed description of existing techniques in Authoring (Subsection 3.5), Context-Awareness (Subsection 3.6) and Interaction-Analysis (Subsection 3.7) was provided earlier in this paper. Besides, here the authors summarise the latest techniques and their advantages, disadvantages and application areas:

- **Authoring:** content can be created either by ‘developers’, ‘experts’ or ‘automatically’, following specific-application (‘algorithmic’) or domain ‘knowledge-based’ rules. ‘Automatic’ techniques improve development costs and industrial implementation while limiting content adaptability. Besides, ‘knowledge-based’ techniques enrich content validity and ‘operation’ adaptability. ‘Automatic knowledge-based’ are the ultimate techniques. These create augmented content automatically from existing data according to ‘operation’ knowledge-domain rules. Nevertheless, they require detailed knowledge-domain representations which have only been achieved for ‘small’ assets in ‘design’ and ‘assembly’ operations.

- **Context-Awareness:** content can be modified based on 'single' or 'multiple' contexts (variables) according to specific-application ('algorithmic) or application-domain 'knowledge-based' rules. 'Multiple-context' provide more accurate contextualisation at the expense of higher development costs compared to 'single-context' techniques. Besides, 'knowledge-based' provide a wider contextualisation but less accurate than 'algorithmic' techniques. 'Multiple-context knowledge-based' are the most advanced. These use knowledge-representations of maintenance 'operations' to contextualise augmented content and are often connected to 'automatic knowledge-based' Authoring tools that share the same knowledge-domain representations. These techniques have been achieved only for 'repair' and 'assembly' operations.
- **Interaction-Analysis:** user-content interactions can be analysed 'automatically' or 'manually'. The same approaches can be used to acquire the data necessary for the analysis. The more automatic these processes become, the more effective analysis is for further content modification at the expense of less content adaptability. 'Automatic data acquisition and analysis' are the ultimate techniques. Their automatic results from user-interaction analysis provide direct rules to improve content creation (Authoring) and adaptation (Context-Awareness). To obtain those direct rules, they require to share knowledge-domain representations with Authoring and Context-Awareness techniques. That is why these techniques have only been achieved for 'assembly' operations in 'small' assets.

4.2.What are the research gaps in A, CA and IA for AR maintenance applications?

Specific discussions about existing A (Subsection 3.5), CA (Subsection 3.6) and IA (Subsection 3.7) techniques identified research gaps about their development. Besides, Subsection 3.2 presents a detailed map of A, CA and IA techniques application in maintenance 'operations' for different 'assets. This map recognised research gaps concerning A, CA and IA application in different maintenance scenarios. Although these research gaps have already been discussed, both kinds are summarised in the following subsections.

4.2.1. Research gaps in Authoring, Context-Awareness and Interaction-Analysis techniques

1. Authoring

Authoring aims to create augmented content. Research has focused on creating 'automatic' methods in order to reduce industrial implementation issues and development costs. Although they are more efficient, they lack of ability to adapt content to different scenarios (data formats, 'tasks', and 'operations'). That is why 'knowledge-based' techniques were proposed. So, the content is directly related to the maintenance knowledge-domain covered by the AR application. These approaches enhance content adaptability to maintenance 'operations', but other issues on industrial implementation still unsolved (e.g. adaptability to existing data formats and data storages, 'tasks', etc.). These are more AR-focused challenges and require from a more fundamental perspective rather than application-centred:

- There is lack of research regarding what kind of content to create depending on the 'tasks' to provide and not only the 'operation'. Further research is required to define knowledge representations for the Authoring domain. So, knowledge-based rules can be applied to Authoring additionally to those of the application ('operation' knowledge domain).

- There is lack of research regarding Authoring adaptability to data formats and databases. Most ‘automatic’ techniques rely on specific data formats to create content from existing data [96,98]. Further research is required to enable automatic data conversions that capture the necessary features for content augmentation (e.g. string arrays from .doc files, small 3D meshes from CAD files, etc.).

Besides, there are certain maintenance ‘operations’ which do not have knowledge representations to enable ‘automatic’ Authoring. These research gaps are discussed in the following Subsection (4.2.2).

2. Context-Awareness

Context-Awareness aims to contextualise content created according to certain real-time variables (e.g. modify animations for assembly training according to user’s expertise level). Research has focused on developing ‘knowledge-based’ techniques. So, knowledge about a certain domain (‘operation’) to identify valid variables to create contextualisation rules (e.g. to identify expertise level by understanding time for a given instruction and years of working experience). Nevertheless, these techniques have some drawbacks regarding industrial implementation and development costs:

- There is lack of research on automatic content contextualisation. Due to the difficulty to classify this contextualisation (e.g. degree of difficulty), most Context-Awareness techniques require to duplicate content instead of modifying existing (e.g. different text instructions depending on difficulty). Further research is required in automatic contextualisation techniques to avoid content duplication.
- There is lack of research on automatic contextual data acquisition. The use of complex variables for contextualisation while level of accuracy derives on difficulties for acquiring data for those variables (e.g. time to conduct an instruction for calculating user’s experience level). Further research is required on obtaining or calculating contextualisation variables or reducing their complexity.
- Although the previous research gaps can be considered ‘operation’ dependent (contextual variables depend on the specific ‘operation’ domain), they can be considered from an AR-centred perspective. Further research is required to understand and describe the knowledge domain of Context-Awareness.

Besides, those two gaps still requiring from research in knowledge-domain representations regarding the context of certain maintenance ‘operations’. These domains are in listed in Subsection 4.2.2.

3. Interaction-Analysis

Interaction-Analysis aims to analyse user-content interaction for enhancing augmented content effectiveness. Research has focused on creating ‘automatic’ techniques which can capture interaction-performance data and analyse it. Moreover, some techniques are able to connect those results with ‘automatic’ Authoring and Context-Awareness techniques, enabling knowledge capture capabilities. Nevertheless, most of these techniques still quite application-specific and almost none achieve knowledge capture. There are various reasons for this:

- There is lack of research on AR interactions and their features. Although they are similar, interactions are defined specifically for each application, and so Interaction-Analysis methods are difficult to extrapolate from one application to another. Further research is required to describe AR interactions and define knowledge representations for the Interaction-Analysis domain.

- There is lack of research on how to connect IA with A and CA techniques. Although the results of IA techniques are supposed to affect A and CA, most papers do not present evidence on how to connect them. Further research is required to provide rules from IA results to connect them automatically with A and CA techniques.

Besides, knowledge-domain representations in certain 'operations' have not achieved to represent user performance, needed for Interaction-Analysis. These domains are in listed in Subsection 4.2.2.

4.2.2. Research gaps in A, CA and IA implementation in maintenance 'operations'

Although some A, CA and IA techniques have been achieved for certain 'operations, they are not directly applicable. This because there are still some research gaps which have not been fulfil for those 'operations':

1. Lack of knowledge-domain representations. There is the need to define knowledge structures such as ontologies or taxonomies to describe those maintenance 'operations'. So, A, CA and IA existing techniques can be applied to those.
2. Lack of 'automatic' Authoring techniques. For those maintenance 'operations' where AR research still at a fundamental stage (e.g. hardware, tracking issues), Authoring still being made by AR developers.
3. Lack of 'knowledge-based' methods for Authoring and Context-Awareness techniques. There are 'operations' where knowledge representations exist but those techniques have not been achieved yet.
4. Lack of 'automatic data acquisition and analysis' Interaction-Analysis techniques. These can only be obtained when 'knowledge-based' A and CA exist. Moreover, these 'operations' require of further methods to merge A, CA and IA techniques.

This list of research gaps establishes a road-map of A, CA and IA research needs depending on the maintenance 'operation' and the 'asset' being considered. The end is to achieve latest techniques in each area: 'automatic knowledge-based' Authoring, 'multiple-context knowledge-based' Context-Awareness and 'automatic data acquisition and analysis' Interaction-Analysis. This is the set that enables AR knowledge capture and has only been achieved for 'assembly' operations in 'small' assets. For the rest of 'operations', Table 11 presents at which research gaps from the previous list need (table letters correspond to the list).

Table 11. SLR results: map of A, CA and IA research gaps in AR applications for maintenance 'operations' classified by 'assets'.

	Assembly	Design	Diagnosis	Management	Repair	Training
'Large' assets	2	2	1, 3	2	2	1, 3
'Medium' assets	1, 3	2	1, 3	4	2	2
'Small' assets	*	4	1, 3	2	4	1, 3

4.3.What are the relations between A, CA and IA techniques and knowledge transfer?

A, CA and IA techniques are related to the augmented content creation, contextualisation and improvement. Augmented content is the AR vehicle for knowledge transfer, as it is this content what puts information into context. Nevertheless, how these techniques affect to knowledge transfer is not a trivial question. Findings from A (3.5), CA (3.6) and IA (3.7) Analysis Subsections are summarised below:

- AR knowledge transfer is affected by Authoring through its ability to create content. If the augmented content is correct, then the knowledge transfer obtained is valid.

- AR knowledge transfer is affected by Context-Awareness through its ability to adapt content. If the content is more accurate according to its context, then the knowledge transfer is more effective.
- AR knowledge transfer is affected by Interaction-Analysis through its ability to improve content. If content's accuracy and correctness are increased, then knowledge transfer is more efficient.

A theoretical explanation can be given to these findings. Authoring creates content based on information. If the information used to create the content is not right, then the knowledge transfer is not valid (e.g. using the wrong 3D animation to explain an instruction). Context-Awareness adapts the content generated to the specific context (e.g. user expertise). If the content is not adapted properly or to the wrong context, then the knowledge transfer is not effective (e.g. using step-by-step 3D animations for simple instructions for an expert). Interaction-Analysis evaluates the user-content interaction (knowledge transfer performance) and provides improvements for content's creation and contextualisation. So, it affects knowledge transfer efficiency by increasing content's correctness and accuracy.

4.4. What knowledge types are transferable by AR?

The analysis of the different types of 'knowledge' considered in each selected relevant paper have found an important outcome: *'only that knowledge that can be represented ('explicit' knowledge) is able to be transferred by AR technologies'.* This finding seems reasonable. Only knowledge that can be transcribed in information can be transferred using Augmented Reality. Another question is whether 'implicit' can be converted into 'explicit' knowledge. Experts in knowledge management and conversion identify the SECI model [6,103] as a valid method to achieve that. Nevertheless, an interesting question for future AR research is whether AR can help to enhance the use of that model in organisations.

Two types of explicit knowledge where identified in the thematic categorisation (Table 6): 'procedural' and 'declarative'. These two are similar to categories to those described by knowledge experts [103]. Besides, findings from the Analysis section (3.3 and 3.4) how these types relate to AR and maintenance applications:

- There appears to be a correlation between 'tasks' and 'knowledge' types provided by AR applications.
- 'Declarative' knowledge is more common in 'simulation' and 'monitoring' tasks and 'procedural' in 'guidance' tasks.
- There appears to be lack of 'tasks' to support certain 'operations': 'guidance' for 'design' and 'diagnosis'.
- Therefore, further research is required to explicit 'procedural' knowledge in 'design' and 'diagnosis' operations.

4.5. What potential applications of AR knowledge transfer are in maintenance contexts?

Knowledge transfer can be considered a primal objective of any AR application. As discussed in previous sections, as long as there are Authoring within an AR application, knowledge transfer is enabled. Then, this knowledge transfer can be mode more effective and efficient through Context-Awareness and Interaction-Analysis, respectively. In the case of maintenance applications, Table 11 identifies the road-map in AR research to achieve effective and efficient knowledge transfer for each maintenance 'operation' and 'asset'. Throughout the analysis conducted in this paper, it has been considered that AR technologies are able to transfer knowledge from data-repositories or experts to AR users. But little has been said about the opposite direction, where knowledge is transferred from AR users to data-repositories. This opposite direction has been described by experts as knowledge capture .

Knowledge capture is defined as *"the process of retrieving either explicit or implicit knowledge that resides within people, artefacts, or organizational entities"* [103]. In the case of AR, it seems reasonable to narrow this definition to the retrieving of explicit knowledge from people (AR users). Unlike knowledge transfer, AR knowledge capture capabilities require more from A, CA and IA techniques to be enabled. This can be theoretically explained through the connection between content, user and knowledge. In knowledge transfer, knowledge is delivered through the content. Instead in knowledge capture, knowledge should be obtained from the content. Therefore, content should be created by the user in order to capture the information and the context of use. That is why Interaction-Analysis and Context-Awareness are also required, so the context and the interaction can be analysed to check whether the content is correct and accurate. Only few evidences [83,88] of AR knowledge capture have been found in this SLR. These recognised that knowledge capture was achieved in 'assembly' of 'small' assets with certain techniques: 'automatic knowledge-based' Authoring, 'multiple-context knowledge-based' Context-Awareness and 'automatic data acquisition and analysis' Interaction-Analysis. Nevertheless, further research is required to specify how knowledge capture can be obtained with AR and what other knowledge management processes can be enhanced through the use of this technology.

5. Discussion

The results (Section 4) offer a discussed view of this SLR objectives and findings. Still, it is needed to assess to what extent its research methods and results are valid. That is the purpose of this section. Research methods are discussed according to their validity and objectivity in Subsection 5.1. Research results are examined regarding their quality, validity and applicability in Subsection 5.2.

5.1. Research methods validity and objectivity

In order to provide a suitable discussion, it is important to define validity and objectivity of the research methods utilised in this SLR. By validity, the authors understand the extent to which the research methods achieve the research objectives. By objectivity, the authors refer to ability to avoid bias in and increase transparency and replicability of the research. In this Subsection, frameworks and methods used within each phase of the SLR (Figure 1) are examined against these two concepts:

- **SLR method selection:** SALSA [29] is a framework that conceptualises the stages of a systematic literature review and identifies the most suitable methods for each phase according to its objectives. It has been selected, against others such as Kitchenham's [104], Cochrane [105] or Xiao and Watson's [106], due to the following reasons. First, its approach is generic enough to be applicable for different reviews. Second, it proposes validated research methods for each phase. Last but not least, several authors have already applied this framework for similar reviews in this research field [8,27].

- **Protocol:** the PICOC framework [28] was used at this stage to determine this review's scope. The SALSA framework [29] identifies some frameworks to do this (PICOC, SPICE, CIMO, etc.). The selection of one depends on the type of research questions to define. For this SLR, the PICOC framework was chosen due to two reasons. First, it is a valid, well-contrasted tool that has been used in other reviews within the same research field [8,27]. Second, it helps to identify the main concepts to define the research methods required for following SLR steps [28]. It is the authors believe that this selection helps to achieve further transparency and replicability for the systematic review proposed.
- **Search:** the definition of search parameters (databases and string) was made based on PICOC framework results and supported on the propositions of similar reviews [8,26,27]. Regarding the database selection, only those which were relevant and provided necessary meta-data were included. Therefore, it is the authors believe that the database selection can provide a relevant sample of papers and the SLR results should not be affected. Regarding the search string, it was created following the guidelines from Booth et. al [28] and only included those terms within the research scope. Therefore, it is the authors believe that the string created covers the research population the SLR was aiming to.
- **Appraisal:** one important topic to discuss is the inclusion/exclusion criteria definition. The criteria were determined utilising the research scope (Table 1), the guidelines from similar works [8,10,27] and the authors experience in the research field. These criteria can be classified in four categories:

1. Criteria directly connected to the research scope (I1, I2, I3, E4, E5): these criteria were defined using the required concepts from the PICOC framework (Table 1): interactions and context. The aim was to select those papers searched by population which had certain relevancy for the topic being reviewed.
2. Criteria indirectly connected to the research scope (E2): the authors noticed that the AR community was not focus in A, CA and IA associated challenges prior to 2012. Either because these challenges were not clearly identified then or because the techniques their selves were not mature enough to be explicitly described yet. These arguments are supported by other authors (e.g. Nee et. al), who did not mention these topics in their reviews before 2012 [25,107] but they did from then onwards [1,4].
3. Criteria related with research/data accessibility (E1, E3, and E8): these help to ensure that selected-relevant papers are fully assessed. So, all the evidence required from them can be extracted.
4. Criteria related with research quality and validity (E6 and E7): these help to ensure that selected-relevant papers present complete, peer-reviewed conclusions. So, the findings used to draw conclusions in this review are correct.

These criteria are supposed to be able to narrow down the papers' population from the search results to a sample specifically related to this SLR scope. Therefore, it could be said that these criteria were complete and sufficient for the purpose of this SLR. Besides, it is also important to note the resulted number of selected-relevant papers. The criteria were applied in order to obtain papers that are relevant for the reviewing topics. So, the number of papers selected should not affect the validity of the SLR results. However, this number is comparable to those in similar reviews [4,8,10,27].

- **Synthesis:** there are two important topics to discuss: themes definition and thematic categorisation. The definition of the right themes is critical to extract the relevant and necessary evidence from papers regarding the SLR questions. Following experts suggestions [8,27,28], these have been defined considering the concepts within the SLR scope (Table 1). Besides, the thematic categorisation helps to classify and analyse the data extracted from the papers. So, its outcomes directly influence the SLR results. Because no method have been found in similar works within the research field, a systematic, reproducible process was created following the guidelines from experts [28]. Moreover, the resulted categories were validated and corrected by comparison with similar works [8,26,27].

- **Analysis:** the analysis was conducted with a combination of narrative, tabular and graphical analysis. In order to increase the reproducibility of the research, it is needed to describe how graphs and tables where selected. This selection was part of the exploratory phase of the analysis. The patterns identified between categories (variables) were transferred to graphs for supporting the narrative analysis. Besides, although the results section (Section 4) includes a summary of the findings, the analysis (Section 3) was included for transparency and reproducibility of the results obtained.
- **Report:** within those suggested by the SALSA framework [28], the PRISMA methodology [30] was the most mature tool identified for reporting. That is why it was selected to write the report and then create the paper by excluding those parts which did not add value to the community. Thus, the authors believe that the article includes all the information required to understand and replicate the SLR.

Based on the previous discussions, some improvements have been identified and are listed below:

- To reduce quality assessment biases and provide additional results to be used during the analysis.
- To enhance validation of thematic categorisation results.
- To provide standardised guidelines for the exploration within the analysis phase.
- To include a standard method for research methods reporting.

Besides these improvements, the application of the SALSA framework along with the research methods selected can be considered a valid approach. Therefore, further applications of it can also be considered within the same research field:

- To review A, CA and IA and their relations with knowledge transfer capabilities in other AR fields of application (e.g. medicine, marketing, manufacturing, etc.).
- To review knowledge transfer capabilities of other visualisation technologies (e.g. Virtual Reality).

5.2. Research results quality, validity and generality

If the research method assessment provides an evaluation of the internal validity of the research, the results assessment does if for the external validity [28]. Three criterions are used to evaluate this SLR findings and results. By quality, the authors refer to the value of the results according to the research questions. By validity, the authors understand the effectiveness of results. By generality, the authors consider the extent to which the results are applicable. Results quality and validity are discussed for each research question independently.

1. **What is the state-of-the-art in A, CA and IA techniques for AR maintenance applications?**

Part of the narrative analysis provided on AR applications (3.2) and A (3.5), CA (3.6) and IA (3.7) techniques is already a description of the state-of-the-art that can be considered a result. Besides, these results are summarised and further discussed in the correspondent results Subsection (4.1). These results explain the latest advancements of A, CA and IA techniques in AR maintenance applications and their benefits and drawbacks to the time when the analysis was done. Even though there could be techniques not covered in this research (e.g. newer papers not included), the categorisation proposed enables to introduce and classify new techniques. Therefore, this SLR results are still valid as long as they are updated with new evidence from latest relevant publications.

2. What are the research gaps in A, CA and IA for AR maintenance applications?

The rest of the narrative analysis provided on AR applications (3.2) and A (3.5), CA (3.6) and IA (3.7) techniques has been used to identify and discuss these research gaps. Due to the scope of this SLR, two types of research gaps have been identified.

One type refers to research gaps in A, CA and IA techniques. These are more AR-focused, fundamental research gaps rather than maintenance-centred. The validity of these results may be affected due to the narrow scope of the SLR considering AR. The gaps identified might have been solved in other papers which were not relevant to this SLR scope (e.g. other application fields, computer science papers, etc.). However, it seems reasonable to believe as no evidence of such papers have been found referenced within the selected-relevant sample.

The other gap type relates to the application of A, CA and IA in maintenance ‘operations’. They identify research gaps within specific ‘operations’ compared to those most advanced. That is why a road-map for future research in AR-maintenance applications. Although these gaps have already been solved for different applications, it is still a contribution to apply those techniques to different scenarios. And so, those can still be considered research gaps.

3. What are the relations between A, CA and IA techniques and knowledge transfer?

These relations have been declared within the results section (4.3). A theoretical discussion was conducted to establish those relations. Besides, the results from that discussion are supported by findings from the Analysis section (3.3 and 3.4) which present evidence from the selected-relevant papers. Therefore, it seems reasonable to believe that the explanation given to this question is sufficient to understand those relations. Nevertheless, further research to understand those relations more in-depth would be advisable.

4. What knowledge types are transferable by AR?

The results related to this part of the analysis (3.3 and 3.4) demonstrate that only ‘explicit’ knowledge can be transferred by AR technologies. Besides, the categories identified (Table 6) within the SLR coincide with the definitions provided by experts in knowledge related research. Even though it could be argued that other knowledge classifications could be used, the one utilised is coherent and consistent with the results obtained. Therefore, it seems reasonable to say that the categorisation obtained is sufficient. Nevertheless, other research gaps along these matters have been identified and discussed within the correspondent results Subsection (4.4).

Those gaps are related to the support provided by AR 'tasks', the 'knowledge' type being transferred and the need to explicit that knowledge. Although the scope of these gaps is outside the scope of this SLR, it seems reasonable to say that they are important to AR related research. It is necessary to understand how certain 'knowledge' can be specified in order to comprehend whether AR can be a useful to transfer it.

5. What potential applications of AR knowledge transfer are in maintenance contexts?

Rather than the application of AR knowledge transfer in maintenance, the section on this SLR question (4.5) discusses the idea of knowledge capture using AR. The idea is supported by evidence from selected-relevant papers and inferred during the Analysis phase of this SLR. The discussion (4.5) provides a theoretical explanation of how AR knowledge captured is achieved with A, CA and IA techniques and how does it affect to the AR research gaps previously identified. Therefore, although the idea was not considered within the initial SLR scope, it seems reasonable to include it as an additional, relevant finding.

Besides, research results should also be discussed according to their validity. Summarising the answer to the SLR questions (Section 4), it can be said that A, CA and IA techniques and AR knowledge transfer capabilities have been reviewed within the context of maintenance applications. The context of maintenance applications has been narrowed to medium-long life complex assets. There were two reasons to establish this scope. First, it includes maintenance applications where knowledge transfer is required. Second, it helps to reject papers where maintenance of low value assets is considered, which can be different in terms of knowledge transfer requirements. Nevertheless, it could be argued than low value assets do not require complex maintenance operations and so these AR applications are closer to manufacturing rather than maintenance operations.

Besides, the results of this research cannot be validated to other AR fields of application, such as manufacturing, medicine, marketing, etc. Further research should be required to extend the description of AR knowledge transfer capabilities and the techniques that enable them for other fields of application. Moreover, there is also an idea behind this research that could be considered for other visualisation or knowledge transfer technologies under research and development. These results could be used as basics to understand by comparison how other technologies' techniques enable knowledge transfer capabilities.

The previous discussions on research method and results cover different perspectives to the results and discussions presented in other sections of this SLR. All can be used as basis to extract conclusions and future works regarding this research.

6. Conclusions and future works

Academic literature reviews in AR have not focus on A, CA and IA techniques for maintenance applications neither in AR knowledge transfer capabilities. Therefore, this paper has aimed to describe the state-of-the-art in A, CA and IA techniques and their relations with AR knowledge transfer capabilities in maintenance contexts. In order to do so, a SLR of 74 relevant papers was conducted.

The SRL research protocol was based on the SALSA Framework [28] and inspired in similar reviews [8,10,27]. The protocol presented (Section 2) ensures both reproducibility and transferability of the study.

The SLR comprised the search and appraisal of applied research in AR-maintenance journal articles. It also included a thematic analysis (Section 3) of 74 relevant-selected papers. The results of such analysis were used to answer five pre-defined research questions: (1) the description of the state-of-the-art of ACAIA techniques in maintenance contexts, (2) their research gaps, (3) their relations with AR knowledge transfer capabilities, (4) the types of knowledge transferrable and (5) potential applications for AR knowledge transfer. The answers and discussions related to SLR questions are reported in Section 4. Besides, research methods and results are discussed in Section 5 according to their validity and applicability.

Overall, this research has led to some conclusions in the area of AR in maintenance, A, CA and IA techniques, and knowledge transfer capabilities. Conclusions from Section 4 and 5 are summarised below:

- A, CA and IA techniques have achieved different levels of technological maturity in different maintenance applications ('operations' by 'asset).
- There appears to be a correlation between these technological maturity levels and the existence of knowledge-domain representations for the maintenance applications ('operations') considered.
- Development costs, industrial implementation and data and maintenance 'operation' adaptability appear to be the research challenges in which A, CA and IA techniques are focused on.
- A, CA and IA affect respectively to AR knowledge transfer validity, effectiveness and efficiency.
- There appears to be a correlation between certain 'tasks' and 'knowledge' types in AR applications.
- There appears to be a positive correlation between advancements in Interaction-Analysis, and Context-Awareness and Authoring advancements classified for maintenance 'operations'.
- Latest advanced techniques in A, CA and IA are respectively: 'automatic knowledge-based', 'multiple-context knowledge-based' and 'automatic data acquisition and analysis'.
- These advanced techniques are capable to trigger AR knowledge capture capabilities.

The research gaps and the conclusions identified by this research also draw a map that points to various future research directions. A summary of all further research works mentioned within the results and discussion sections is listed below:

- **SLR methods improvements:** (i) standard methods for thematic categorisation; (ii) standard methods for thematic exploratory analysis; and (iii) standard reporting of narrative/tabular analysis.
- **SLR methods applicability:** (i) to conduct similar reviews in other fields of application within AR; and (ii) to conduct similar reviews to other knowledge transfer technologies.
- **Authoring:** (i) to define a knowledge representation of the Authoring domain; and (ii) to enable automatic data conversions considering special features of content augmentation.
- **Context-Awareness:** (i) to study automatic contextualisation for avoiding content duplication; (ii) to study automatic context data acquisition for enhancing contextualisation accuracy; and (iii) to define a knowledge representation of the Context-Awareness domain.
- **Interaction-Analysis:** (i) to study AR user-content interactions from a generic perspective; (ii) to define a knowledge representation of the Interaction-Analysis domain; and (iii) to study methods for automatically varying A and CA results depending on IA outcomes.

- **Road-map for A, CA and IA in maintenance applications** (Table 11)**:** (i) to define knowledge-domain representations of 'diagnosis' and 'training' of 'large' assets, 'assembly' and 'diagnosis' in 'medium' assets, and 'diagnosis' and 'training' of 'small' assets; (ii) to apply 'automatic' Authoring in 'assembly', 'design', 'management' and 'repair' operations in 'large' assets, 'design', 'repair' and 'training' operations in 'medium' assets, and 'management' operations in 'small' assets; (iii) to apply 'knowledge-based' Authoring and Context-Awareness methods in diagnosis' and 'training' of 'large' assets, 'assembly' and 'diagnosis' in 'medium' assets, and 'diagnosis' and 'training' of 'small' assets; and (iv) to apply 'automatic data acquisition and analysis' Interaction-Analysis methods in 'management' of 'medium' assets and 'design' and 'repair' of 'small' assets.
- **Knowledge types transferrable by AR:** (i) to study knowledge representations to explicit 'procedural' knowledge in 'design' and 'diagnosis' operations.
- **AR knowledge transfer applications in maintenance contexts:** (i) to study how knowledge capture can be obtained in AR applications; (ii) to study where AR knowledge capture can have value within maintenance 'operations'; and (iii) to study which other knowledge-management processes can be enhanced by the use of AR in maintenance-related organisations.

Augmented Reality has been revealed as an impactful technology for organisations to transfer knowledge (from information systems to users) and capture and discover it (from users to information systems). Nevertheless, there are still some questions that have not been answered yet: what are the requirements to achieve it in real-world scenarios? What other technologies could be integrated with AR to achieve more powerful applications? What would be the role of AR in industrial organisations? What would be the role of AR in knowledge management? Even though AR is a maturing technology close to achieve real-life implementation, there are still many questions to answer about what its full potential is.

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